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PREFACE

This volume contains all abstracts submitted for publication during calendar year 1984 by the staff and students of the Woods Hole Oceanographic Institution. Because some of the abstracts may not be published in the journal to which they have been submitted initially, we have purposely omitted identifying the journals. The volume is intended to be informative, but not a bibliography.

The abstracts are listed by title in the Table of Contents and are grouped into one of our five departments, marine policy, or the student category. An author index is presented in the back to facilitate locating specific papers.

A handwritten signature in dark ink, appearing to read "Derek W. Spencer", is written over a horizontal line.

Derek W. Spencer
Associate Director for Research

TABLE OF CONTENTS

DEPARTMENT OF BIOLOGY

B-1

Animal Physiology and Biochemistry

PECTORAL FIN LOCOMOTION: ACCELERATION PATTERNS DURING STEADY SWIMMING BY CUNNERS AND TAUTOGS (LABRIDAE)	
Marvin A. Freadman	B-3
CARDIORESPIRATORY DYNAMICS OF <u>Limulus polyphemus</u> (L.): RELATIONSHIPS DURING REST, VENTILATION AND SWIMMING ACTIVITY	
Marvin A. Freadman and Winsor Hayes Watson, III	B-3
A TESTOSTERONE HYDROXYLATING CYTOCHROME P-450 ISOZYME PURIFIED FROM THE MARINE TELEOST <u>Stenotomus chrysops</u>	
Alan V. Klotz, John J. Stegeman and Chris Walsh	B-3
GROWTH AND BIOCHEMICAL COMPOSITION OF THE LARVAE OF <u>Teredo navalis</u> L. AND <u>Bankia gouldi</u> (Bartsch)	
Roger Mann and Scott M. Gallager	B-4
GROWTH, MORPHOMETRY AND BIOCHEMICAL COMPOSITION OF THE WOOD BORING MOLLUSCS <u>Teredo navalis</u> L., <u>Bankia gouldi</u> (Bartsch) AND <u>Nototeredo knoxi</u> (Bartsch)	
Roger Mann and Scott M. Gallager	B-4
OSMOREGULATION IN THE BROOK TROUT, <u>Salvelinus fontinalis</u> .	
I. DIEL, PHOTOPERIOD AND GROWTH RELATED PHYSIOLOGICAL CHANGES IN FRESHWATER	
Stephen D. McCormick and Robert J. Naiman	B-5
OSMOREGULATION IN THE BROOK TROUT, <u>Salvelinus fontinalis</u> .	
II. EFFECTS OF SIZE, AGE AND PHOTOPERIOD ON SEAWATER SURVIVAL AND IONIC REGULATION	
Stephen D. McCormick and Robert J. Naiman	B-5
PHYSIOLOGICAL SMOLT CHARACTERISTICS OF ANADROMOUS AND NON-ANADROMOUS BROOK TROUT (<u>Salvelinus fontinalis</u>) AND ATLANTIC SALMON (<u>Salmo salar</u>)	
Stephen D. McCormick, Robert J. Naiman and Ellyn T. Montgomery	B-6

Aquaculture

SAMPLING OF BIVALVE LARVAE	
Roger Mann	B-6
DEGRADATION OF <u>Artemia</u> LIPIDS UNDER STORAGE	
Glenn C. Sasaki and Judith M. Capuzzo	B-7

Benthos

LIFE HISTORY AND PRODUCTION OF THREE AMPHIPOD SPECIES ON GEORGES BANK	
Jeremy S. Collie	B-7
DEEP-SEA FAUNA OF SEDIMENTS IN THE VICINITY OF HYDROTHERMAL VENTS	
J. Frederick Grassle, L. Susan Brown-Leger, Linda S. Morse-Porteous, Rosemarie F. Petrecca and Isabelle P. Williams	B-7
SUBTIDAL MACROBENTHOS OF NARRAGANSETT BAY. FIELD AND MESOCOSM STUDIES OF THE EFFECTS OF EUTROPHICATION AND ORGANIC INPUT ON BENTHIC POPULATIONS	
J. Frederick Grassle, Judith P. Grassle, L. Susan Brown-Leger, Rosemarie F. Petrecca and Nancy J. Copley	B-8

Biogeography and Systematics

MICTACEA, A NEW ORDER OF CRUSTACEA PERACARIDA	
Thomas E. Bowman, Susan P. Garner, Robert R. Hessler, Thomas M. Iliffe and Howard L. Sanders	B-8
STUDIES ON DEEP-SEA PROTOBRANCHIA (BIVALVIA); THE FAMILY MALLETIIDAE	
Howard L. Sanders and John A. Allen	B-8
<u>Hirsutia bathyalis</u> , A NEW UNUSUAL DEEP-SEA PERACARIDAN CRUSTACEAN FROM THE TROPICAL ATLANTIC	
Howard L. Sanders, Robert R. Hessler and Susan P. Garner	B-8

ADAPTATIONS OF Ptychodera flava (ENTEROPNEUSTA:PTYCHODERIDAE) FOR DISPERSAL AND COLONIZATION

Rudolf S. Scheltema	B-9
INTER-RELATIONSHIPS BETWEEN LARVAL DISPERSAL AND OTHER FACTORS DETERMINING GEOGRAPHIC RANGE: EXAMPLES FROM INTERTIDAL AND SUBLITTORAL MOLLUSCS	
Rudolf S. Scheltema	B-9
LARVAL DISPERSAL AND GEOGRAPHIC RANGE OF SUBLITTORAL INVERTEBRATES ON CENTRAL PACIFIC ISLANDS	
Rudolf S. Scheltema	B-9
THE RELATIONSHIP BETWEEN MODE OF DEVELOPMENT AND GEOGRAPHIC RANGE IN INTERTIDAL AND SUBLITTORAL PROSOBRANCH GASTROPOD MOLLUSCS	
Rudolf S. Scheltema	B-10

Ecosystem Studies

Predation

PREDATORY CONTROL OF COPEPOD SEASONAL CYCLES ON GEORGES BANK

Cabell S. Davis	B-10
---------------------------	------

Riverine Systems

PARTICULATE ALLOCHTHONOUS INPUTS: RELATIONSHIPS WITH STREAM SIZE IN AN UNDISTURBED WATERSHED

M. Elizabeth Connors and Robert J. Naiman	B-11
ECOSYSTEM ALTERATION OF SUBARCTIC WATERSHEDS BY BEAVER (<u>Castor canadensis</u>)	
Robert J. Naiman, Jerry M. Melillo and John E. Hobbie	B-11

Salt Marsh Systems

FACTORS CONTROLLING THE GROWTH FORM OF Spartina alterniflora: Feedbacks Between Above-ground Production, Sediment Oxidation, Nitrogen and Salinity

Brian L. Howes and John W. H. Dacey	B-12
THE ROLE OF ONE SALT MARSH IN COASTAL PRODUCTIVITY	
John M. Teal	B-12
DECOMPOSITION IN SALT MARSH ECOSYSTEMS: THE PHASES AND MAJOR FACTORS AFFECTING DISAPPEARANCE OF ABOVE-GROUND ORGANIC MATTER	
Ivan Valiela, John M. Teal, Sarah Allen, Richard Van Etten, Dale Goehringer and Suzanne Volkmann	B-12

Geochemistry

HENRY'S LAW CONSTANTS FOR DIMETHYLSULFIDE IN FRESHWATER AND SEAWATER

John W. H. Dacey, Stuart G. Wakeham and Brian L. Howes	B13
--	-----

SHORT-TERM ENDPRODUCTS OF SULFATE REDUCTION: FORMATION OF ACID VOLATILE SULFIDES, ELEMENTAL SULFUR, AND PYRITE

Gary M. King, B. L. Howes and J. W. H. Dacey	B-13
RESIDENTIAL WASTEWATER-GROUND WATER INTERACTIONS IN THE VICINITY OF MARES POND, FALMOUTH, CAPE COD	
Ralph F. Vaccaro, Nathaniel Corwin and James R. Mitchell	B-14

Marine Mammals

INVESTIGATION OF SPERM WHALE ACOUSTIC BEHAVIORS IN THE SOUTHEAST CARIBBEAN

William A. Watkins, Karen E. Moore and Peter Tyack	B-14
SENSORY BIOPHYSICS OF MARINE MAMMALS	
William A. Watkins and Douglas Wartzok	B-14

Marine Pollution

FUTURE STRATEGIES FOR NEARSHORE WASTE DISPOSAL

J. M. Capuzzo, W. V. Burt, I. W. Duedall, D. R. Kester and P. K. Park	B-15
---	------

Microbiology

A NEW EXTREMELY THERMOPHILIC, SULFUR-REDUCING HETEROTROPHIC MARINE BACTERIUM	
Shimshon Belkin and Holger W. Jannasch	B-15
BIOLOGICAL AND ABIOLOGICAL SULFUR REDUCTION AT HIGH TEMPERATURES	
Shimshon Belkin, Carl O. Wirsen and Holger W. Jannasch	B-15
SULFUR EMISSION AND TRANSFORMATIONS AT DEEP SEA HYDROTHERMAL VENTS	
Holger W. Jannasch	B-16
GEO-MICROBIOLOGY OF DEEP SEA HYDROTHERMAL VENTS	
Holger W. Jannasch and Michael J. Mottl	B-16
THE BIOCHEMICAL VERSATILITY OF CHEMOSYNTHETIC BACTERIA AT DEEP SEA HYDROTHERMAL VENTS	
Holger W. Jannasch and Carl O. Wirsen	B-16
VARIABILITY OF PRESSURE ADAPTATION IN DEEP SEA BACTERIA	
Holger W. Jannasch and Carl O. Wirsen	B-16
<u>Thiomicrospira crunogena</u> SP. NOV., A COLORLESS SULFUR OXIDIZING BACTERIUM FROM A DEEP SEA HYDROTHERMAL VENT	
Holger W. Jannasch, Carl O. Wirsen, D. C. Nelson and L. A. Robertson	B-17
A PASSIVE DIFFUSION TECHNIQUE FOR THE CONCENTRATION OF SHORT CHAIN VOLATILE FATTY ACIDS FROM SEAWATER	
John J. Molongoski and Craig D. Taylor	B-17
DNA BASE COMPOSITION AND GENOME SIZE OF THE PROCARYOTIC SYMBIONT IN <u>Riftia pachyptila</u> (POGONOPHORA)	
Douglas C. Nelson, John B. Waterbury and Holger W. Jannasch	B-17

Phytoplankton

SINKING CHARACTERISTICS OF DINOFLAGELLATE CYSTS	
Donald M. Anderson, John J. Lively, Ellen M. Reardon and Carl A. Price	B-17
ENCYSTMENT OF THE ESTUARINE DINOFLAGELLATE <u>Gyrodinium uncatenum</u> : TEMPERATURE AND NUTRIENT EFFECTS	
Donald M. Anderson, M. A. Tyler and D. W. Coats	B-18
INORGANIC CARBON UPTAKE BY PHYTOPLANKTON IN VINEYARD SOUND, MASSACHUSETTS:	
I. MEASUREMENTS OF THE PHOTOSYNTHESIS-IRRADIANCE RESPONSE OF WINTER AND EARLY-SPRING ASSEMBLAGES	
Patricia M. Glibert, Mark R. Dennett and Joel C. Goldman	B-18
INORGANIC CARBON UPTAKE BY PHYTOPLANKTON IN VINEYARD SOUND, MASSACHUSETTS:	
II. COMPARATIVE PRIMARY PRODUCTIVITY AND NUTRITIONAL STATUS OF WINTER AND SUMMER ASSEMBLAGES	
Patricia M. Glibert, Mark R. Dennett and Joel C. Goldman	B-19
GRAZING AND NUTRIENT REGENERATION IN THE MARINE MICROBIAL FOOD CHAIN	
Joel C. Goldman and David A. Caron	B-19
PHOTOSYNTHETIC RESPONSES OF 15 PHYTOPLANKTON SPECIES TO AMMONIUM PULSING	
Joel C. Goldman and Mark R. Dennett	B-19
SUSCEPTIBILITY OF SOME MARINE PHYTOPLANKTON SPECIES TO CELL BREAKAGE DURING FILTRATION AND POST-FILTRATION RINSING	
Joel C. Goldman and Mark R. Dennett	B-19
CRYPTIC PARALYTIC SHELLFISH POISONS	
Sherwood Hall	B-20
DINOFLAGELLATE NEUROTOXINS RELATED TO SAXITOXIN: STRUCTURES OF TOXINS C3 AND C4, AND CONFIRMATION OF THE STRUCTURE OF NEOSAXITOXIN	
Sherwood Hall, S. D. Darling, G. L. Boyer, P. B. Reichardt and H.-W. Liu	B-20
PHOTOSYNTHATE PARTITIONING IN CULTURED MARINE PHYTOPLANKTON: METABOLIC PATTERNS IN 10 SPECIES IN RESPONSE TO AMMONIUM PULSING	
Gary L. Hitchcock and Joel C. Goldman	B-20
PHOTOSYNTHATE PARTITIONING IN CULTURED MARINE PHYTOPLANKTON. GROWTH AND METABOLIC PATTERNS IN A MARINE DIATOM UNDER CONSTANT AND VARIABLE LIGHT INTENSITIES	
Gary L. Hitchcock, Joel C. Goldman and Mark R. Dennett	B-21
ADAPTATION AND EQUIVALENCE IN THE OPEN OCEAN PHYTOPLANKTON	
Edward M. Hulburt	B-21
THE SINGLENES, RESPONSIVENESS, AND ADAPTEDNESS OF A PHYTOPLANKTON POPULATION	
Edward M. Hulburt	B-21
USE OF LOGICAL EQUIVALENCE IN MODELING ECOLOGICAL RELATIONS OF OCEANIC PHYTOPLANKTON	
Edward M. Hulburt	B-22

COMPARISON OF TOXICITY BETWEEN POPULATIONS OF Gonyaulax tamarensis OF EASTERN NORTH AMERICAN WATERS

- Lucie Maranda, Donald M. Anderson and Yuzuru Shimizu B-22
 AN UNUSUAL PHYCOERYTHRIN FROM A MARINE CYANOBACTERIUM
 Linda Oug, Alexander N. Glazer and John B. Waterbury B-22
 THE ABUNDANCE AND DISTRIBUTION OF THE TOXIC DINOFLAGELLATE, Gonyaulax tamarensis,
 IN LONG ISLAND ESTUARIES
 Suzzane E. Schrey, Edward J. Carpenter and Donald M. Anderson B-23
 THE EFFECT OF ZOOPLANKTON GRAZING ON ESTUARINE BLOOMS OF THE TOXIC DINOFLAGELLATE
Gonyaulax tamarensis
 Carl J. Watras, Veronique C. Garcon, Robert J. Olson, Sallie W. Chisholm
 and Donald M. Anderson B-23

Population Ecology

- GENETIC DIFFERENTIATION OF POPULATIONS OF THE PLANKTONIC COPEPOD Labidocera aestiva
 Ann Bucklin and Nancy Marcus B-24
 THE EVOLUTIONARY DEMOGRAPHY OF VEGETATIVE REPRODUCTION
 Hal Caswell B-24
 SLUTSKY'S EQUATION AND THE PERTURBATION ANALYSIS OF OPTIMAL LIFE HISTORIES
 Hal Caswell and Leslie Real B-24
 POPULATION DYNAMICS OF MARINE COPEPODS: THE IMPORTANCE OF GENETIC VARIATION
 Nancy H. Marcus B-25
 RECRUITMENT OF INDIVIDUALS INTO THE PLANKTON: THE IMPORTANCE OF BIOTURBATION
 Nancy H. Marcus and Jutta Schmidt-Gengenbach B-25
 LABORATORY EXPERIMENTS ON THE EFFECTS OF A GASTROPOD (Hydrobia minuta) ON SURVIVAL
 OF AN INFAUNAL DEPOSIT-FEEDING POLYCHAETE (Capitella capitata, SPECIES TYPE I)
 Peter S. Petraitis B-25

Zooplankton

- SPATIAL AND TEMPORAL ABUNDANCE PATTERNS OF CHAETOGNATHS IN THE WESTERN NORTH ATLANTIC. I. HYDROGRAPHIC AND SEASONAL ABUNDANCE PATTERNS
 Jerry Cheney B-26
 SPATIAL AND TEMPORAL ABUNDANCE PATTERNS OF CHAETOGNATHS IN THE WESTERN NORTH ATLANTIC. II. VERTICAL DISTRIBUTIONS AND MIGRATIONS
 Jerry Cheney B-26
 FOOD CONCENTRATIONS ON GEORGES BANK: NON-LIMITING EFFECT ON DEVELOPMENT AND SURVIVAL OF LABORATORY REARED Pseudocalanus SP. AND Paracalanus parvus (COPEPODA, CALANOIDA).
 Cabell S. Davis B-27
 INTERACTION OF A COPEPOD POPULATION WITH THE MEAN CIRCULATION ON GEORGES BANK
 Cabell S. Davis B-27
 EVOLUTION OF ZOOPLANKTON SIZE STRUCTURE AND TAXONOMIC COMPOSITION IN A WARM CORE GULF STREAM RING
 Cabell S. Davis and Peter H. Wiebe B-27
 NOT ALL CTENOPHORES ARE HERMAPHRODITES
 G. R. Harbison and R. L. Miller B-28
 ON THE CLASSIFICATION AND EVOLUTION OF THE CTENOPHORA
 G. R. Harbison B-28
 THE CONCENTRATING OF ORGANISMS AT FRONTS: A COLD-WATER FISH AND A WARM-CORE GULF STREAM RING
 Donald B. Olson and Richard H. Backus B-28
 EVOLUTION OF ZOOPLANKTON BIOMASS STRUCTURE IN GULF STREAM WARM-CORE RINGS
 Peter H. Wiebe, Valerie Barber, Steven H. Boyd, Cabell Davis and Glenn R. Flierl B-29

Organic and Biological Chemistry

THE RELEASE OF FREE AMINO ACIDS BY HETEROTROPHIC MARINE MICROFLAGELLATES	
Agneta Andersson, Cindy Lee, Farooq Azam and Ake Hagström	C-3
SCLEROSPONGE GROWTH RATE AS DETERMINED BY ^{210}Pb AND ^{14}C CHRONOLOGIES	
Livia M. Benavides and Ellen R. M. Druffel	C-3
BIOGEOCHEMISTRY OF PCBs IN INTERSTITIAL WATERS OF A COASTAL MARINE SEDIMENT	
Bruce J. Brownawell and John W. Farrington	C-3
SOURCES AND DISTRIBUTION PROCESSES OF CHEMICAL CONTAMINANTS IN THE COASTAL ZONE	
John W. Farrington	C-3
AROMATIC HYDROCARBONS IN NEW YORK BIGHT POLYCHAETES: U.V.-FLUORESCENCE ANALYSES AND GC/GCMS ANALYSES	
John W. Farrington, Stuart G. Wakeham, Joaquim B. Livramento, Bruce W. Tripp and John M. Teal	C-4
FIELD AND LABORATORY STUDIES OF THE ONTOGENY AND ECOLOGY OF <i>Globorotalia truncatulinoides</i> (d'Orbigny) AND <i>Globorotalia hirsuta</i> (d'Orbigny) IN THE SARGASSO SEA	
Christoph Hemleben, Michael Spindler, Ingrid Breitingner and Werner G. Deuser	C-4
SEASONALITY IN THE FLUXES OF SUGARS, AMINO ACIDS AND AMINO SUGARS TO DEEP OCEAN: SARGASSO SEA	
Venugopalan Ittekkot, Werner G. Deuser and Egon T. Degens	C-4
U.S. "MUSSEL WATCH" PROGRAM: TRANSURANIC ELEMENT DATA FROM WOODS HOLE OCEANOGRAPHIC INSTITUTION 1976-1983	
Julianne Palmieri, Hugh Livingston and John W. Farrington	C-5
METHODOLOGY FOR SAMPLING AND ANALYSIS OF LIPIDS IN AEROSOLS FROM THE REMOTE MARINE ATMOSPHERE	
Edward T. Peltzer, Jane B. Alford and Robert B. Gagosian	C-5
PARTICLE SIZE DISTRIBUTION OF LIPIDS IN AEROSOLS OFF THE COAST OF PERU	
Jürg K. Schneider and Robert B. Gagosian	C-5
USING SENTINEL ORGANISMS TO MONITOR CHEMICAL CHANGES IN THE COASTAL ZONE: PROGRESS OR PARALYSIS	
B. W. Tripp and J. W. Farrington	C-6
WAX ESTERS AND TRIACYLGLYCEROLS IN SINKING PARTICULATE MATTER IN THE PERU UPWELLING AREA (15°S, 75°W)	
Stuart G. Wakeham	C-6
THE BIOGEOCHEMISTRY OF TOLUENE IN COASTAL SEAWATER: RADIOTRACER EXPERIMENTS IN CONTROLLED ECOSYSTEMS	
Stuart G. Wakeham, Elizabeth A. Canuel, Peter H. Doering, John E. Hobbie and John V. K. Helfrich	C-7
VARIABILITY IN LIPID FLUX AND COMPOSITION OF PARTICULATE MATTER IN THE PERU UPWELLING REGION	
Stuart G. Wakeham, John W. Farrington and Robert B. Gagosian	C-7
DIMETHYLSULFIDE IN A STRATIFIED COASTAL SALT POND	
Stuart G. Wakeham, Brian L. Howes and John W. H. Dacey	C-7
ATMOSPHERIC TRANSFORMATIONS OF FLUXES OF LIPIDS AT ENEWETAK ATOLL	
Oliver C. Zafiriou, Robert B. Gagosian, Edward T. Peltzer, Jane B. Alford and Theodore C. Loder	C-8

Seawater and Geochemistry

ASPECTS OF THE AROMATIC HYDROCARBON GEOCHEMISTRY OF RECENT SEDIMENTS IN THE GEORGES BANK REGION	
Paul D. Boehm and John W. Farrington	C-8
MEASUREMENTS OF TOTAL CARBON DIOXIDE AND ALKALINITY IN THE NORTH ATLANTIC OCEAN IN 1981	
Peter G. Brewer, Alvin L. Bradshaw and Robert T. Williams	C-8
RARE EARTH ELEMENTS IN THE PACIFIC AND ATLANTIC OCEANS	
Hein J. W. DeBaar, Michael P. Bacon, Peter G. Brewer and Kenneth W. Bruland	C-9
ANOMALIES IN RARE EARTH DISTRIBUTIONS IN SEA WATER: Gd AND Tb	
Hein J. W. DeBaar, Peter G. Brewer and Michael P. Bacon	C-9
SEA SURFACE TEMPERATURE ANOMALIES IN THE TROPICAL PACIFIC OCEAN AS RECORDED IN BANDED CORALS: IMPLICATIONS FOR THE CARBON DIOXIDE CYCLE	
Ellen R. M. Druffel	C-9

PETROLOGICAL AND GEOCHEMICAL VARIATIONS ALONG THE MID-ATLANTIC RIDGE BETWEEN 46°S AND 32°S: INFLUENCE OF THE TRISTAN DA CUNHA MANTLE PLUME	
Susan Humphris, Geoffrey Thompson, Jean-Guy Schilling and Richard Kingsley . . .	C-10
GENERATION AND MIGRATION OF LIGHT HYDROCARBONS	
John M. Hunt	C-10
GEO-MICROBIOLOGY OF DEEP SEA HYDROTHERMAL VENTS	
Holger W. Jannasch and Michael J. Mottl	C-11
THE USE OF TRACERS AND WATER MASSES TO ESTIMATE RATES OF RESPIRATION	
William J. Jenkins	C-11
SEASONAL OXYGEN CYCLING AND PRIMARY PRODUCTION IN THE SARGASSO SEA	
W. J. Jenkins and J. C. Goldman	C-11
HIGH RESOLUTION ISOTOPE STUDY OF THE LAST DEGLACIATION BASED ON BERMUDA RISE CORES	
Lloyd D. Keigwin and Ellen R. M. Druffel	C-12
HELIUM ISOTOPIC SYSTEMATICS WITHIN THE NEOVOLCANIC ZONES OF ICELAND	
Mark D. Kurz, Peter S. Meyer and Haraldur Sigurdsson	C-12
CHEMISTRY OF HOT WATERS SAMPLED FROM BASALTIC BASEMENT IN HOLE 504B, DEEP SEA DRILLING PROJECT LEG 83, COSTA RICA RIFT	
M. J. Mottl, E. M. Druffel, S. R. Hart, J. R. Lawrence and E. Saltzman	C-12
CaCO ₃ SOLUBILITY IN MARINE SEDIMENTS: EVIDENCE FOR EQUILIBRIUM AND NON-EQUILIBRIUM BEHAVIOR	
F. L. Sayles	C-13
THE DISTRIBUTION OF ^{239,240} Pu, ¹³⁷ Cs, AND ⁵⁵ Fe IN CONTINENTAL MARGIN SEDIMENTS: RELATION TO SEDIMENTARY REDOX ENVIRONMENT	
F. L. Sayles and H. D. Livingston	C-13
HOTSPOT-MIGRATING RIDGE INTERACTION IN THE SOUTH ATLANTIC	
J.-G. Schilling, G. Thompson, R. Kingsley and S. Humphris	C-13
HEAT-TRANSFER EXPERIMENT IN MARINE PELAGIC CLAY: IMPLICATION FOR SUBSEABED DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE AND CONTACT METAMORPHISM OF SEDIMENTS IN THE GUAYMAS BASIN, GULF OF CALIFORNIA	
W. E. Seyfried, Jr. and F. L. Sayles	C-13
PERIDOTITES FROM THE MID-ATLANTIC RIDGE AT 43°N AND THEIR PETROGENETIC RELATION TO ABYSSAL THOLEIITES	
Tsugio Shibata and Geoffrey Thompson	C-14
MIGRATION OF C ₁ -C ₈ HYDROCARBONS IN MARINE SEDIMENTS	
Jean K. Whelan, John M. Hunt, John Jasper and Alain Huc	C-15
PHOTOCHEMISTRY OF NATURAL WATERS	
O. C. Zafiriu, J. Joussot-Dubien, R. G. Zepp and R. G. Zika	C-15

Radiochemistry

A PORE WATER STUDY OF PLUTONIUM IN A SEASONALLY ANOXIC LAKE	
Ken O. Buesseler, Gaboury J. Benoit and Edward R. Sholkovitz	C-15
RADIOCESIUM AND OTHER NUCLIDES IN THE NORWEGIAN-GREENLAND SEAS 1981-1982	
Susan A. Casso and Hugh D. Livingston	C-15
RADIOMETRIC DETERMINATION OF THE GROWTH RATE OF <u>Nautilus</u> IN NATURE	
J. Kirk Cochran and Neil H. Landman	C-16
WOODS HOLE OCEANOGRAPHIC INSTITUTION RADIOCARBON LABORATORY: SAMPLE TREATMENT AND GAS PREPARATION	
Ellen R. M. Druffel and Sheila M. Griffin	C-16
VERTICAL PROFILE OF ARTIFICIAL RADIONUCLIDE CONCENTRATIONS IN THE CENTRAL ARCTIC OCEAN	
H. D. Livingston, S. L. Kupferman, V. T. Bowen and R. M. Moore	C-16
ARTIFICIAL RADIONUCLIDE TRACER SUPPLY TO THE DENMARK STRAIT OVERFLOW BETWEEN 1972 AND 1981	
Hugh D. Livingston, James H. Swift and H. Gote Östlund	C-17

Instruments and Statistics

REMOVAL OF BIAS FROM THE SELECTION OF SAMPLES OF MATERIAL FOR CHEMICAL ANALYSIS	
Donald C. Bankston	C-17
AN AUTOMATED CRYOGENIC CHARCOAL TRAP SYSTEM FOR HELIUM ISOTOPE MASS SPECTROMETRY	
D. E. Lott and W. J. Jenkins	C-17

Geology

RECENT SEA LEVELS FROM TIDE GAUGES: PROBLEMS AND PROGNOSIS	
D.G. Aubrey	GG-3
RELATIVE SEA LEVELS OF JAPAN FROM TIDE-GAUGE RECORDS	
D.G. Aubrey and K.O. Emery	GG-3
NORTHWESTERN EUROPEAN PALEOGENE MAGNETO-BIOSTRATIGRAPHY AND PALEO GEOGRAPHY:	
CALCAREOUS NANNOFOSSIL EVIDENCE	
Marie-Pierre Aubry	GG-3
MAGNETO- AND CALCAREOUS NANNOFOSSIL STRATIGRAPHY OF THE LOWER PALAEOGENE OF THE	
HAMPSHIRE-LONDON BASIN	
M-P. Aubry, E.A. Hailwood and H.A. Townsend	GG-4
THE PLIO/PLEISTOCENE BOUNDARY IN DEEP SEA SEDIMENTS	
W.A. Berggren and Lloyd Burckle	GG-4
SEISMIC STRATIGRAPHY OF THE OCEANIC MOHO BASED ON OPHIOLITE MODELS	
Thomas M. Brocher, Jeffrey A. Karson and John A. Collins	GG-4
GEOMORPHOLOGY, SHALLOW STRUCTURE AND GEOLOGICAL HAZARDS IN THE EAST CHINA SEA	
Jorge Butenko, John D. Milliman and Ye Yincin	GG-4
METAMORPHISM IN THE BAY OF ISLANDS OPHIOLITE COMPLEX	
J.A. Karson, D.L. Elthon, J.F. Casey and M. Titus	GG-5
DEFORMED AND METAMORPHOSED OCEANIC CRUST ON THE MID-ATLANTIC RIDGE	
J.A. Karson and H.J.B. Dick	GG-5
PROPERTIES OF SUSPENDED SEDIMENT OVER THE HEBBLE AREA ON THE NOVA SCOTIAN RISE	
I.N. McCave	GG-6
ANALYSIS OF A LONGITUDINAL RIPPLE FROM THE NOVA SCOTIAN CONTINENTAL RISE	
I.N. McCave, C.D. Hollister, D.J. DeMaster, C.A. Nittrouer,	
A.J. Silva and J.Y. Yingst	GG-6
OLIGOCENE GLACIO-EUSTACY AND EROSION ON THE MARGINS OF THE NORTH ATLANTIC	
Kenneth G. Miller, Gregory S. Mountain and Brian E. Tucholke	GG-7
THE NORTHERN RED SEA: CONTINENTAL RIFTING AND SALT TECTONICS	
Elazar Uchupi and David A. Ross	GG-7

Geophysics

GRAVITY FIELD OF VENUS AT CONSTANT ALTITUDE AND COMPARISON WITH EARTH	
Carl Bowin, Geoffrey Abers and Loren Shure	GG-7
RESIDUAL GEIOD ANOMALIES IN ATLANTIC OCEAN BASIN: RELATIONSHIP TO MANTLE PLUMES	
Carl Bowin, Geoffrey Thompson and J.G. Schilling	GG-8
ANOMALOUSLY THIN CRUST IN OCEANIC FRACTURE ZONES: NEW SEISMIC CONSTRAINTS	
FROM THE KANE FRACTURE ZONE	
Marie-Helene Cormier, Robert S. Detrick and G. Michael Purdy	GG-8
HEAT FLOW IN THE BALEARIC AND TYRRHENIAN BASINS, WESTERN MEDITERRANEAN	
I. Hutchison, R. P. Von Herzen, K. E. Loudon, J. G. Sclater and J. Jemsek	GG-9
COSTA RICA RIFT BOREHOLE SEISMIC EXPERIMENT, DSDP HOLE 504B	
S. A. Little and R. A. Stephen	GG-9
MESOZOIC AND CENOZOIC GEOLOGY OF THE U.S. ATLANTIC CONTINENTAL SLOPE AND RISE	
Gregory S. Mountain and Brian E. Tucholke	GG-9
GRAVITATIONAL AND MAGNETIC FIELDS OF SOME SIMPLE SOLIDS OF REVOLUTION	
Robert L. Parker and Loren Shure	GG-11
DEVELOPMENT OF NEW TECHNIQUES: DEEP SEISMIC STUDIES BY REFRACTION METHODS	
G.M. Purdy	GG-11
SEISMIC STRUCTURE OF THE OCEAN CRUST	
G.M. Purdy and J.I. Ewing	GG-11
A PRELIMINARY HARMONIC SPLINE MODEL FROM MAGSAT DATA	
L. Shure, R.L. Parker and R.A. Langel	GG-12
THE DIRECT WAVE ROOT IN MARINE SEISMOLOGY	
R. A. Stephen and S.T. Bolmer	GG-12
WIRELINE RE-ENTRY TEST ON DSDP LEG 88	
R.A. Stephen, F.K. Duennebie and D.R. Bellows	GG-13
MICROEARTHQUAKE BENEATH THE MEDIAN VALLEY OF THE MID-ATLANTIC RIDGE NEAR 23 N:	
HYPOCENTERS AND FOCAL MECHANISMS	
Douglas R. Toomey, Sean C. Solomon, G.M. Purdy and Mark H. Murray	GG-13

TESTING MODELS OF CONTINENTAL RIFTING AND EXTENSION: THE LIGURIAN BASIN
(W. MEDITERRANEAN)

- R. Von Herzen, J.-P. Rehault, J. Jemsek, D. L. Williams and J. Sclater GG-13
A MECHANISM FOR MAGMATIC ACCRETION UNDER SPREADING CENTERS
J.A. Whitehead, Jr., H.J.B. Dick and H. Schouten GG-14

Paleoceanography

THE EOCENE/OLIGOCENE EVENT IN THE DEEP SEA

- Bruce H. Corliss, Marie-Pierre Aubry, William A. Berggren, Juliane M. Fenner,
Lloyd D. Keigwin, Jr. and Gerta Keller GG-14
STABLE ISOTOPIC RESULTS ON UPPER MIOCENE AND LOWER PLIOCENE FORAMINIFERA
FROM SITE 552A
Lloyd D. Keigwin, Jr. GG-14
CARBON ISOTOPES IN DEEP-SEA BENTHIC FORAMINIFERA: PRECESSION AND CHANGES IN
LOW-LATITUDE BIOMASS
Lloyd D. Keigwin and Edward A. Boyle GG-15

Paleontology

NEOGENE BENTHIC FORAMINIFERA OF THE HATTON-ROCKALL BASIN

- Paul E. Belanger and William A. Berggren GG-15
MICROHABITATS OF BENTHONIC FORAMINIFERA WITHIN DEEP-SEA SEDIMENTS
Bruce H. Corliss GG-15
EVIDENCE FOR CONTROL OF ABYSSAL AGGLUTINATED FORAMINIFERAL COMMUNITY STRUCTURE
BY SUBSTRATE DISTURBANCE: RESULTS FROM THE HEBBLE AREA
Michael A. Kaminski GG-16
SPECIES FORMATION THROUGH PUNCTUATED GRADUALISM IN PLANKTONIC FORAMINIFERA
Bjorn A. Malmgren, William A. Berggren and G.P. Lohmann GG-16
OLIGOCENE-MIOCENE BIOSTRATIGRAPHY, MAGNETOSTRATIGRAPHY, AND ISOTOPIC STRATIGRAPHY
OF THE WESTERN NORTH ATLANTIC
Kenneth G. Miller, Marie-Pierre Aubry, M.J. Khan, A.J. Melillo,
D.V. Kent and William A. Berggren GG-16

Petrology

MINERALOGIC VARIABILITY OF THE UPPERMOST MANTLE ALONG MID-OCEAN RIDGES

- Henry J.B. Dick, Robert L. Fisher and Wilfred B. Bryan GG-17

Sedimentology

THE QUANTITATIVE DESCRIPTION OF BEACH CYCLES

- David G. Aubrey and Robert M. Ross GG-17
A STUDY OF NON-LINEAR TIDAL PROPAGATION IN SHALLOW INLET/ESTUARINE SYSTEMS
PART I: OBSERVATIONS
D.G. Aubrey and P.E. Speer GG-18
KINEMATIC AND DYNAMIC ESTIMATES FROM ELECTROMAGNETIC CURRENT METER DATA
David G. Aubrey and John H. Trowbridge GG-18
DYNAMIC RESPONSE OF SPHERICAL ELECTROMAGNETIC CURRENT METERS
David G. Aubrey, John H. Trowbridge and Wayne D. Spencer GG-18
CARBON DEPOSITION RATES AND DEEP WATER RESIDENCE TIME IN THE EQUATORIAL ATLANTIC
OCEAN THROUGHOUT THE LAST 160,000 YEARS
W. B. Curry and G. P. Lohmann GG-19
SEAFLOOR ZONATION IN SEDIMENT TEXTURE ON THE NOVA SCOTIAN LOWER CONTINENTAL RISE
Mavis L. Driscoll, Brian E. Tucholke and Nick McCave GG-19
THEORETICAL AND OBSERVATIONAL ESTIMATES OF NEARSHORE BEDLOAD TRANSPORT RATES
M. R. Goud and D. G. Aubrey GG-20
OCEANIC PARTICLES AND PELAGIC SEDIMENTS IN THE WESTERN NORTH ATLANTIC OCEAN
Susumu Honjo GG-20
STUDY OF OCEAN FLUXES IN TIME AND SPACE BY BOTTOM-TETHERED SEDIMENT TRAP ARRAYS:
A RECOMMENDATION
Susumu Honjo GG-20

MICRITIC CEMENT IN MICROBORINGS IS NOT NECESSARILY A SHALLOW-WATER INDICATOR	
James E. Hook, Stjepko Golubic and John D. Milliman	GG-21
EROSION, TRANSPORT AND DEPOSITION OF FINE-GRAINED MARINE SEDIMENTS	
I.N. McCave	GG-21
SEDIMENTOLOGY AND STRATIGRAPHY OF BOX-CORES FROM THE HEBBLE SITE ON THE NOVA SCOTIAN CONTINENTAL RISE	
I.N. McCave	GG-21
SEDIMENTATION UNDER DEEP-SEA CURRENT SYSTEMS: PRE-HEBBLE IDEAS	
I.N. McCave and C.D. Hollister	GG-22
TRANSPORT OF RIVER SEDIMENT IN THE CHANGJIANG ESTUARY AND ADJACENT SHELF	
John D. Milliman, Shen Huang-ting, Yang Zuo-sheng and Robert H. Meade	GG-22
MODERN HUANGHE-DERIVED MUDS ON THE OUTER SHELF OF THE EAST CHINA SEA: IDENTIFICATION AND POTENTIAL TRANSPORT MECHANISMS	
John D. Milliman, Robert C. Beardsley, Yang Zuo-sheng and Richard Limeburner	GG-22
RHYTHMIC BEACH CUSP FORMATION: A CONCEPTUAL SYNTHESIS	
Richard J. Seymour and David G. Aubrey	GG-22
SEA-FLOOR MORPHOLOGY OUTSIDE A GROUNDED, SURGING GLACIER: BRASVELLBREEN, SVALBARD	
Anders Solheim and Stephanie Pfirman	GG-23
A STUDY OF NON-LINEAR TIDAL PROPAGATION IN SHALLOW INLET/ESTUARINE SYSTEMS	
PART II: THEORY	
Paul E. Speer and David G. Aubrey	GG-23
LATE PLEISTOCENE SEDIMENTATION ON THE WESTERN NOVA SCOTIAN SLOPE AND RISE	
Stephen A. Swift	GG-24
CLOSE-UP STEREO PHOTOGRAPHS OF ABYSSAL BEDFORMS ON THE NOVA SCOTIAN CONTINENTAL RISE	
Stephen A. Swift, Charles D. Hollister and Richard S. Chandler	GG-24
PLANKTONIC FORAMINIFERA: FACTORS CONTROLLING SINKING SPEEDS	
Kozo Takahashi and Allan W.H. Be	GG-24

Wave Dynamics

PERFORMANCE OF BOTTOM-MOUNTED DIRECTIONAL WAVE GAGES	
David G. Aubrey and Winfield Hill	GG-25
DYNAMIC RESPONSE OF ELECTROMAGNETIC CURRENT METERS	
David G. Aubrey, Wayne D. Spencer and John H. Trowbridge	GG-25
INNER SHELF SAND TRANSPORT WAVE MEASUREMENTS: POINT SAPIN, NEW BRUNSWICK, CANADA	
David G. Aubrey and Wayne D. Spencer	GG-26

Acoustic Signal Processing

ON THE MAXIMUM ENTROPY SPECTRUM FOR A CERTAIN CLASS OF CORRELATION FUNCTIONS

Ehud Weinstein OE-3

PERFORMANCE ANALYSIS OF TIME-DELAY ESTIMATION SYSTEMS

Ehud Weinstein OE-3

SOME RELATIONS BETWEEN THE VARIOUS CRITERIA FOR AUTOREGRESSIVE MODEL
ORDER ESTIMATION

Ehud Weinstein and David Borenstein OE-3

ON THE FINITE MAXIMUM ENTROPY EXTRAPOLATION

Ehud Weinstein and Meir Feder OE-3

CONVERGENCE ANALYSIS OF LMS FILTERS WITH UNCORRELATED GAUSSIAN DATA

E. Weinstein and A. Feuer OE-4

FUNDAMENTAL LIMITATIONS IN PASSIVE TIME DELAY ESTIMATION:

Part II - WIDEBAND SYSTEMS

Ehud Weinstein and Anthony J. Weiss OE-4

LOWER BOUNDS ON THE MEAN SQUARE ERROR IN RANDOM PARAMETER ESTIMATION

Ehud Weinstein and Anthony J. Weiss OE-4

LOWER BOUNDS ON THE MEAN SQUARE ESTIMATION ERROR

Ehud Weinstein and Anthony J. Weiss OE-4

SUPER RESOLUTION OF ACOUSTIC TOMOGRAPHY MULTIPATH DATA

Jules S. Jaffe OE-5

Coastal Dynamics

RIPPLED SCOUR DEPRESSIONS ON THE CONTINENTAL SHELF OFF CENTRAL CALIFORNIA

D.A. Cacchione, D.E. Drake, W.D. Grant and G.B. Tate OE-5

BOTTOM STRESS ESTIMATES AND THEIR PREDICTION ON THE NORTHERN CALIFORNIA

CONTINENTAL SHELF DURING CODE-1: THE IMPORTANCE OF WAVE-CURRENT INTERACTION

W.D. Grant, A.J. Williams and S.M. Glenn OE-5

GeologyPROJECT CYATHERM: DETAILED INVESTIGATION OF HYDROTHERMAL ACTIVITY AT 12°48'N
ON THE EAST PACIFIC RISE

R.D. Ballard OE-6

MICROTOPOGRAPHY OF A CONTINENTAL RIFT ZONE: THE GULF OF ELAT-AQABA

R.D. Ballard and Z. Ben-Avraham OE-6

SUBMERSIBLE OBSERVATIONS ON THE EAST PACIFIC RISE: A MODEL FOR GROWTH
OF SULFIDE DEPOSITS

R. Hekinian, J. Francheteau and R.D. Ballard OE-6

Instrumentation

A CCD CHIRP-Z FFT DOPPLER SIGNAL PROCESSOR FOR LASER VELOCIMETRY

Y.C. Agrawal OE-7

QUADRATURE DEMODULATION IN LASER DOPPLER VELOCIMETRY

Yogi C. Agrawal OE-7

DIRECTIONAL LASER VELOCIMETRY WITHOUT FREQUENCY BIASING - PART II

Y.C. Agrawal and J.B. Riley OE-7

OPTICAL PARTICLE SIZING FOR HYDRODYNAMICS BASED ON NEAR FORWARD SCATTERING

Yogi C. Agrawal and James B. Riley OE-8

CTD LOWERING MECHANICS

H.O. Berteaux and R.G. Walden OE-8

CHARACTERISTICS OF A PHOTOVOLTAIC BATTERY CHARGING SYSTEM FOR THE RELAYS PROGRAM

Clayton W. Collins, Jr. OE-8

A MINIATURE URETHANE MOLDED ACOUSTIC TRANSDUCER

Christopher Van Rensselaer Dunn OE-9

USE OF RADIO-CONTROLLED MINIATURE AIRCRAFT FOR DRIFTER AND DYE CURRENT STUDIES
IN A TIDAL INLET

F.R. Hess and D.G. Aubrey OE-9

DIRECT OPTICAL ASSESSMENT OF MACROSCOPIC AGGREGATES IN THE DEEP OCEAN	
Susumu Honjo, Kenneth W. Doherty, Yogesh C. Agrawal and Vernon L. Asper . . .	OE-9
PREPARATION OF FROZEN-HYDRATED SPECIMENS FOR HIGH RESOLUTION ELECTRON MICROSCOPY	
J.S. Jaffe and R.M. Glaeser	OE-10
POPUP: A PROTOTYPE BOTTOM-MOORED LONG-TERM CURRENT PROFILER	
Arthur D. Voorhis and Albert M. Bradley	OE-10
BOTTOM-MOUNTED PROFILING WINCH	
R.G. Walden and C.W. Collins, Jr.	OE-10
HEBBLE SEA DUCT SEMIANNUAL PROJECT REPORT NUMBER 4	
Clifford L. Winget	OE-10
BASS, AN ACOUSTIC CURRENT METER ARRAY FOR BENTHIC FLOW FIELD MEASUREMENTS	
Albert J. Williams, 3rd	OE-11

Ocean Acoustics

A UNIFORMLY VALID SOLUTION FOR ACOUSTIC NORMAL MODE PROPAGATION IN A RANGE-VARYING OCEAN	
Yves Desaubies	OE-11
RICHARDSON NUMBER APPROACH TO INTERNAL WAVE INSTABILITY IN THE OCEAN AND STRATOSPHERE	
Yves Desaubies	OE-11
STATISTICAL ASPECTS OF SOUND PROPAGATION IN THE OCEAN	
Yves Desaubies	OE-11
GEOACOUSTIC MODELS FOR THE ICELANDIC BASIN	
George V. Frisk, James A. Douth and Earl E. Hays	OE-12
SHALLOW WATER WAVEGUIDE CHARACTERIZATION USING THE HANKEL TRANSFORM	
George V. Frisk and James F. Lynch	OE-12
A CANONICAL OCEAN BOTTOM SOUND VELOCITY PROFILE	
Hiroshi Kawahara and George V. Frisk	OE-12
RAY THEORY MODELING APPLIED TO LOW FREQUENCY ACOUSTIC INTERACTION WITH HORIZONTALLY STRATIFIED OCEAN BOTTOMS	
Martin W. Lawrence	OE-13
THEORETICAL ANALYSIS OF ABSS DATA FOR HEBBLE	
James F. Lynch	OE-13
ON THE USE OF FOCUSED HORIZONTAL ARRAYS AS MODE SEPARATION AND SOURCE LOCATION DEVICES IN OCEAN ACOUSTICS	
James F. Lynch, Daniel K. Schwartz and Kondagunta Sivaprasad	OE-13
ON THE USE OF FOCUSED HORIZONTAL ARRAYS AT MODE SEPARATION AND SOURCE LOCATION DEVICES IN OCEAN ACOUSTICS PART II: THEORETICAL AND NUMERICAL	
James F. Lynch, Daniel K. Schwartz and Kondagunta Sivaprasad	OE-13
A HYBRID NUMERICAL/ANALYTIC TECHNIQUE FOR THE COMPUTATION OF WAVE FIELDS IN STRATIFIED MEDIA BASED ON THE HANKEL TRANSFORM	
Douglas R. Mook, George V. Frisk and Alan V. Oppenheim	OE-14
TOMOGRAPHIC MAPS OF THE OCEAN MESOSCALE-1: PURE ACOUSTICS	
B. Cornuelle, C. Wunsch, D. Behringer, T. Birdsall, M. Brown, R. Heinmiller, R. Knox, K. Metzger, W. Munk, J. Spiesberger, R. Spindel, D. Webb and P. Worcester	OE-14
GULF STREAM VARIABILITY FOR ACOUSTIC TOMOGRAPHY	
P. Malanotte-Rizzoli, J.L. Spiesberger and M. Chajes	OE-14
LINEARIZED GEOPHYSICAL INVERSIONS IN Laterally INHOMOGENEOUS MEDIA: BIASES	
John L. Spiesberger	OE-15
NON-RECIPROCITY OF ACOUSTIC RAY TRAVEL TIMES SUBJECT TO MESOSCALE CURRENTS	
John Spiesberger	OE-15
OCEAN ACOUSTIC TOMOGRAPHY: TRAVEL-TIME BIASES	
John L. Spiesberger	OE-15
SIGNAL PROCESSING IN OCEAN TOMOGRAPHY	
Robert C. Spindel	OE-16
SOUND TRANSMISSION IN THE OCEAN	
Robert C. Spindel	OE-16
RECIPROCAL ACOUSTIC TRANSMISSIONS: RESULTS FOR MESOSCALE MONITORING OF OCEAN CURRENTS	
Peter F. Worcester, Robert C. Spindel and Bruce M. Howe	OE-16

Ocean Dynamics

A DESCRIPTION OF THE BOTTOM BOUNDARY LAYER AT THE HEBBLE SITE: LOW FREQUENCY FORCING, BOTTOM STRESS AND TEMPERATURE STRUCTURE

William D. Grant, Albert J. Williams, 3rd and Thomas F. Gross

OE-17

THE VERTICAL STRUCTURE OF TURBULENCE BENEATH GENTLY BREAKING WIND WAVES

E.A. Terray and L.F. Bliven OE-17

Submersible Engineering

USER MANUAL FOR THE ALVIN DISCRETE DATA SYSTEM

John J. Akens OE-17

WOODS HOLE FORTH

John J. Akens OE-18

ATLANTIS II: A NEW SUPPORT SHIP FOR ALVIN

Barrie B. Walden and Arnold G. Sharp OE-18

Underwater Robotics

REMOTELY OPERATED VEHICLE DEVELOPMENT AT WOODS HOLE'S DEEP SUBMERGENCE LABORATORY

Robert D. Ballard OE-18

DEVELOPMENT STATUS: ARGO DEEP OCEAN INSTRUMENT PLATFORM

Stewart E. Harris, William M. Marquet and Robert D. Ballard OE-18

AN ADVANCED OBSERVATION AND INSPECTION REMOTELY OPERATED VEHICLE FOR 6,000

METER OPERATIONS

W.K. Stewart OE-19

MAN MACHINE INTERFACE AND CONTROL CONCEPTS FOR THE JASON PROGRAM

Dana R. Yoerger OE-19

ROBUST TRAJECTORY CONTROL OF UNDERWATER VEHICLES USING NONLINEAR DESIGN TECHNIQUES

Dana R. Yoerger and Jean-Jacques E. Slotine OE-19

Coastal Circulation and Dynamics

THE NANTUCKET SHOALS FLUX EXPERIMENT (NSFE79) PART I: A BASIC DESCRIPTION OF THE CURRENT AND TEMPERATURE VARIABILITY

Robert C. Beardsley, David C. Chapman, Kenneth H. Brink, Steven R. Ramp,
and Ronald J. Schlitz PO-3

DISCHARGE OF THE CHANGJIANG (YANGTZE RIVER) INTO THE EAST CHINA SEA

Robert C. Beardsley, Richard Limeburner, Honghua Yu and Glenn A. Cannon PO-3

INTRUSIONS OF OUTER SHELF AND SLOPE WATER WITHIN THE NEARSHORE ZONE OFF LONG ISLAND, NEW YORK

James H. Churchill PO-4

PROPERTIES OF FLOW WITHIN THE COASTAL BOUNDARY LAYER OFF LONG ISLAND, NEW YORK

James H. Churchill PO-4

THE RESPONSE OF STRATIFIED, FRICTIONAL FLOW OF SHELF AND SLOPE WATERS TO FLUCTUATING LARGE-SCALE, LOW-FREQUENCY WIND FORCING

Allan J. Clarke and Kenneth H. Brink PO-4

CIRCULATION INDUCED BY RIVER INFLOW IN WELL-MIXED WATER OVER A SLOPING CONTINENTAL SHELF

Gabriel T. Csanady PO-5

THE INFLUENCE OF WIND STRESS AND RIVER RUNOFF ON A SHELF-SEA FRONT

Gabriel T. Csanady PO-5

"PYCNOGRAPHIC" CURRENTS OVER THE UPPER CONTINENTAL SLOPE

Gabriel T. Csanady PO-5

A ZERO POTENTIAL VORTICITY MODEL OF THE NORTH BRAZILIAN COASTAL CURRENT

Gabriel T. Csanady PO-6

HYDROGRAPHIC AND CURRENT OBSERVATIONS ON THE CONTINENTAL SLOPE AND SHELF OF THE WESTERN EQUATORIAL ATLANTIC

Charles N. Flagg and Scott E. McDowell PO-6

Instrumentation

A NEW ALGORITHM FOR CTD OXYGEN CALIBRATION

W. Brechner Owens and Robert C. Millard, Jr. PO-7

Laboratory Models

THE DEFLECTION OF A BAROCLINIC JET BY A WALL IN A ROTATING FLUID

John A. Whitehead, Jr. PO-7

LABORATORY OBSERVATIONS OF A FRESH WATER GRAVITY CURRENT ON A SHELF:

THE GENERATION AND EFFECTS OF SHELF WAVES

John A. Whitehead, Jr. PO-7

A POSSIBLE COHERENT STRUCTURE IN THE OCEAN: EDDY GENERATION BY A DENSITY CURRENT

John A. Whitehead, Jr. PO-8

A MECHANISM FOR MAGMATIC ACCRETION UNDER SPREADING CENTRES

John A. Whitehead, Jr., Henry J. B. Dick and Hans Schouten PO-8

Large Scale Oceanic Heat and Water Properties

STRONG-CURRENT EVENTS RELATED TO A SUBTROPICAL FRONT IN THE NORTHEAST ATLANTIC

Gerold Siedler, Walter Zenk and William J. Emery PO-8

HEAT AND FRESH WATER BUDGETS OF THE INDIAN OCEAN REVISITED

John M. Toole and Mary E. Raymer PO-9

Ocean Circulation

DIAGNOSTIC MODEL OF CIRCULATION IN THE EQUATORIAL PACIFIC OCEAN

Harry L. Bryden and Esther C. Brady PO-9

PROFILING THE GULF STREAM WITH A CURRENT METER MOORING

Mindy M. Hall and Harry L. Bryden PO-10

ON THE RELATIONSHIP BETWEEN THE DEEP CIRCULATION AND THE GULF STREAM	
Nelson G. Hogg and Henry M. Stommel	PO-10
ESTIMATES OF THE GEOSTROPHIC STREAM FUNCTION IN THE WESTERN NORTH PACIFIC FROM XBT SURVEYS	
Chester J. Koblinsky, Robert L. Bernstein, William J. Schmitz, Jr. and Pearn P. Niiler	PO-10
THE 26-DAY OSCILLATION IN THE EQUATORIAL INDIAN OCEAN	
James R. Luyten and Dean H. Roemmich	PO-11
EASTWARD FLOW THROUGH THE MID-ATLANTIC RIDGE FRACTURE AT 11°N AND ITS INFLUENCE ON THE ABYSSAL WATER MASS OF THE EASTERN BASIN	
Michael S. McCartney, Sara L. Bennett, Mary E. Raymer and Mary L. Bremer . . .	PO-11
AVERAGE VELOCITY AND TRANSPORT OF THE GULF STREAM NEAR 55°W	
Philip L. Richardson	PO-12
DRIFTING BUOY TRAJECTORIES IN THE ATLANTIC NORTH EQUATORIAL COUNTERCURRENT DURING 1983	
Philip L. Richardson	PO-12
MOORED CURRENT METER MEASUREMENTS IN THE ATLANTIC NORTH EQUATORIAL COUNTERCURRENT DURING 1983	
Philip L. Richardson	PO-12
SOFAR FLOAT TRAJECTORIES ASSOCIATED WITH THE NEWFOUNDLAND BASIN	
William J. Schmitz, Jr.	PO-13
NEAR EQUATORIAL CTD OBSERVATIONS AT 85°W IN OCTOBER 1982	
John M. Toole	PO-13

Rings, Eddies

EDDY POTENTIAL VORTICITY FLUXES IN THE GULF STREAM RECIRCULATION	
Ellen D. Brown, W. Brechner Owens and Harry L. Bryden	PO-13
AN OBJECTIVE ANALYSIS OF THE POLYMODE LOCAL DYNAMICS EXPERIMENT	
II. STREAMFUNCTION AND POTENTIAL VORTICITY FIELDS DURING THE INTENSIVE PERIOD	
Bach Lien Hua, James C. McWilliams and W. Brechner Owens	PO-14
UPPER OCEAN VELOCITY STRUCTURE OF GULF STREAM WARM CORE RING 82B	
Terrence M. Joyce and Maureen A. Kennelly	PO-14
WINTERTIME CONVECTION IN A GULF STREAM WARM-CORE RING	
Terrence M. Joyce and Marvel C. Stalcup	PO-14
SMALL-SCALE CYCLONES ON THE PERIPHERY OF A GULF STREAM WARM-CORE RING	
Maureen A. Kennelly, Robert H. Evans and Terrence M. Joyce	PO-15
ON THE STRUCTURE AND ORIGIN OF A SMALL CYCLONIC EDDY OBSERVED DURING THE POLYMODE LOCAL DYNAMICS EXPERIMENT	
Eric J. Lindstrom, Curtis C. Ebbesmeyer and W. Brechner Owens	PO-15
DISTRIBUTION AND COMPOSITION OF BIOGENIC PARTICULATE MATTER IN A GULF STREAM WARM CORE RING	
David M. Nelson, Hugh W. Ducklow, Gary L. Hitchcock, Mark A. Brzezinski, Timothy J. Cowles, Christopher Garside, Richard W. Gould, Jr., Terrence M. Joyce, Christopher Langdon, James J. McCarthy and Charles S. Yentsch . . .	PO-15
ON THE GEOSTROPHIC VOLUME TRANSPORT IN HIGH EDDY ENERGY AREAS OF KUROSHIO EXTENSION AND GULF STREAM	
Pearn P. Niiler, William J. Schmitz and Dong-Kyu Lee	PO-16
A TWO-LAYER DIAGNOSTIC MODEL OF THE LONG TERM PHYSICAL EVOLUTION OF WARM CORE RING 82B	
Donald B. Olson, Raymond W. Schmitt, Maureen A. Kennelly and Terrence M. Joyce	PO-16
A STATISTICAL DESCRIPTION OF THE VERTICAL AND HORIZONTAL STRUCTURE OF EDDY VARIABILITY ON THE EDGE OF THE GULF STREAM RECIRCULATION	
W. Brechner Owens	PO-17
WINTERTIME CONVECTION IN WARM-CORE RINGS: THERMOCLINE VENTILATION AND THE FORMATION OF MESOSCALE LENSES	
Raymond W. Schmitt and Donald B. Olson	PO-17

Theoretical Models

ON THE NUMERICAL TREATMENT OF CROSS-SHELF OPEN BOUNDARIES IN A BAROTROPIC COASTAL OCEAN MODEL	
David C. Chapman	PO-18

MULTILAYER HYDRAULIC CONTROL WITH APPLICATION TO THE ALBORAN SEA CIRCULATION	
Nelson G. Hogg	PO-18
THE HETON, AN ELEMENTARY INTERACTION BETWEEN DISCRETE BAROCLINIC GEOSTROPHIC VORTICES, AND ITS IMPLICATIONS CONCERNING EDDY HEAT-FLOW	
Nelson G. Hogg and Henry M. Stommel	PO-18
HETONIC EXPLOSIONS: THE BREAKUP AND SPREAD OF WARM POOLS AS EXPLAINED BY BAROCLINIC POINT VORTICES	
Nelson G. Hogg and Henry M. Stommel	PO-19
BAROCLINIC INSTABILITY IN A MERIDIONALLY VARYING TWO-LAYER MODEL: LINEAR THEORY	
Stephen P. Meacham	PO-19
BAROCLINIC INSTABILITY IN A MERIDIONALLY VARYING TWO-LAYER MODEL: WEAKLY NON-LINEAR THEORY	
Stephen P. Meacham	PO-20
A NUMERICAL STUDY OF THE ROLES OF SUB-GYRE SCALE MIXING AND THE WESTERN BOUNDARY CURRENT ON HOMOGENIZATION OF A PASSIVE TRACER	
David L. Musgrave	PO-20
ON THE CIRCULATION OF THE WARM WATER OF THE SUBTROPICAL GYRES	
Joseph Pedlosky	PO-20
CROSS-GYRE VENTILATION OF THE SUBTROPICAL GYRE: AN INTERNAL MODE IN THE VENTILATED THERMOCLINE	
Joseph Pedlosky	PO-21
THE INSTABILITY OF CONTINUOUS HETON CLOUDS	
Joseph Pedlosky	PO-21
ON THE DYNAMICS OF THE COUPLED MIXED LAYER-THERMOCLINE SYSTEM AND THE DETERMINATION OF THE OCEANIC SURFACE DENSITY	
Joseph Pedlosky, Wendy M. Smith and James R. Luyten	PO-21

Upper Ocean, Surface Layer Processes and Meteorology

AIR-SEA MOMENTUM TRANSFER BY MEANS OF SHORT WIND-WAVES	
Gabriel T. Csanady	PO-22
THE INFLUENCE OF WINDS AND TOPOGRAPHY ON THE SEA SURFACE TEMPERATURE PATTERNS OVER THE NORTHERN CALIFORNIA SLOPE	
Kathryn A. Kelly	PO-22
SURFACE WIND MEASUREMENTS IN SEQUAL I	
Richard E. Payne	PO-22
NEAR SURFACE VELOCITY VARIABILITY AT INERTIAL AND SUBINERTIAL FREQUENCIES IN THE VICINITY OF THE CALIFORNIA CURRENT	
Robert A. Weller	PO-23

Technical Reports

ANALYSIS OF FLOW WITHIN THE COASTAL BOUNDARY LAYER OFF LONG ISLAND, NEW YORK	
James H. Churchill	PO-23
SLOPE WATER INTRUSIONS WITHIN THE NEARSHORE WATERS OFF LONG ISLAND, NEW YORK	
James H. Churchill	PO-23
MODELS AND SIMULATIONS OF TRACER DISPERSAL BY MID-OCEAN MESOSCALE EDDIES	
Dale B. Haidvogel and Thomas Keffer	PO-24
THE VELOCITY STRUCTURE OF WARM CORE RING 82B AND ASSOCIATED CYCLONIC FEATURES	
Maureen A. Kennelly	PO-24
GULF STREAM RECIRCULATION EXPERIMENT (GUSREX) AND LINE EXPERIMENT	
SOFAR FLOAT DATA 1980 - 1982	
Maureen A. Kennelly and Theresa K. McKee	PO-24
MOORED CURRENT METER DATA FROM THE ATLANTIC NORTH EQUATORIAL COUNTERCURRENT NEAR 6°N, 28°W (FEBRUARY - SEPTEMBER, 1983), VOLUME XXXIV	
Ellen Levy and Philip L. Richardson	PO-25
MOORED CURRENT METER DATA FROM THE ATLANTIC NORTH EQUATORIAL COUNTERCURRENT NEAR 6°N, 28°W (SEPTEMBER, 1983 - MARCH, 1984), VOLUME XXXVI	
Ellen Levy and Philip L. Richardson	PO-25
A COMPILATION AND DESCRIPTION OF HYDROGRAPHIC TRANSECTS OF THE MID-ATLANTIC BIGHT SHELF-BREAK FRONT	
Vincent D. Lyne and Gabriel T. Csanady	PO-25
THE LONG TERM UPPER OCEAN STUDY (LOTUS) CRUISE SUMMARY AND HYDROGRAPHIC DATA REPORT,	

OCEANUS 141, OCTOBER 1983, AND OCEANUS 145, JANUARY 1984	
Ellyn T. Montgomery, Nancy J. Pennington and Melbourne G. Briscoe	PO-25
THE LONG TERM UPPER OCEAN STUDY (LOTUS) CRUISE SUMMARY AND HYDROGRAPHIC DATA REPORT	
OCEANUS 154, MAY 1984	
Ellyn T. Montgomery, Nancy J. Pennington and Melbourne G. Briscoe	PO-26
HYDROGRAPHIC STUDY OF BUZZARDS BAY, 1982-1983, DATA REPORT	
Leslie K. Rosenfeld, Richard P. Signell and Glenn G. Gawarkiewicz	PO-26
A COMPILATION OF MOORED CURRENT METER DATA FROM THE REGION OF THE NORTH PACIFIC	
BOUNDARY CURRENT, VOLUME XXXIII	
Ann Spencer, Dolores H. Chausse and W. Brechner Owens	PO-26
A COMPILATION OF MOORED CURRENT METER AND WIND RECORDER DATA, Volume XXXV, LONG-TERM	
UPPER OCEAN STUDY (LOTUS), (MOORINGS 764, 765, 766, 767, 770) MAY 1982-APRIL 1983	
Susan A. Tarbell, Nancy J. Pennington and Melbourne G. Briscoe	PO-26
DRIFTER STUDIES IN WARM CORE RINGS	
Cynthia T. Tynan and Stanford B. Hooker	PO-26

REVIEW OF INDONESIAN MARINE FISHERIES

Conner Bailey, A. Dwiponggo and Ferial Marahundin MP-3
SEJARAH KERAJAAN MELAYU PATANI

Conner Bailey and John N. Miksic, Translators MP-3

ECONOMICS OF NON-FUEL MINERALS

James M. Broadus MP-4

POLYMETALLIC SULFIDES AND POLICY SPHERES

James M. Broadus and Robert E. Bowen MP-4

RIVALRY AND COORDINATION IN MARINE HARD MINERALS REGULATION

James M. Broadus and Porter Hoagland, III MP-4

ECONOMIC SIGNIFICANCE OF POLYMETALLIC SULFIDES

James M. Broadus MP-5

COASTAL AND MARINE RESOURCES MANAGEMENT FOR THE GALAPAGOS ISLANDS

James M. Broadus, Ivon Pires, Arthur Gaines, Conner Bailey, Robert Knecht
and Biliana Cicin-Sain MP-5

ADJACENT STATE ISSUES FOR THE UNITED STATES IN ESTABLISHING AN EXCLUSIVE

ECONOMIC ZONE: THE CASES OF CANADA AND MEXICO

Robert E. Bowen and Timothy M. Hennessey MP-6

U.S. EEZ RELATIONS WITH CANADA AND MEXICO

Robert E. Bowen and Timothy M. Hennessey MP-6

U.S.-MEXICAN PARLEY DEBATES RELATIONS ON MARINE RESOURCES

Biliana Cicin-Sain, Michael K. Orbach and Jorge A. Vargas MP-6

A MODEL FOR ASSESSING MEAN AGE-SPECIFIC FECUNDITY IN SEA TURTLE POPULATIONS

Nat B. Frazer MP-6

PROTECTING CARIBBEAN WATERS: THE CARTAGENA CONVENTION

Nat B. Frazer and M. J. Peterson MP-7

GROWTH CURVES FOR CAPTIVE LOGGERHEAD TURTLES, Caretta caretta, IN
NORTH CAROLINA, USA

Nat B. Frazer and Frank J. Schwartz MP-7

GROWTH IN WEIGHT FOR LOGGERHEAD TURTLES, Caretta caretta, REARED IN CAPTIVITY
FOR 14 YEARS IN NORTH CAROLINA

Frank J. Schwartz and Nat B. Frazer MP-7

PRELIMINARY GROWTH MODELS FOR GREEN, Chelonia mydas, AND LOGGERHEAD,
Caretta caretta, SEA TURTLES IN THE WILD

Nat B. Frazer and Llewellyn M. Ehrhart MP-8

THE RELATIONSHIP OF CLUTCH SIZE AND FREQUENCY TO BODY SIZE IN LOGGERHEAD TURTLES,
Caretta caretta

Nat B. Frazer and James I. Richardson MP-8

SEASONAL VARIATION IN CLUTCH SIZE FOR LOGGERHEAD SEA TURTLES, Caretta caretta,
NESTING ON LITTLE CUMBERLAND ISLAND, GEORGIA USA

Nat B. Frazer and James I. Richardson MP-8

A GUIDE TO THE USE AND EVOLUTION OF THE 1982 CONVENTION ON THE LAW OF THE SEA

John King Gamble MP-8

THE LIMITS OF "MUDDLING THROUGH" IN NATURAL RESOURCE MANAGEMENT

Timothy M. Hennessey MP-9

THE MANAGEMENT OF OCEAN AND COASTAL RESOURCES IN COLOMBIA: AN ASSESSMENT

Robert W. Knecht, Biliana Cicin-Sain, James M. Broadus, Maynard E. Silva,
Robert E. Bowen, Henry S. Marcus and Susan B. Peterson MP-9

EVALUATING THE RISKS OF OFFSHORE OIL DEVELOPMENT

William Lahey and Thomas Leschine MP-9

ECONOMIC EVALUATION OF ETHANOL FUEL PRODUCTION FROM AGRICULTURAL CROPS AND
RESIDUES IN CALIFORNIA

Mark Meo MP-10

SELECTION OF FEEDSTOCKS FOR SMALL AND INTERMEDIATE SCALE FUEL ETHANOL DISTILLERIES

Mark Meo MP-11

CONFIDENCE BUILDING MEASURES IN LATIN AMERICA

Michael A. Morris MP-11

SOUTHERN CONE EEZ PRACTICE

Michael A. Morris MP-11

COMPARATIVE MARITIME LIENS: ANGLO-BASED AND LATIN-BASED LAW IN THE AMERICAS

Ivon Pires MP-12

PRIORITY OF MARITIME LIENS IN THE WESTERN HEMISPHERE: HOW SECURE IS YOUR CLAIM?

Ivon Pires MP-12

A CHANGING OCEAN POLICY HORIZON FOR MARINE SCIENCE	
David A. Ross	MP-12
EEZ OFFERS A CHANCE FOR FOREIGN COLLABORATION	
David A. Ross	MP-13
THE ANTARCTIC TREATY: HISTORY, SUBSTANCE AND SPECULATION	
Kurt M. Shusterich	MP-13
ARCTIC ISSUES COMING TO FORE	
Kurt M. Shusterich	MP-13
MARINE RESOURCE DEVELOPMENT IN BELIZE	
Kurt Shusterich	MP-13
LAND GRANT AND SEA GRANT: IMPLICATIONS AND LIMITATIONS OF THE MODEL	
Maynard E. Silva	MP-14
THE LAW OF THE SEA AND THE U.S. EXCLUSIVE ECONOMIC ZONE: PERSPECTIVES ON MARINE TRANSPORTATION AND FISHERIES	
Maynard Silva and William Westermeyer	MP-14
UNITED STATES ARCTIC INTERESTS	
William Westermeyer and Kurt Shusterich, Editors	MP-14

EDDY FORCING OF THE MEAN CIRCULATION IN THE WESTERN NORTH ATLANTIC	
Ellen D. Brown	GS-3
THE ROLE OF HETEROTROPHIC MICROFLAGELLATES IN PLANKTON COMMUNITIES	
David A. Caron	GS-3
SODIUM AND GLUCOSE TRANSPORT ACROSS THE IN VITRO PERFUSED MIDGUT OF THE BLUE CRAB, <u>Callinectes sapidus</u> Rathbun	
Ka Hou Chu	GS-5
THE MARINE GEOCHEMISTRY OF THE RARE EARTH ELEMENTS	
Hein J. W. de Baar	GS-5
INITIAL SETTLEMENT OF MARINE INVERTEBRATE LARVAE: THE ROLE OF PASSIVE SINKING IN A NEAR-BOTTOM TURBULENT FLOW ENVIRONMENT	
Cheryl Ann Hannan	GS-6
THE THERMOCLINE AND CURRENT STRUCTURE IN SUBTROPICAL/SUBPOLAR BASINS	
Rui Xin Huang	GS-7
ASYMPTOTIC ANALYSIS OF OCEAN BOTTOM REFLECTED ACOUSTIC FIELDS	
Hiroshi Kawahara	GS-8
BAROCLINIC INSTABILITY OF A MERIDIONALLY VARYING BASIC STATE	
Stephen P. Meacham	GS-9
BIOCHEMICAL CHANGES ASSOCIATED WITH EMBRYONIC AND LARVAL DEVELOPMENT IN THE AMERICAN LOBSTER <u>Homarus americanus</u> Milne Edwards	
Glenn Craig Sasaki	GS-9
INTERACTION OF HIGH FREQUENCY INTERNAL WAVES AND THE BOTTOM BOUNDARY LAYER ON THE CONTINENTAL SHELF	
Lawrence P. Sanford	GS-10
TIDAL DISTORTION IN SHALLOW ESTUARIES	
Paul E. Speer	GS-10
CHEMISTRY OF SUBMARINE HYDROTHERMAL SOLUTIONS AT 21° NORTH, EAST PACIFIC RISE AND GUAYMAS BASIN, GULF OF CALIFORNIA	
Karen L. Von Damm	GS-10

DEPARTMENT OF BIOLOGY

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John M. Weil, Department Chairman

ANIMAL PHYSIOLOGY

AND BIOCHEMISTRY

PECTORAL FIN LOCOMOTION: ACCELERATION PATTERNS DURING STEADY SWIMMING BY CUNNERS AND TAUTOGS (LABRIDAE)

Marvin A. Freadman

Acceleration patterns of two pectoral fin swimmers (Labridae: Tautog, Tautoga onitis, cunner, Tautogolabrus adspersus) were measured with implanted miniature accelerometers. The fishes were swimming steadily in a water tunnel treadmill and increments of flow velocity were selected to monitor acceleration during a hierarchy of swimming modes displayed by these animals. The accelerometer detects instantaneous acceleration and instantaneous deceleration of the body during swimming and a polygraph record from the device represents the interplay between thrust, drag, and mass of a swimming fish. No lateral acceleration of the body was found during asynchronous and synchronous pectoral fin movements at slow and intermediate swimming velocities (implying continuous thrust production) but acceleration in this plane was detected as the animals shift to body/caudal fin propulsion at higher swimming velocities. Forward acceleration was recorded during all swimming modes utilized by the pectoral fin swimmers. This shift in propulsive mode probably increases the swimming drag dramatically. This is in contrast to records from a mackerel (body/caudal fin swimmer over entire swimming velocity range) in which substantial lateral as well as forward acceleration was found. The accelerometers permit qualitative interpretations of swimming drag but quantitative determinations remain problematic due to defining a point in the records where thrust is zero, if there is such a point. Some discussion of the problems of interpretation of accelerometer records is provided with a viewpoint on how flow visualization and quantification may help resolve the difficulties and also aid development of hydromechanical models of swimming.

Supported by: NIH Grant 1 F32 AM05976 and OIP at WHOI.

WHOI Contribution No. 5712.

CARDIORESPIRATORY DYNAMICS OF Limulus polyphemus (L.): RELATIONSHIPS DURING REST, VENTILATION AND SWIMMING ACTIVITY

Marvin A. Freadman and Winsor Hayes Watson, III

We measured heart activity, ventilatory activity, pressures in the heart and the branchiocardiac canals in 11 adult Limulus polyphemus (restrained and free-swimming) during various forms of the animal's respiratory and swimming repertoire under normoxic conditions. We found covariation of the heart and ventilation rates during intermittent ventilation, hyperventilation, gill cleaning and swimming as well as evidence of phasic coordination. During ventilation, hyperventilation and swimming (produced by rapid ventilatory appendage movements), pressures in the branchiocardiac canals leading to the heart from the gills rise to high levels. During quiescent periods, with no ventilatory activity occurring, there are no pressure pulses in the canals but the pressure is greater than zero. We suggest ventilatory movements and rapid swimming movements enhance the flow of low pressure blood, returning from the body, to the heart. Thus the ventilatory appendage movements aid blood flow to the pericardial cavity and heart and constitute an accessory pumping mechanism.

Supported by: OIP at WHOI and a Faculty Research Grant from the University of New Hampshire.

WHOI Contribution No. 5711.

A TESTOSTERONE HYDROXYLATING CYTOCHROME P-450 ISOZYME PURIFIED FROM THE MARINE TELEOST Stenotomus chrysops

Alan V. Klotz, John J. Stegeman and Chris Walsh

A cytochrome P-450 isozyme (cytochrome P-450A; $M_r = 52.5$ K), purified from the liver microsomes of the marine fish Stenotomus chrysops, catalyzed the hydroxylation of testosterone almost exclusively at the 6 β position when reconstituted. This activity was maximal (0.8 nmol/min/nmol cytochrome P-450) when cytochrome P-450A was reconstituted with purified scup NADPH-cytochrome P-450 reductase and it was markedly stimulated by addition of purified scup cytochrome b_5 . Purified cytochrome P-450A had a CO-ligated, reduced difference spectrum λ_{max} at 447.5 nm, like the blueshifted CO, reduced chromophore of the major aromatic hydrocarbon hydroxylating isozyme, cytochrome P-450E. In a recon-

stituted system, cytochrome P-450A had little benzo[α]-pyrene hydroxylase activity (0.16 nmol/min/nmol cytochrome P-450) or ethoxycoumarin O-deethylase activity; but, as with testosterone hydroxylase, both of these activities of cytochrome P-450A preferred scup NADPH cytochrome P-450 reductase and were stimulated by scup cytochrome b₅. We propose that the cytochrome P-450A isozyme may be directed toward steroid substrates and is a major contributor to the testosterone 6 β -hydroxylase activity observed in liver microsomes. Cytochrome P-450A also bears many physicochemical properties in common with an isosafrole-inducible rat liver cytochrome P-450 form, including relative molecular weight, substrate profile and stimulation by cytochrome b₅ in reconstitutions for catalytic activity. If cytochrome P-450A is also induced by aromatic hydrocarbons, then this regulation may provide a link between environmental exposure and steroid balance.

Supported by: NSF Grant OCE80-18569 and NIH Grant GM21643.

WHOI Contribution No. 5590.

GROWTH AND BIOCHEMICAL COMPOSITION OF THE LARVAE OF Teredo navalis L. AND Bankia gouldi (Bartsch)

Roger Mann and Scott M. Gallagher

The biochemical composition of larvae of Teredo navalis L. and Bankia gouldi (Bartsch) was examined throughout larvae development at 23°C and 30-32 o/oo salinity in the presence of the phytoplankton food Isochrysis aff. galbana (clone T-ISO), during a delay of metamorphosis in the presence of food but absence of a wood substrate, and during periods of enforced starvation. Newly released T. navalis larvae had a mean length (L) and height (H) of 89.3 and 76.1 μ m respectively. The first appearance of pediveliger larvae at 212.1 μ m L and 230.0 μ m H occurred at 27 days after release. Larval dry weight increased from 0.292 μ g to 1.96 μ g during this period. Newly formed straight hinge larvae of B. gouldi had dimensions of 62.8 μ m L and 49.8 μ m H. Metamorphically competent B. gouldi larvae had dimensions of 230 μ m L and 282.9 μ m H and were first observed 28 days after fertilization. Larval dry weight increased from 0.058 μ g to 2.20 μ g during this period. During enforced delay of metamorphosis ash-free dry weight of T. navalis larvae decreased whereas ash free dry weight of B. gouldi larvae increased. During the early days of shelled larval development both species showed a similar decrease in relative (μ g/mg dry weight)

content of all of lipid, protein and carbohydrate; however, this was reflected in absolute content (μ g) in only T. navalis. During enforced starvation the major proportion of both weight and caloric losses are in the form of protein. Lipid also contributes significantly to these losses whereas the contribution of carbohydrate is small.

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WHOI Contribution No. 5680.

GROWTH, MORPHOMETRY AND BIOCHEMICAL COMPOSITION OF THE WOOD BORING MOLLUSCS Teredo navalis L., Bankia gouldi (Bartsch) AND Nototeredo knoxi (Bartsch)

Roger Mann and Scott M. Gallagher

Growth, morphometry and biochemical composition of the wood boring molluscs Teredo navalis L., Bankia gouldi (Bartsch) and Nototeredo knoxi (Bartsch) were examined. Animals were maintained in fir dowels for up to 232 days post settlement in a constant flow of filtered sea water at 18-23°C and 30-32 o/oo salinity in either the absence (T. navalis and B. gouldi only) or presence (all species) of a supplement of the phytoplankton food Isochrysis aff. galbana (clone T-ISO). With only one exception, the final sample of phytoplankton supplemented T. navalis at 182 days, no difference was observed in the mean length of animals growing unaccompanied by other individuals in a single dowel and the grand mean for all animals in that species-feeding regime combination. Variability in length at any one species-food regime combination was considerable. The presence of a phytoplankton supplement did not increase the growth rate of T. navalis but did increase the growth rate of B. gouldi. Growth in T. navalis and N. knoxi was comparable and characterized by gradual increase in length with time; however, growth in B. gouldi was characterized by an initial period of slower growth than either T. navalis or N. knoxi followed by a period of much faster growth than either of the other species. At 60 days post settlement a subsample of 41 B. gouldi from the filtered sea water regime showed gonadal development with a male:female ratio of 2.33:1. Females were significantly longer than males. At 55 days post settlement only one N. knoxi from a subsample of 22 individuals exhibited gonadal development. With increasing length the shape of the tube bored by T. navalis and B. gouldi was char-

acterized as a truncated cone progressing towards a cylinder; the relationship of calculated tube volume, $V(\text{mm}^3)$, and tube length, $L(\text{mm})$, are described by the relationship $V = aL^b$ with b values in the range 1.26-1.43. In N. knoxi, by contrast, the calculated b value was 2.09. The relationship of tube volume to dry tissue weight (W mg) of the individual was more variable and probably influenced by spawning activity. In the absence of a phytoplankton supplement, both T. navalis and B. gouldi exhibited consistently higher carbohydrate (generally >16.5% of ash-free dry weight) than lipid content (generally <5% of ash-free dry weight) throughout the dry tissue weight ranges <2-65.48 and <4-121.75 mg, respectively. By contrast, the presence of a phytoplankton supplement resulted in higher percentage ash and lipid contents in both T. navalis and B. gouldi in the dry tissue weight ranges 16.1-171.2 and 11.69-115.5 mg, respectively, with lipid content generally exceeding that of carbohydrates. N. knoxi in the dry tissue weight range 11.7-53.2 mg exhibited biochemical composition similar to that of T. navalis and B. gouldi maintained in the phytoplankton supplemented regime.

In press: Journal of Experimental Marine Biology and Ecology.

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WHOI Contribution No. 5682.

OSMOREGULATION IN THE BROOK TROUT, Salvelinus fontinalis.

I. DIET, PHOTOPERIOD AND GROWTH RELATED PHYSIOLOGICAL CHANGES IN FRESHWATER

Stephen D. McCormick and Robert J. Naiman

1. Brook trout (Salvelinus fontinalis) raised from eggs under two photoperiod and two feeding regimes were tested for physiological changes preparatory for transition from freshwater to sea water. Size, age, growth rate, photoperiod, and diel rhythms were examined for possible influences on plasma osmolarity, $[\text{Na}^+]$, $[\text{Cl}^-]$, $[\text{K}^+]$, $[\text{Mg}^{2+}]$, thyroxine concentration, hematocrit, and gill Na^+, K^+ -ATPase activity of brook trout in freshwater.

2. Significant diel cycles were found in plasma osmolarity, $[\text{Na}^+]$ and thyroxine concentration.

3. Significant size and/or age related changes occurred for plasma osmolarity, $[\text{Na}^+]$, $[\text{K}^+]$ and hematocrit, but could explain little of their total variation ($0.02 < r^2 < 0.18$).

4. A sexually dimorphic response to

photoperiod was observed in hematocrit for both mature and immature fish, with hematocrit of mature females declining in autumn and hematocrit of immature males increasing in autumn.

5. Gill Na^+, K^+ -ATPase activity did not respond to photoperiod or feeding treatment and showed no change with size or age.

6. Plasma thyroxine levels responded to feeding and photoperiod treatment. There was a significant correlation between the percent mean difference in plasma thyroxine and the mean difference in growth rate between high and low feed fish ($r^2 = 0.51$), suggesting a relationship between thyroxine and growth.

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WHOI Contribution No. 5597.

OSMOREGULATION IN THE BROOK TROUT, Salvelinus fontinalis.

II. EFFECTS OF SIZE, AGE AND PHOTOPERIOD ON SEAWATER SURVIVAL AND IONIC REGULATION

Stephen D. McCormick and Robert J. Naiman

1. Brook trout (Salvelinus fontinalis) of a single genetic stock, and hatched at the same time, were raised under two photoperiod and two feeding regimes to obtain fish of the same age but with different sizes and photoperiod experiences. In 11 experiments over 1.5 yrs, fish were gradually exposed to 32 ppt sea water for 20 d to investigate the ontogeny of salinity tolerance.

2. Daily changes in plasma osmolarity, $[\text{Na}^+]$, $[\text{Cl}^-]$, $[\text{K}^+]$, $[\text{Mg}^{2+}]$, thyroxine, hematocrit and gill Na^+, K^+ -ATPase during adaptation to 10, 20 and 32 ppt were examined in one experiment.

3. Size was the primary determinant of sea water survival ($r^2 = 0.77$); the effect of size on sea water survival slowed after fish reached a fork length of 14 cm. The effect of age on sea water survival ($r^2 = 0.65$) was through its covariance with size.

4. Photoperiod affected sea water survival only through its influence on the timing of male maturation, which decreased salinity tolerance.

5. Regulation of plasma osmolarity, $[\text{Na}^+]$, $[\text{Cl}^-]$, $[\text{K}^+]$, $[\text{Mg}^{2+}]$ and hematocrit in

sea water increased linearly with size over the entire range of sizes (6-32 cm).

6. Gill Na^+ , K^+ -ATPase activity after 20 d in sea water decreased with increasing size of brook trout, possibly reflecting decreased demand for active ion transport in larger fish.

7. Plasma thyroxine concentrations declined in sea water, but no definitive role of this hormone in sea water adaptation was found.

8. Size dependent survival and osmoregulatory ability of brook trout is compared to other salmonids and a conceptual model is developed.

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WHOI Contribution No. 5595.

PHYSIOLOGICAL SMOLT CHARACTERISTICS OF
ANADROMOUS AND NON-ANADROMOUS
BROOK TROUT (*Salvelinus fontinalis*) AND
ATLANTIC SALMON (*Salmo salar*)

Stephen D. McCormick, Robert J. Naiman
and Ellyn T. Montgomery

Anadromous brook trout, *Salvelinus fontinalis*, of Rivière à la Truite, Québec, were examined for physiological changes associated with smoltification and compared to non-anadromous brook trout from the adjacent Matamek River. There were no differences ($p > 0.05$) in plasma thyroxine concentration, gill Na^+ , K^+ -ATPase activity, hematocrit or osmoregulatory ability between the populations. Moisture content was different ($p < 0.05$) between the populations, but the same pattern of declining moisture content as summer progressed existed in both populations. Silver coloration of brook trout in Rivière à la Truite was associated with larger fish and higher gill Na^+ , K^+ -ATPase activity ($p < 0.05$), but not with changes in plasma thyroxine concentration, moisture content, hematocrit or condition factor. Silver coloration was absent in Matamek River brook trout. Brook trout at high salinity estuarine sites had greater gill Na^+ , K^+ -ATPase activity and hypoosmoregulatory ability than those from low salinity sites. Silvering of Atlantic Salmon (*Salmo salar*) in Rivière à la Truite was associated ($p < 0.05$) with larger fish, higher gill Na^+ , K^+ -ATPase activity, higher plasma thyroxine and lower hematocrit. Gill

Na^+ , K^+ -ATPase activity of highly silvered freshwater Atlantic salmon was greater than that of highly silvered brook trout. Estuarine Atlantic salmon had significantly higher plasma thyroxine concentration and gill Na^+ , K^+ -ATPase activity than estuarine brook trout. Based on the physiological parameters studied, we conclude that smoltification is undeveloped in brook trout and that estuarine residence is important for salt water acclimation and eventual seaward migration.

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WHOI Contribution No. 5732.

A Q U A C U L T U R E

SAMPLING OF BIVALVE LARVAE

Roger Mann

Bivalve veliger larvae are small, usually less than 300 microns in maximum dimension, and swim weakly in either vertically oriented straight lines or helices. They have no capability to swim in the horizontal plane, such movement is passive. Active avoidance of net or pumped sampling systems is probably negligible. Representative, quantitative sampling of bivalve veliger larvae throughout the water column is, however, confounded by active depth regulation of larvae in response to pressure, gravity, light, salinity and temperature stimuli. These responses vary between species and between different developmental stages within a species. Design of sampling protocol requires some prior knowledge of larval swimming behaviour.

Identification of bivalve veliger larvae in formalin preserved samples relies heavily on shape and morphometric measurements. Recently, a combination of optical and scanning electron microscopy techniques have been employed to provide much improved accuracy in identification of bivalve veliger larvae. Identification and enumeration present a limited information set to the fishery biologist. Simple assays of the quality or viability of larvae collected in the field have been lacking; however, recent work with visual lipid specific stains in cultured bivalve larvae has demonstrated a

strong qualitative relationship between larval lipid content and ability of those larvae to metamorphose. Lipid is important to bivalve larvae as both an energy reserve and in maintaining low specific gravity. Lipid specific staining can be effected quickly and easily on field collected plankton samples and provides an index of larval condition on individual animals. Present work focuses on development of a quantitative visual assay of larval lipid content which will provide a valuable supplement to data on larval speciation, size and numbers.

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WHOI Contribution No. 5663.

DEGRADATION OF Artemia LIPIDS UNDER STORAGE

Glenn C. Sasaki and Judith M. Capuzzo

The total lipid, lipid class and fatty acid composition of Artemia were examined for evidence of enzymatic or oxidative degradation during sample storage. A variety of storage techniques were tested with storage times of 7, 30 or 105 days. At -20°C, enzymatic degradation resulting in the formation of free fatty acids from phosphatidyl (P.) choline and P. ethanolamine was found to occur in trace amounts after 7 days and significant amounts after 105 days. No evidence of oxidative degradation of fatty acid double bonds was seen. Lipid classes were determined using an Iatroscan (TLC-FID) and a new solvent system for neutral lipid analysis is introduced.

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WHOI Contribution No. 5594.

B E N T H O S

LIFE HISTORY AND PRODUCTION OF THREE AMPHIPOD SPECIES ON GEORGES BANK

Jeremy S. Collie

As part of the Georges Bank Benthic Monitoring Program, size-frequency analysis was used to study the life history and production of three benthic amphipod species: Ampelisca agassizi, Unicicola inermis and Ericthonius fasciatus. Abundant over large areas of Georges Bank, these amphipods are important prey of yellowtail flounder. From benthic grab samples collected quarterly during 1981 to 1983, over 200 individuals of each species were measured from each sampling date. The computer program NORMSEP was used to separate the length-frequency distributions into cohorts. Growth and mortality rates were determined by following cohorts through time; production was calculated as the sum of growth increments. Differences in the population dynamics of the three species are exemplified by the annual production-to-biomass ratios. E. fasciatus has the highest P/B ratio (4.4), followed by U. inermis (2.5) and A. agassizi (1.5). These results, the first direct production estimates for benthic macrofaunal species on Georges Bank, are compared to production estimates for other marine amphipod species. Amphipod production rates on Georges Bank appear to be as high as production rates of related near-shore species.

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WHOI Contribution No. 5762.

DEEP-SEA FAUNA OF SEDIMENTS IN THE VICINITY OF HYDROTHERMAL VENTS

J. Frederick Grassle, L. Susan Brown-Leger, Linda S. Morse-Porteous, Rosemarie F. Petrecca and Isabelle P. Williams

The soft sediments of three hydrothermal vent areas have been quantitatively sampled. Each area has a different fauna. The most active sites of hydrothermal discharge have reduced densities of both individuals and species and the most extreme conditions favor single species of polychaetes and bivalves. Communities adjacent to areas of mineral deposition in the Galapagos Mounds have as rich and diverse a deep-sea community as any known. In the Pacific the only data for comparison come from shallower or deeper depths.

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WHOI Contribution No. 5763.

SUBTIDAL MACROBENTHOS OF NARRAGANSETT BAY.
FIELD AND MESOCOSM STUDIES OF THE EFFECTS
OF EUTROPHICATION AND ORGANIC INPUT ON
BENTHIC POPULATIONS

J. Frederick Grassle, Judith P. Grassle,
L. Susan Brown-Leger,
Rosemarie F. Petrecca and Nancy J. Copley

Benthic macrofaunal populations in Narragansett Bay and replicate mesocosms representative of portions of Narragansett Bay respond rapidly to variation in food supply. During five years of sampling, sharp increases in August mortalities occur when estimated carbon demands for benthic respiration exceed the amount of organic carbon reaching the bottom. Rapid recovery following these periods of high mortality indicate a very resilient community. Benthic population densities in mesocosms rapidly increase in response to external additions of plant material and to within system increases in productivity from nutrient additions. Larval immigration and predation are also important in determining population densities in the experimental systems, but these variables are less easy to control and the effects are less obvious.

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WHOI Contribution No. 5605.

B I O G E O G R A P H Y A N D
S Y S T E M A T I C S

MICTACEA, A NEW ORDER OF
CRUSTACEA PERACARIDA

Thomas E. Bowman, Susan P. Garner,
Robert R. Hessler, Thomas M. Iliffe
and Howard L. Sanders

A new order, Mictacea, is proposed within the superorder Peracarida for Hirsutia bathyalis Sanders, Hessler, and Garner and Mictocaris halo Bowman and Iliffe. The new order is characterized by a unique combination of characters, most of which are not unique to the Mictacea, but are found in at least one other peracaridan order.

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WHOI Contribution No. 5823.

STUDIES ON DEEP-SEA PROTOBRANCHIA
(BIVALVIA); THE FAMILY MALLETIIDAE

Howard L. Sanders and John A. Allen

This paper redefines the deep water protobranch bivalve family Malletiidae and describes the functional morphology, growth and geographical distribution of nine species obtained from abyssal and slope depths of the Atlantic. Three new species are described, all from the Guinea Basin.

Subtle differences in the shell shape between different populations are, where possible, quantified and described. The differences are discussed in relation to reproduction and isolation, taking into account possible slow rates of gene flow and the emergence of sibling species.

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Hirsutia bathyalis, A NEW UNUSUAL DEEP-SEA
PERACARIDAN CRUSTACEAN
FROM THE TROPICAL ATLANTIC

Howard L. Sanders, Robert R. Hessler
and Susan P. Garner

A new species, Hirsutia bathyalis, created for a single, small peracaridan crustacean collected at a depth of 1000 meters from the seafloor off northeastern South America, provides the basis for one of two new families, the Hirsutiidae, of the new order Mictacea erected by Bowman et al. (1985) in the present number of this journal. Hirsutia uniquely possesses a number of morphological features found neither in other peracaridan orders nor in the second species, Mictocaris halo, and family, the Mictocaridae, of the Mictacea (Bowman and Iliffe, 1985; immediately following paper). These include: paragnaths that have elongate, slender anterior extensions that are probably sensory; an absence of grooming armature on the medial surface of the mandibular palp; unusually long setal armature on the pereopodal basal-endopodal shaft relative to other peracaridan Crustacea; "oostegites" that arise from the posterior rather than medial surface of the coxa as in all other known Peracarida, supporting Claus's (1885) century-old contention that oostegites are modified epipodites. The morphology of Hirsutia suggests that it possesses the potential of being a facultative carnivore.

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ADAPTATIONS OF Ptychodera flava
(ENTEROPNEUSTA:PTYCHODERIDAE)
FOR DISPERSAL AND COLONIZATION

Rudolf S. Scheltema

Ptychodera flava is a worm-like infaunal species of hemichordate with an Indo-west Pacific geographic range. The species has a planktonic larva that is widely distributed by currents of the warm-temperate and tropical Pacific Ocean. In the Atlantic, Ptychodera bahamensis likewise has a planktonic larva also widely dispersed by ocean currents. However, bottom populations of Ptychodera bahamensis, insofar as known, are entirely restricted to the western tropical Atlantic. Owing to the great similarity of both larvae and adults, several authors have regarded the two species as synonyms. Over their 3.5 to 9 months of planktonic life, the tornaria of Ptychodera flava may be transported thousands of kilometers. Previously published drift-bottle data suggest that tornaria transported by the Pacific South Equatorial Current have a 3.9% probability of encountering another island. In contrast, larvae of Ptychodera bahamensis have only an 0.2% probability of transport across the Atlantic, a fact that (in addition to ecological constraints for its establishment) may contribute to its absence in the eastern Atlantic. It is inferred that populations of Ptychodera flava on the major Hawaiian Islands can be maintained from larvae of local origin. In the absence of any significant differential selection, it is calculated that a larval flux of only 2.6% between islands would be required to offset the effect of random drift. The establishment of Ptychodera species in new regions may be facilitated by asexual reproduction.

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INTER-RELATIONSHIPS BETWEEN LARVAL
DISPERSAL AND OTHER FACTORS DETERMINING
GEOGRAPHIC RANGE: EXAMPLES FROM
INTERTIDAL AND SUBLITTORAL MOLLUSCS

Rudolf S. Scheltema

The geographic patterns of distribution among marine molluscs are determined (1) by dispersal; e.g., the active migration of

adults or the passive transport either of planktonic larvae or by some form of rafting; (2) by ecological constraints, the physical or biological environment that restricts where a species may survive and reproduce; and (3) by past historical events such as climatic change or the opening and closing of seaways over geologic time. The range of a species at any particular moment is determined by an equilibrium between its ability to disperse and the ecologic or geomorphologic constraints that restrict the expansion of its geographic distribution.

The significance of planktonic larvae for the dispersal of gastropod species is inferred from a comparison between the mode of development (i.e., planktonic or non-planktonic) and geographic range. Prosobranchs having a planktonic veliger stage on the average have significantly greater geographic range than those lacking a planktonic larva. Length of planktonic development is unrelated to geographical distribution so long as no major barrier to dispersal exists; e.g., a wide area of open ocean. The difference between these species with teleplanic larvae and those that have actaeplanic veligers lies in the ability of the former to cross biogeographic barriers such as ocean basins, to colonize oceanic islands and to make possible genetic exchange between very widely separated and isolated populations.

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LARVAL DISPERSAL AND GEOGRAPHIC RANGE
OF SUBLITTORAL INVERTEBRATES ON CENTRAL
PACIFIC ISLANDS

Rudolf S. Scheltema

The geologic origin of central Pacific islands by volcanic activity at "hot spots" through a pre-existing ocean floor requires that their original colonization must have been the result of long-distance dispersal. It is proposed that for most sublittoral invertebrates such dispersal was by means of planktonic larvae. Evidence from surface plankton samples shows that the larvae of a wide variety of benthic invertebrates, including but not restricted to those of gastropods and bivalve molluscs, sipunculans, polychaetes, echinoderms, and brachyuran decapod crustacea, occur in the surface waters of the tropical Pacific Ocean. Data from drift bottles in the South Equatorial Current give an average surface velocity of 20 km day⁻¹, enough to account for the dispersal of larvae from 1200 to 3700 km over the 2 to 6 months (or

sometimes longer) required for the development of teleplanic larvae. Maximum values twice the mean have been recorded (4486 km in 86 days) and such velocities could result in even higher rates of larval transport. The likelihood that a larva in the South Equatorial Current will encounter an island is computed to be near one in twenty-six (i.e., 3.9% of the larvae will reach a landfall). Because most benthic invertebrates with planktonic larvae spawn large numbers of eggs, the number of larvae available for colonizing "foreign" islands may be quite large if the proportion of those escaping the circulation of their parent island and entrained into a major current is great enough. The low endemism and large percentage of Indo-West Pacific species on central Pacific islands suggest that enough immigration of larvae occurs to maintain gene-flow; indirect stepwise dispersal with other remote regions apparently offsets any differentiation by genetic drift. Selection among sublittoral invertebrates is insufficient in most instances to result in species radiation as observed in insects (e.g., Hawaii). It is concluded that the most likely explanation for the widespread persistence of sublittoral invertebrates on central Pacific islands is their capacity for dispersal by means of planktonic larvae.

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THE RELATIONSHIP BETWEEN MODE
OF DEVELOPMENT AND GEOGRAPHIC RANGE
IN INTERTIDAL AND SUBLITTORAL
PROSOBRANCH GASTROPOD MOLLUSCS

Rudolf S. Scheltema

Evidence from the intertidal and sublittoral prosobranch molluscan fauna of Beaufort, North Carolina and Woods Hole, Massachusetts, U.S.A. shows that species with a planktonic larval development have, on the average, significantly greater geographic ranges than those that lack a planktonic stage. However, length of planktonic development is unrelated to geographical distribution so long as there exists no major barrier to dispersal. For example, a species with an actaeplanic larva, notwithstanding its planktonic stage of less than 6 weeks, may have a wide geographic distribution, presumably the result of stepwise dispersal. Such species are restricted, however, to the western Atlantic Ocean (i.e., North, Central and South America) and are likely to show genetic differences between distant points within their ranges or to have clines of genetic

variation along latitudinally disposed populations. On the other hand, a species with a teleplanic larva (sometimes remaining planktonic for as long as 12 months) not only has a large geographic range, but also is able to cross biogeographic barriers such as large expanses of open ocean. Indeed, three-quarters of all species known to have teleplanic larvae also are amphi-Atlantic in distribution. Furthermore, in contrast to species with actaeplanic larvae, those with teleplanic veligers are expected to be panmictic over large areas of their geographic range. Prosobranch species with a teleplanic larva are restricted to lower latitudes; 25 percent of the Beaufort fauna for which larval development is known have teleplanic veliger larvae, whereas no instance is known from the Woods Hole fauna.

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E C O S Y S T E M S T U D I E S

PREDATION

PREDATORY CONTROL OF COPEPOD SEASONAL
CYCLES ON GEORGES BANK

Cabell S. Davis

A simulation model of copepod population dynamics (development rate, fecundity, and mortality) was used to compute the predatory consumption necessary to control population growth in three dominant copepod species (Pseudocalanus sp., Paracalanus parvus, and Calanus finmarchicus) on Georges Bank, given observed seasonal cycles of copepod and predator populations. The model also calculated secondary production of each species. Copepod development rate and fecundity were functions of temperature while mortality was a function of predator abundance and consumption rate. Temperature and predator abundance (chaetognaths, ctenophores, and Centropages spp.) were input to the model daily. Model runs were made with various consumption rates until the model output matched observed copepod seasonal cycles. Computed consumption rates were low compared with published values from field and laboratory studies indicating that, even at conservative estimates of consumption, predators are able to control these copepod populations. Combined annual secondary production by the small copepod species, Pseudocalanus sp. and Paracalanus parvus, was over twice that of the larger Calanus

finmarchicus with P. parvus having the highest total annual production.

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RIVERINE SYSTEMS

PARTICULATE ALLOCHTHONOUS INPUTS: RELATIONSHIPS WITH STREAM SIZE IN AN UNDISTURBED WATERSHED

M. Elizabeth Connors and Robert J. Naiman

Four streams of a pristine boreal watershed in eastern Québec, Canada, were examined to assess the composition, seasonal pattern, and ash-free dry mass (AFDM) of particulate allochthonous input. Study sites on streams ranging from first to sixth order exhibited significant differences in the types and magnitude of litter input. Composition of litterfall varied according to vegetation and physical structure of the riparian zone. Although the forest in the watershed is dominated by conifers, deciduous leaves dominated annual budgets and seasonal input patterns. Annual litterfall per unit area of stream surface declined exponentially with increasing stream order ($r^2 = 0.98$), from 307-534 g AFDM $m^{-2} yr^{-1}$ in a first order stream to 15-17 g AFDM $m^{-2} yr^{-1}$ in a sixth order stream. Lateral inputs of 25-70 g AFDM $m^{-1} yr^{-1}$ were not related to stream size, but were strongly influenced by riparian structure and entrainment of organic matter during spring flooding. Total input per unit stream length increased logarithmically with increasing order ($r^2 = 0.87$), approaching 1000 g AFDM $m^{-1} yr^{-1}$ in the fifth and sixth order streams. A watershed budget calculated from these results estimates a total input of 729 t/yr to streams of this 673 km^2 watershed. When particulate allochthonous input is compared to primary production measurements in these streams, 81-95% of the organic carbon supplied to the first and second order streams is allochthonous, but 85-95% of the supply to the fifth and sixth order streams is autochthonous. While these trends agree with predictions of the synthetic continuum model, the importance of local effects in our results illustrates the need for a more mechanistic approach in allochthonous input research.

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ECOSYSTEM ALTERATION OF SUBARCTIC WATERSHEDS BY BEAVER (Castor canadensis)

Robert J. Naiman, Jerry M. Melillo
and John E. Hobbie

Beaver (Castor canadensis) alter the structure and dynamics of aquatic ecosystems with a minimum of direct energy or nutrient transfer. Through dam building and feeding activities, beaver act as a keystone species to alter hydrology, channel geomorphology, biogeochemical pathways, and community productivity. In this article we consider the affects of beaver activity on several major ecosystem components and processes of boreal forest drainage networks in Quebec, Canada. The density of dams on small streams (<4th order) average 10.6/km, retaining up to 6,500 m^3 of sediment. The wetted surface area of the channel is increased up to several hundred-fold. Beaver are also active in larger order streams (>5th order), but their effects are most noticeable along river banks and in floodplains.

Carbon budgets comparing a riffle on 2nd order Beaver Creek with a beaver pond downstream show, per unit area, that the pond sequesters only 30% of the carbon received by the riffle annually. However, because the pond has a surface area 7-times greater than the riffle, it sequesters nearly twice as much carbon as the riffle per unit of channel length. Carbon in the pond has an estimated turnover time of 185 yrs compared to about 20 yrs for the riffle. The stream metabolism index (SMI), a measure of ecosystem efficiency for the utilization or storage of organic inputs, is 1.74 for the pond compared to 0.25 for the riffle; the turnover length (S) for particulate carbon is 73 m for the pond compared to 1158 m for the riffle. Thus beaver ponds are quantitatively shown to be important sites for organic matter processing. Beaver induced alterations to the structure and function of stream ecosystems suggest that historic removal of beaver had substantial effects on lotic ecosystem dynamics long before extensive research began. Our results suggest that current concepts addressing the organization and diversity of unaltered stream ecosystems require modification, and that a pristine drainage network is substantially

different in its biogeochemical economy than most drainage networks are today. To illustrate this latter point we present a conceptual model of functional stream order displacement by beaver activity along the stream-river continuum, discussing the concept in terms of a shifting mosaic on the landscape which has both spatial and temporal components.

We conclude that beaver are a significant and essential component of drainage networks and that their removal has a substantial influence on the biogeochemical dynamics and structure of stream ecosystems in North America.

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SALT MARSH SYSTEMS

FACTORS CONTROLLING THE GROWTH FORM OF Spartina alterniflora: Feedbacks Between Above-ground Production, Sediment Oxidation, Nitrogen and Salinity

Brian L. Howes and John W. H. Dacey

We investigated the relationship between above-ground biomass of Spartina alterniflora and sediment oxidation status (Eh), available ammonium concentration and interstitial salinity at 21 sites in a New England salt marsh. Sediment Eh gave the best prediction of above-ground biomass. The relationship between sediment oxidation and above-ground production existed between years and marshes. Measurements in nitrogen fertilized areas indicate that increasing plant production leads to more oxidized sediments. Sediment oxidation in vegetated sediments occurs via air entry, which was found to cause a rapid and significant rise in sediment oxidation potential. Air enters the sediment in response to water removal from the sediment by evapotranspiration in short grass zones and evapotranspiration and drainage in creek-bank zones. We propose a feedback model for factors controlling growth of S. alterniflora.

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WHOI Contribution No. 5650.

THE ROLE OF ONE SALT MARSH IN COASTAL PRODUCTIVITY

John M. Teal

We have been intensively studying the ecology of Great Sippewissett Salt Marsh, Massachusetts, for the last 12 years by experimentally fertilizing marsh plots at different levels of nutrients with fertilizers that both do and do not contain sewage sludge and its contaminants. Plant productivity is limited by nitrogen availability which is in turn modified by sediment oxidation-reduction potential. Species composition of the plant cover is also affected by nitrogen. At greater levels of nitrogen availability, nitrogen in the grasses increases. This leads to increased populations and/or productivity of herbivores, detritivores and decomposers. The nitrogen budget for the marsh shows that it imports nitrate and exports nitrogen gas, particulate organic nitrogen and ammonia. The sulfur cycle is dominant in underground decomposition and transports energy to the sediment surface. A variety of fishes, especially young stages including those of commercially important species, make use of the marsh as a feeding place. Heavy metal pollutants which form insoluble sulfides tend to be immobilized in sediments and not accumulated in organisms; e.g., lead. Those such as cadmium which form soluble complexes in sea water do not accumulate in the marsh and do, at least, temporarily accumulate in organisms. Organic pollutants are bound to sediments and the one studied, Aldrin, disappeared about two years after it was added.

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Utilization of Coastal Ecosystems:
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Brazil, Vol. 1. L. N. Chao and W.
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DECOMPOSITION IN SALT MARSH ECOSYSTEMS: THE PHASES AND MAJOR FACTORS AFFECTING DISAPPEARANCE OF ABOVE-GROUND ORGANIC MATTER

Ivan Valiela, John M. Teal,
Sarah Allen, Richard Van Etten,
Dale Goehringer and
Suzanne Volkmann

Decay of litter of salt marsh grasses occurs in three phases. First there is an early phase lasting less than a month, with fast rates of weight loss, during which 5-40% of the litter is lost, probably by leaching of soluble compounds. The second phase is slower and lasts up to a year, during which microbial degradation of organic matter, and subsequent leaching of hydrolyzed substances, remove an additional 40-70% of the original material. The third phase may last an additional year, during which decay is very slow since only relatively refractory materials remain. By this third stage, as little as 10% of the original material may remain.

Manipulative experiments show that the rates of weight loss depend on several factors, and that the importance of each factor varies during different phases of decay. Differences in the chemical makeup of litter are the major factors affecting the amount of decay during the leaching and decomposer phases. Such chemical differences may be due to differences in plant species producing the litter or in growing conditions. Nitrogen has a particularly important effect. The internal nitrogen content of the litter affects loss of weight during the leaching phase, while the external supply of nitrogen increases decay somewhat during the decomposer phase. Temperature is a somewhat less important factor, but does increase decay during the decomposer phase. The feeding activity of large detritus-feeding invertebrates produces a small but significant increase in decay rate during the decomposer phase.

Decay rate in litterbags mimics decay of litter in the field. The turnover of litter of *Spartina alterniflora* was 1.1-1.4 yr⁻¹. Litter of *S. patens* turns over more slowly, 2.1 yr⁻¹. Turnover of litter is accelerated up to 24% under experimentally nutrient-enriched conditions compared to control litter. Since eutrophication of salt marshes both enriches litter and changes species of plants, it has broad consequences for ecological processes dependent on decomposition of organic matter.

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GEOCHEMISTRY

HENRY'S LAW CONSTANTS FOR DIMETHYLSULFIDE IN FRESHWATER AND SEAWATER

John W. H. Dacey, Stuart G. Wakeham
and Brian L. Howes

Henry's law constants for dimethylsulfide were measured in several natural waters of varying salinity and in distilled water over a range in temperature from 0°-32°C. Fitting our data to the equation $\ln H \text{ (atm L mol}^{-1}\text{)} = A/T(^{\circ}\text{K}) + C$, $A = -3463 \text{ (+/-75)}$ and -3547 (+/-16) and $C = 12.20 \text{ (+/-0.26)}$ and 12.64 (+/-0.06) , for distilled water and seawater respectively (standard errors in parentheses). These solubilities support the concept that the concentration of dimethylsulfide in the atmosphere is far from equilibrium with seawater.

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SHORT-TERM ENDPRODUCTS OF SULFATE REDUCTION: FORMATION OF ACID VOLATILE SULFIDES, ELEMENTAL SULFUR, AND PYRITE

Gary M. King, B. L. Howes
and J. W. H. Dacey

Rates of sulfate reduction, oxygen uptake and carbon dioxide production in sediments from the short *Spartina alterniflora* region of Great Sippewissett Marsh were measured simultaneously during late summer. Surface sediments (0-2 cm) were dominated by aerobic metabolism which accounted for 51% of the total carbon dioxide production over 0-15 cm. Rates of sulfate reduction agreed well with rates of total carbon dioxide production below 2 cm depth indicating that sulfate reduction was the primary pathway for sub-surface carbon metabolism. Sulfate reduction rates were determined using a radiotracer technique coupled with a chromous chloride digestion and carbon disulfide extraction of the sediment to determine the extent of formation of radiolabelled elemental sulfur and pyrite during short-term (48 hr) incubations. In the surface 10 cm of the marsh sediments investigated, about 50% of the reduced radiosulfur was recovered as dissolved or acid volatile sulfides, 37% as elemental sulfur, and only about 13% was

recovered in a fraction operationally defined as pyrite. Correlations between the extent of sulfate depletion in the marsh sediments and the concentrations of dissolved and acid volatile sulfides supported the results of the radiotracer work. Our data suggest that sulfides and elemental sulfur may be major short-term end-products of sulfate reduction in salt marshes.

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WHOI Contribution No. 5855.

RESIDENTIAL WASTEWATER-GROUND WATER INTERACTIONS IN THE VICINITY OF MARES POND, FALMOUTH, CAPE COD

Ralph F. Vaccaro, Nathaniel Corwin
and James R. Mitchell

Repetitive observations of conservative and non conservative parameters at a single ground water source are used to evaluate the extent of septic leachate infiltration and the relative contributions of physical as opposed to biological processes in waste water attenuation. Indications are that the levels of total leachate infiltration varied between 8 and 12% at the well point. Physical processes, such as dilution, accounted for about 90% of the observed difference in the composition of well water as opposed to concentrated septic leachate. As for the remaining 10%, biological processes accounted for about 95 and 60% respectively of the nitrogen and organic carbon attenuation in excess of that accounted for by dilution. Nitrate contamination poses the more serious long-term threat to on-lot sources of potable water because organic carbon regeneration in ground water proceeds faster and more completely than does combined nitrogen.

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WHOI Contribution No. 5665.

M A R I N E M A M M A L S

INVESTIGATION OF SPERM WHALE ACOUSTIC BEHAVIORS IN THE SOUTHEAST CARIBBEAN

William A. Watkins, Karen E. Moore
and Peter Tyack

Two cruises to the southeast Caribbean were taken to study the behavioral contexts of cove sounds (patterned click sequences)

produced by sperm whales. Observations were made in deep water west of the Lesser Antilles from St. Lucia to the Grenadines in November 1983 and from Guadeloupe to Martinique in March 1984. Along with other smaller cetaceans, 54 sperm whales were seen in November in the southern area and 55 in March in the northern area. Military sonar signals apparently silenced and scattered the sperm whales in the aftermath of the U.S. intervention (Oct. 1983) in Grenada; otherwise, the whales behaved in ways similar to those that we have observed previously in other waters. The sperm whales were noted to dive for periods longer than an hour during apparent foraging routines. Breathing rates during typical surfacing periods averaged 30 sec between blows. Whales often appeared to be associated with dense layers of sound scattering organisms at 80- to 90-m depths, and they could only be followed by high-frequency sonar as far as this layer. Some of the sperm whale codas appeared to be individually distinctive, in agreement with earlier work, but a particular five-click coda pattern with possible agonistic significance tended to be used by a number of whales as they joined or left a group.

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WHOI Contribution No. 5699.

SENSORY BIOPHYSICS OF MARINE MAMMALS

William A. Watkins and Douglas Wartzok

The underwater existence of marine mammals has encouraged a variety of special biophysical adaptations to their environment. Their sensory and communication systems reflect the transmission properties of sea water. For example, vision is keen in spectra that penetrate water best, vocalization is broad-band and used at the frequencies that appear to fit their activities best - the differences in sensory use match the intriguing variety of behavior observed for each species. To date, most of the observations of animal interactions with their marine environment have dealt with sound; there has been some work on vision and studies are underway to determine animal sensitivities to hydrodynamic pressure, chemical traces and magnetic fields. Known vocalizations of marine mammal species are reviewed. Methods for observation of sensory mechanisms are indicated. Other aspects of marine mammal biophysics are discussed, including vibrissal sensation and the biophysics of movement in a fluid environment.

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WHOI Contribution No. 5599.

MARINE POLLUTION

FUTURE STRATEGIES FOR NEARSHORE WASTE DISPOSAL

J. M. Capuzzo, W. V. Burt, I. W. Duedall,
D. R. Kester and P. K. Park

Nearshore environments receive anthropogenic wastes from ocean dumping activities, pipeline discharges, atmospheric fallout, riverine input, and other non-point pollution sources. These environments are valuable as natural resources and are important ecological systems. In the past, in the United States, little attention was given to management aspects, and several laws now in force assign three disposal media (land, sea, and air) to different governmental agencies. A better method for considering the regulation of wastes would be the use of an integrated approach. Management of waste disposal in nearshore environments should consider a set of site-selection criteria dealing with physical, geochemical, sedimentary, and biological aspects of the ocean. Disposal systems and the waste discharges should be selected or designed to maximize dispersion of the wastes. Models can be developed to determine the residence time of some wastes in the ocean. Synthetic organic compounds and pathogens are two classes of contaminants requiring careful control, since their long-term effects are unknown. Point-source control, recycling, and development of substitute technologies are all effective measures that will decrease the amount of wastes produced. The use of the ocean for waste disposal will require more research to determine the transport, sedimentation, chemical kinetics, association of organic material with solid particles, bioavailability, and effects of contaminants on populations and communities.

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MICROBIOLOGY

A NEW EXTREMELY THERMOPHILIC, SULFUR-REDUCING HETEROTROPHIC MARINE BACTERIUM

Shimshon Belkin and Holger W. Jannasch

An extremely thermophilic (optimum growth at 88°C), anaerobic bacterium was isolated from a shallow submarine thermal spring. It appears to be an obligate heterotroph, capable of reducing sulfur to H₂S. Oxygen sensitivity is apparent only at and above those temperatures where growth occurs, while the cultures retain their viability for long periods under air at 4°C. Insensitivity to chloramphenicol, vancomycin and streptomycin, and lack of muramic acid in its cell wall, indicate a possible affiliation of the new isolate to the thermoacidophilic archaeobacteria. However, its neutrophilic and heterotrophic nature, as well as its DNA base composition (39.1 mol % guanine plus cytosine) set it apart from the known genera of this group.

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WHOI Contribution No. 5756.

BIOLOGICAL AND ABIOLOGICAL SULFUR REDUCTION AT HIGH TEMPERATURES

Shimshon Belkin, Carl O. Wirsén
and Holger W. Jannasch

Reduction of elemental sulfur was studied in the presence and absence of thermophilic sulfur-reducing bacteria, at temperatures ranging from 65° to 110°C, in anoxic artificial seawater media. Above 80°C, significant amounts of sulfide were produced abiotically at linear rates, presumably by the disproportionation of sulfur. These rates increased with increasing temperature and pH and were enhanced by yeast extract. In the same medium, the sulfur respiration of two recent thermophilic isolates, a eubacterium and an archaeobacterium, resulted in sulfide production at exponential rates. While not essential for growth, sulfur increased the cell yield in both strains up to 4 fold. It is suggested that sulfur respiration is favored at high temperatures, and that this process is not limited to archaeobacteria, but is shared by other extreme thermophiles.

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WHOI Contribution No. 5803.

SULFUR EMISSION AND TRANSFORMATIONS AT
DEEP SEA HYDROTHERMAL VENTS

Holger W. Jannasch

According to presently available data, global sulfur emissions from deep sea hydrothermal vents are estimated at 30 mill. tons annually. A comparison of this quantity to the seawater sulfate entrainment during hydrothermal cycling indicates a net loss of sulfur caused by polymetal-sulfide deposition. The re-distribution of sulfur above the seafloor is determined by (a) the forceful emission of hydrothermal fluid from the hot (275° to 350°C) "black smokers" into the water column with the ultimate chemical oxidation of hydrogen sulfide to sulfate, (b) re-dissolution of anhydrite deposits, and (c) the microbial chemolithotrophic sulfur oxidation at warm (8° to 23°C) vents with the concomitant reduction of inorganic to organic carbon and production of rich animal populations.

Supported by: NSF Grants OCE80-24253 and OCE83-08631.

WHOI Contribution No. 5726.

GEO-MICROBIOLOGY OF DEEP SEA
HYDROTHERMAL VENTS

Holger W. Jannasch and Michael J. Mottl

During the cycling of seawater through the earth's crust along the mid-ocean ridge system, geothermal energy is transferred into chemical energy in the form of reduced inorganic compounds. They are derived from the reaction of seawater with crustal rocks at high temperatures. Emitted from warm (<25°C) and hot (~350°C) submarine vents, this chemical energy is used by chemolithotrophic bacteria for the reduction of CO₂ (assimilation) to organic carbon. Thus, bacteria form the base of the food chain which permits copious populations of certain adapted invertebrates to grow in the immediate surroundings of the vents. Reduced sulfur compounds appear to represent the major electron donor for aerobic microbial metabolism, while methane-, hydrogen-, iron- and manganese-oxidizing bacteria have also been observed. Methanogenic and sulfur respiring isolates are representatives of anaerobic chemosynthesis. Bacteria grow abundantly in the shallow crust where upwelling hot, reducing waters mix with downwelling cold, oxygenated waters. The predominant production of biomass, however, is based on hitherto unknown symbiotic associations between chemolithotrophic bacteria and certain invertebrates, which have also been found as fossils in cretaceous sulfide ores of ophiolite deposits.

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WHOI Contribution No. 5764.

THE BIOCHEMICAL VERSATILITY OF
CHEMOSYNTHETIC BACTERIA AT DEEP SEA
HYDROTHERMAL VENTS

Holger W. Jannasch and Carl O. Wirsen

The biochemical versatility of vent bacteria is suggested to be the reason for the observed high efficiency in the use of available inorganic chemical energy sources for the chemosynthetic production of organic carbon. This versatility is based primarily on the diversity of bacterial species and metabolic types, including the adaptation to elevated temperatures. The sulfur oxidizers appear to be the most significant chemosynthetic producers because of their flexibility in the use of inorganic and organic sources of energy (obligate and facultative chemolithoautotrophy as well as mixotrophy) and because of the relative high concentrations of reduced sulfur compounds found at all those vents where an abundance of the characteristic populations of invertebrates were observed.

In press: Proceedings of the
Biological Society, Washington.

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WHOI Contribution No. 5720.

VARIABILITY OF PRESSURE ADAPTATION
IN DEEP SEA BACTERIA

Holger W. Jannasch and Carl O. Wirsen

Isolations of pressure-adapted deep sea bacteria from depths of 1400 to 5100 m resulted in a variety of psychrophilic barotolerant and barophilic strains. Growth rates determined at different pressures indicated a gradual transition between the two types of pressure-adapted isolates. The presence of barotolerant bacteria in deep water, sustained by sinking particulate matter, causes the non-barophilic response of natural populations; i.e., increased growth after decompression. With increasing pressure-adaptation in barophilic isolates the maximum growth rates at optimum pressures decrease. Thus, the observed general slow-down of microbial activity in the deep sea takes effect regardless of the common occurrence of psychrophilic and barophilic bacteria. The highest degree of barophilism was observed in isolates from

nutrient-rich habitats such as intestinal tracts of deep sea animals or decaying carcasses. Detailed studies with an isolate, growing barophilically on a complex as well as a single-carbon-source medium, showed that (1) culturing at pressures lower than optimal for growth resulted in the formation of cell filaments, (2) growth was unaffected by repeated compression/ decompression cycles, and (3) no perceptible differences in the distribution of radio-labeled carbon from an amino acid mixture occurred in cells grown at, below, and above the pressure optimal for growth.

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WHOI Contribution No. 5615.

Thiomicrospira crunogena SP. NOV.,
A COLORLESS SULFUR OXIDIZING BACTERIUM
FROM A DEEP SEA HYDROTHERMAL VENT

Holger W. Jannasch, Carl O. Wirsen,
D. C. Nelson and L. A. Robertson

A new species of the genus Thiomicrospira has been isolated from the 21°N deep sea (2600 m) hydrothermal vent area of the East Pacific Rise. The organism is an obligate chemolithoautotrophic sulfur oxidizer and differs from the two other species of this genus by its DNA base composition and by its growth rate and optimal pH in thiosulfate medium. The new species has been named T. crunogena ("spring born") and deposited in the ATCC as well as the Delft Culture Collection.

Supported by: NSF Grant OCE83-08631.

WHOI Contribution No. 5688.

A PASSIVE DIFFUSION TECHNIQUE FOR THE
CONCENTRATION OF SHORT CHAIN VOLATILE
FATTY ACIDS FROM SEAWATER

John J. Molongoski and Craig D. Taylor

A technique is described which concentrates volatile fatty acids from seawater while simultaneously separating them from interfering salts. The method is reliant upon the passive diffusion of volatile compounds from acidified seawater samples and their subsequent absorption onto a base-impregnated filter. The method is simple, efficient, and adaptable to most commonly used methods of volatile acid analysis.

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and OCE82-10420.

WHOI Contribution No. 5849.

DNA BASE COMPOSITION AND GENOME SIZE OF
THE PROCARYOTIC SYMBIONT IN
Riftia pachyptila (POGONOPHORA)

Douglas C. Nelson, John B. Waterbury
and Holger W. Jannasch

It has been proposed that Riftia pachyptila, a pogonophoran tube worm abundant at hydrothermal deep sea vents, metabolizes solely via a chemoautotrophic symbiosis. The symbionts resemble sulfur oxidizing bacteria and form the specific "trophosome" tissue. Samples of DNA purified from trophosome and vestimentum (muscle) tissues of R. pachyptila were comparatively characterized (a) by thermal denaturation studies, and (b) by analysis of renaturation kinetics. The results show that the great majority of trophosome DNA is homogeneous and procaryotic with a base ratio of approximately 58 mole % G+C. Its genome size (kinetic complexity) is typical of free living bacteria. Approximately 5% of trophosome DNA appears to be invertebrate DNA equivalent to that found in the vestimentum tissue which lacks symbionts.

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WHOI Contribution No. 5667.

P H Y T O P L A N K T O N

SINKING CHARACTERISTICS OF
DINOFLLAGELLATE CYSTS

Donald M. Anderson, John J. Lively,
Ellen M. Reardon and Carl A. Price

This study reports the first direct measurements of the density and sinking rates of marine dinoflagellate cysts from cultures and natural sediments. Cysts of Gyrodinium uncatenum, Gonyaulax tamarensis, and Scrippsiella trochoidea had densities of 1.14, 1.24, and 1.32 g cm⁻³ respectively. No significant differences between cultured and natural cyst densities were observed. Measured settling velocities ranged from 0.008 to 0.013 cm sec⁻¹ (6 to 11 m d⁻¹). Settling rates calculated using the measured

densities and reasonable assumptions about shape and orientation during descent were within 10-20% of measured sinking rates, confirming that the sinking characteristics of cysts can be described by a modification of Stokes' Law for non-spherical particles in a viscous medium. The three cyst-types examined are more dense and fall significantly faster than most vegetative phytoplankton cells. Removal of an outer layer of short calcite spines from S. trochoidea cysts reduced cell density and radius both by 7% and the sinking rate by 37%. The faster settling velocity of the spiny cyst is not considered a general effect common to all ornamented cyst-types but presumably applies only to those with numerous, short spines or processes and to those with an outer membrane that smooths surface projections. Morphological features can thus markedly affect the rate of cyst deposition, but the adaptive significance of surface ornamentation remains unknown.

In Press: Limnology and
Oceanography.

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ments Division, Office of
Oceanography and Marine Service,
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80EV10413.

WHOI Contribution No. 5740.

ENCYSTMENT OF THE ESTUARINE DINOFLAGELLATE
Gyrodinium uncatenum: TEMPERATURE AND
NUTRIENT EFFECTS

Donald M. Anderson, M. A. Tyler
and D. W. Coats

Sexual reproduction and encystment of the marine dinoflagellate Gyrodinium uncatenum (Hulburt) were induced in nitrogen and phosphorus-limited batch cultures. Sexuality did not occur under nutrient replete conditions even when growth rate was reduced by non-optimal temperatures. Growth was optimal over a broader temperature range than encystment and virtually no cysts were produced at some low and high temperatures where growth occurred.

Most cells initiated sexuality as intracellular pools of each limiting nutrient reached minimum or subsistence levels as much as four days after extracellular nutrients were exhausted. High nitrogen cell quotas during the phosphorous experiment indicate that sexuality was induced by a shortage of phosphorus and not by an indirect effect on nitrogen uptake.

Total cyst yield corresponded to successful encystment of 9-13% of the motile

populations, yet 60 to 85% of the plateau-phase motile cells were planozygotes (swimming zygotes formed from fusing gametes). Batch culture studies monitoring total cyst yield may thus seriously underestimate the extent of sexuality. More importantly, the number of cysts produced in a dinoflagellate population may be significantly reduced by environmental factors acting on the cells after sexual induction and fusion.

In press: Journal of Phycology.

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and OCE82-08739.

WHOI Contribution No. 5658.

INORGANIC CARBON UPTAKE BY PHYTOPLANKTON IN
VINEYARD SOUND, MASSACHUSETTS: 1. MEASURE-
MENTS OF THE PHOTOSYNTHESIS-IRRADIANCE
RESPONSE OF WINTER AND EARLY-SPRING
ASSEMBLAGES

Patricia M. Glibert, Mark R.
Dennett and Joel C. Goldman

The photosynthesis-irradiance dependence of natural phytoplankton assemblages from surface waters of Vineyard Sound, Massachusetts, was investigated over a several month period during late winter - early spring 1982, when water temperatures were -0.5 to 8.5°C. Maximal photosynthetic rates not only were consistently observed between 7 - 15% I_0 , but were substantially higher than previously reported rates for cold water assemblages, averaging $10 - 20 \mu\text{g C} \cdot \mu\text{g chl a}^{-1} \cdot \text{h}^{-1}$. At higher light intensities photoinhibition was severe and developed within minutes to tens of minutes of the start of the experiment. Several lines of evidence, however, suggest that photoinhibition in situ may be much less than that measured in incubations of >30 min duration; residence time of phytoplankton at surface light intensities is sufficiently short and adaptation of photosynthetic capacity appears to have occurred to approximately the mean depth of the water column. These results further highlight the importance of establishing the time-dependent photosynthetic responses of phytoplankton and the relationship to the physical mixing regime in estimating primary productivity.

In press: Journal of Experimental
Marine Biology and Ecology.

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WHOI Contribution No. 5659.

INORGANIC CARBON UPTAKE BY PHYTOPLANKTON
IN VINEYARD SOUND, MASSACHUSETTS:
II. COMPARATIVE PRIMARY PRODUCTIVITY AND
NUTRITIONAL STATUS OF WINTER AND SUMMER
ASSEMBLAGES

Patricia M. Glibert, Mark R. Dennett
and Joel C. Goldman

Using time-course, natural-light incubations, we assessed the rate of carbon uptake at a range of light intensities, the effect of supplemental additions of nitrogen (as NH_4^+ or urea) on light and dark carbon uptake, and the rates of uptake of NH_4^+ and urea by phytoplankton from Vineyard Sound, Massachusetts, from February through August 1982. During the winter, photoinhibition was severe, becoming manifested shortly after the start of an incubation, whereas during the summer, there was little to no evidence of photoinhibition during the first several hours after the start of an incubation. At light levels which were not photo-inhibiting nor light-limiting, rates of carbon uptake normalized per liter were high and approximately equal during winter and summer ($22\text{--}23 \mu\text{g C l}^{-1}\text{h}^{-1}$) and low during spring ($<10 \mu\text{g C l}^{-1}\text{h}^{-1}$). In contrast, on a chlorophyll *a* basis, rates of carbon fixation were as high during spring ($15\text{--}20 \mu\text{g C } (\mu\text{g chl } a^{-1}) \text{ h}^{-1}$) when concentrations of chlorophyll *a* were at the yearly minimum ($<0.5 \mu\text{g l}^{-1}$) as during the summer when chlorophyll *a* concentrations were substantially higher ($0.8\text{--}1.3 \mu\text{g l}^{-1}$). Highest rates of NH_4^+ and urea uptake were observed during summer, and at no time of the year was there evidence for severe nitrogen deficiency, although moderate nitrogen nutritional stress was apparent during the summer months.

In press: Journal of Experimental
Marine Biology and Ecology.

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Schepp Foundation.

WHOI Contribution No. 5725.

GRAZING AND NUTRIENT REGENERATION IN
THE MARINE MICROBIAL FOOD CHAIN

Joel C. Goldman and David A. Caron

There is a growing appreciation that phagotrophy by a ubiquitous and diverse group of heterotrophic microflagellates, generally less than $10 \mu\text{m}$ in diameter, is the major process regulating the density of planktonic bacteria in the oceans. In reconsidering the ways in which bacterial populations are regulated by microflagel-

lates, conspicuously little attention has been given to the possibility that these voracious predators may play an equally important role in cropping phytoplankton populations in the sea and in recycling nutrients. We report results demonstrating that phagotrophic feeding on phytoplankton by heterotrophic microflagellates, similar in size to their prey, does indeed occur, and that these protozoans may contribute significantly to energy flow and nutrient regeneration in pelagic surface waters.

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WHOI Contribution No. 5739.

PHOTOSYNTHETIC RESPONSES OF 15
PHYTOPLANKTON SPECIES TO AMMONIUM PULSING

Joel C. Goldman and Mark R. Dennett

In a series of short-term NH_4^+ pulsing experiments on 15 marine phytoplankton species previously grown to steady state under NH_4^+ -limitation in continuous culture we found no evidence that transient exposure to high NH_4^+ concentration led to suppression of initial photosynthesis in 13 species. In one chlorophyte, *Nannochloris* sp., we found significant initial suppression, however. A similar, but less dramatic, response to NH_4^+ pulsing was found in the prasinophyte, *Platymonas* sp. These results point toward rather diverse modes of coupling between transient CO_2 fixation and NH_4^+ uptake, but are consistent with our earlier conclusion that rapid NH_4^+ uptake, but relatively undisturbed photosynthesis, is the common response of marine phytoplankton exposed to euphermal patches of NH_4^+ in the pelagic environment.

In press: Marine Ecology Progress
Series.

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WHOI Contribution No. 5695.

SUSCEPTIBILITY OF SOME MARINE
PHYTOPLANKTON SPECIES TO CELL BREAKAGE
DURING FILTRATION AND
POST-FILTRATION RINSING

Joel C. Goldman and Mark R. Dennett

Several fragile phytoplankton species among a diverse group of 13 species were found to be very susceptible to cell breakage when exposed to the air under vacuum between the filtration and rinsing steps used to terminate ^{14}C fixation experiments

and remove residual $^{14}\text{C-HCO}_3^-$. Up to 60% of fixed carbon after 15 min incubation was found in the rinse. Losses were even greater when cultures were pulsed with NH_4^+ at the start of the incubation, probably because rapid NH_4^+ uptake leads to the accumulation of a large pool of soluble and low molecular weight compounds. Most likely, the cells, when exposed to the air, are subject to extreme osmotic shock and rupture. Unaccountable losses of ^{14}C occurred with polycarbonate filters relative to glass-fiber filters. In addition, vacuum pressure differentials greater than 25-100 mm Hg across polycarbonate filters also caused cell breakage that led to the accumulation of ^{14}C in the filtrate. Avoiding air exposure of the filter between the filtration and rinse steps or eliminating the rinse step entirely and acid-soaking or fuming the filters led to virtually complete recovery of fixed carbon. Our results based on 15 min incubations may not be directly comparable to longer-term incubations, but they do serve to highlight our concerns about filtration procedures in general.

In press: Journal of Experimental Marine Biology and Ecology.

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WHOI Contribution No. 5705.

CRYPTIC PARALYTIC SHELLFISH POISONS

Sherwood Hall

The saxitoxins from dinoflagellates of the genus Protogonyaulax may accumulate in shellfish and, being potent neurotoxins, pose a serious threat to public health. Six of the saxitoxins are sulfamates which have relatively low toxicity, but are easily hydrolyzed to the respective carbamates with corresponding increases in potency. This paper presents some of the chemistry and public health implications of these toxins.

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WHOI Contribution No. 5666.

DINOFLAGELLATE NEUROTOXINS RELATED TO SAXITOXIN: STRUCTURES OF TOXINS C3 AND C4, AND CONFIRMATION OF THE STRUCTURE OF NEOSAXITOXIN

Sherwood Hall, S. D. Darling, G. L. Boyer, P. B. Reichardt and H.-W. Liu

By x-ray crystallography of the 11B epimer, toxins C3 and C4 are shown to be 21-sulfo-N-1-hydroxysaxitoxin-11 and 11B-hydroxysulfate, confirming the position and identity of the 3 substituents which, with the parent compound, form the array of 12 saxitoxins found in Protogonyaulax.

Published in: Tetrahedron Letters.

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WHOI Contribution No. 5657.

PHOTOSYNTHATE PARTITIONING IN CULTURED MARINE PHYTOPLANKTON: METABOLIC PATTERNS IN 10 SPECIES IN RESPONSE TO AMMONIUM PULSING

Gary L. Hitchcock and Joel C. Goldman

Ten phytoplankton species were cultured under steady-state conditions of nitrogen limitation ($\text{N:P} = 10$) and then enriched with $16 \mu\text{ atoms l}^{-1}$ of NH_4^+ . The fate of ^{14}C incorporation was followed in control and enriched (pulsed) cells in 15 minute incubations by solvent fractionation into low molecular weight (LMW), lipid, TCA-soluble (polysaccharide) and particulate (protein) fractions. After 15 minutes the accumulation factor (A_{15} ; the ratio of total ^{14}C incorporation in the presence or absence of NH_4^+) ranged from 0.84 to 1.13, indicating little suppression or stimulation of total carbon uptake in the species examined. However, nearly 1.5-fold more carbon was incorporated into LMW materials in six of ten species when NH_4^+ pulsed. Concurrently, 50% less ^{14}C was fixed into the TCA-soluble fraction. This response was particularly evident in species other than diatoms; in diatoms there was less partitioning into LMW materials at the expense of polysaccharides. A separate series of experiments were conducted with the Chlorophyte Dunaliella tertiolecta preconditioned at specific growth rates (μ of 0.4 and 0.7 day^{-1}). Total ^{14}C fixation was only slightly

stimulated by NH_4^+ pulsing, but a higher proportion of ^{14}C was fixed into LMW, and less into TCA-soluble materials, when NH_4^+ pulsed. By separating the LMW fraction from D. tertiolecta with ion-exchange resins, we found that NH_4^+ pulsing increased the proportion of ^{14}C into anionic and cationic compounds (primarily organic acids and amino acids, respectively) at the expense of neutral compounds (sugars).

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WHOI Contribution No. 5818.

PHOTOSYNTHATE PARTITIONING IN CULTURED MARINE PHYTOPLANKTON. GROWTH AND METABOLIC PATTERNS IN A MARINE DIATOM UNDER CONSTANT AND VARIABLE LIGHT INTENSITIES

Gary L. Hitchcock, Joel C. Goldman and Mark R. Dennett

Exponential phase cultures of the marine diatom Chaetoceros simplex (clone Bbsm) were maintained at 15, 60 and 470 $\mu\text{E m}^{-2} \text{s}^{-1}$ and 20°C to determine the rates at which photosynthesis and partitioning of carbon were altered in response to short-term transitions in irradiance. Growth, based on carbon uptake, equalled cell division rates for a minimum of three hours in control cultures during exposure to 60 and 470 $\mu\text{E m}^{-2} \text{s}^{-1}$. Carbon fixation was also measured during alternating high (470)-low (15) light exposures of 30 minutes duration; after two hours of light cycling cells lost the ability to maintain a carbon fixation rate at 470 $\mu\text{E m}^{-2} \text{s}^{-1}$ equivalent to that in control cultures. Under constant light of 470 $\mu\text{E m}^{-2} \text{s}^{-1}$, the labelling of low molecular weight (LMW) compounds was linear with time for up to 4h and accounted for nearly 70% of total carbon-14 fixed. Lipids (chloroform-soluble) and polysaccharides (TCA-soluble) were uniformly labelled for only 2h, representing 9 to 15%, respectively, of total carbon-14 fixed. At 15 $\mu\text{E m}^{-2} \text{s}^{-1}$, the relative proportion of carbon-14 in the LMW, lipid, and TCA-soluble fractions decreased, while protein labelling was proportionately greater. When re-exposed to 470 $\mu\text{E m}^{-2} \text{s}^{-1}$, cells previously incubated at 15 $\mu\text{E m}^{-2} \text{s}^{-1}$ resumed carbon fixation into the LMW, lipid, and protein fractions; carbon partitioning into the polysaccharide fraction was initially suppressed, recovering within 30 to 60 minutes. During alternating periods of 30 minutes at 470 and 15 $\mu\text{E m}^{-2} \text{s}^{-1}$, carbon fixation into LMW, lipid, and TCA-soluble fractions occurred only at the higher intensity, while protein

labelling was unaffected by fluctuations in light intensity. These patterns suggest that short-term (15 to 30 minute) light fluctuations in situ could have a major influence on the pattern of carbon partitioning in marine phytoplankton.

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WHOI Contribution No. 5733.

ADAPTATION AND EQUIVALENCE IN THE OPEN OCEAN PHYTOPLANKTON

Edward M. Hulburt

If species 'x' is adapted to nutrient changes, then it is responsive to these conditions; and, certainly, if it is responsive to these conditions, then it is adapted to them. There is another expression that is equivalent to this one (that says the same thing): either species 'x' is adapted and responsive to these conditions or it is neither adapted nor responsive to them. In the phytoplankton of the western North Atlantic the option just mentioned is resolved so that Emiliana huxleyi as species 'x' is adapted and responsive and Cyclococcolithus leptoporus as species 'x' is not adapted and not responsive.

Supported by: WHOI.

WHOI Contribution No. 5809.

THE SINGLENESS, RESPONSIVENESS, AND ADAPTEDNESS OF A PHYTOPLANKTON POPULATION

Edward M. Hulburt

Phytoplankton species abundances in the Caribbean Sea and western North Atlantic are examined to show how the name of each species may be replaced by "marked responsiveness" for those species that achieve marked abundance and replaced by "slight responsiveness" for those always in low abundance. In a move toward synthesis, "the population" and "variable responsiveness" are brought in as single entities descriptive of all the species in their varying amounts. Yet this is too broad when responsiveness is linked to adaptedness. "If the population has responsiveness to improved nutrient conditions, then it has adaptedness to these conditions" is a connection requiring the counter-connection "if it lacks adaptedness, then it lacks responsiveness to these conditions too." In order to confirm the first connection, a single population is needed; in order to confirm the counter-connection, a second

population is needed. Two more populations are needed for impoverished nutrient conditions. In this way the species data of the Caribbean is tailored to four populations. The data of the western North Atlantic is similarly tailored so that commitment to four populations is made in order to confirm the formulae italicized.

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WHOI Contribution No. 5724.

USE OF LOGICAL EQUIVALENCE IN MODELING ECOLOGICAL RELATIONS OF OCEANIC PHYTOPLANKTON

Edward M. Hulburt

Compound statements describing comparative ecological observations show relationship when the statements are equivalent. Such compounds are models that serve as vehicles for observation. Two examples are the following. "If x is adapted to nutrient conditions of the southern Sargasso Sea, then x is not inherently responsive." Let ' x ' be any species except *E. huxleyi*. The equivalent formula is "If x is inherently responsive, then x is not adapted to nutrient conditions of the southern Sargasso Sea." Let ' x ' be *E. huxleyi*. This is the first example. The second example is "If x is a population experimentally responding to year-round temperatures or x is a population observationally responding to year-round temperatures, then x is adapted to year-round temperatures" equivalent to "If x is not adapted to year-round temperatures, then x is not a population experimentally responding and observationally responding to year-round temperatures." Experimental and observational confirmation for several species is presented.

From these examples it can be seen that there are two intertwined threads to the following study. One is the presentation of compound statements as models. In the first example there are two parts, one after "if" and the other after "then" in the first formula or model; and these same parts are in the equivalent. In the second example there are three parts (clauses) to model and to its equivalent. Having three parts makes possible a number of models and equivalents. The second thread is the presentation of data to support or confirm those parts concerned with the response of population or species. The data will be found to confirm some of the three-part equivalents but not others. Thus model and observation must go hand in hand to achieve a relevant whole.

In press: Ecological Modelling.

Supported by: WHOI.

WHOI Contribution No. 5765.

COMPARISON OF TOXICITY BETWEEN POPULATIONS OF *Gonyaulax tamarensis* OF EASTERN NORTH AMERICAN WATERS

Lucie Maranda, Donald M. Anderson
and Yuzuru Shimizu

Isolates of the dinoflagellate *Gonyaulax tamarensis* were established from benthic cysts or motile cells collected along the northwestern Atlantic coast from the Bay of Fundy to Long Island. All clones were grown under the same conditions and assayed in a blind test for toxin content and composition. Differences in toxin content (μ mole unit/cell) spanning 2 orders of magnitude were found, with decreasing toxicity from north to south. Some isolates had undetectable toxin levels. The low toxicity of southern strains of *G. tamarensis* may explain the historical absence of paralytic shellfish poisoning (PSP) in areas where cysts and motile cells have been reported. The cause of the observed geographic pattern is unknown, but it does suggest that there may be an environmentally-determined southern limit to the regional PSP problem.

Qualitative data on the toxin composition of some clones indicate that saxitoxin, neosaxitoxin, and gonyautoxins II, III, and IV are generally present. A more quantitative approach (i.e., one which examines each isolate for all of the 12 *Gonyaulax* toxins) is needed, however, to fully utilize the potential of toxin composition in discriminating between strains.

In Press: Estuarine, Coastal and Marine Science.

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WHOI Contribution No. 5766.

AN UNUSUAL PHYCOERYTHRIN FROM A MARINE CYANOBACTERIUM

Linda Oug, Alexander N. Glazer
and John B. Waterbury

Many marine *Synechococcus* strains contain phycoerythrins with absorption maxima at ~ 490 nm and ~ 550 nm due to the

presence of phycoerythrin (PUB) and phycoerythrobilin (PEB) prosthetic groups, respectively. Such phycoerythrins are characteristic of red algae, but not of cyanobacteria isolated from fresh water or soil, whose phycoerythrins contain solely PEB. Phycoerythrin purified from Synechococcus WH8103 exhibits molecular properties typical of red algal phycoerythrins, but its PUB/PEB ratio of 1.58 is the highest known for any phycoerythrin. The protein has absorption maxima at 492 nm (ϵ $2.78 \times 10^6 \text{ M}^{-1}\text{cm}^{-1}$) and 553 nm (ϵ $1.14 \times 10^6 \text{ M}^{-1}\text{cm}^{-1}$) and fluoresces maximally at 565 nm with a quantum yield of 0.5.

Phycoerythrin conjugates are currently important reagents for cell sorting and analysis where the argon-ion laser line at 488 nm is employed for excitation. Conjugates of Synechococcus WH8103 phycoerythrin would increase the sensitivity of such analyses ~ 1.9-fold over that available with other phycoerythrin conjugates.

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WHOI Contribution No. 5574.

THE ABUNDANCE AND DISTRIBUTION OF THE TOXIC DINOFLAGELLATE, Gonyaulax tamarensis, IN LONG ISLAND ESTUARIES

Suzanne E. Schrey, Edward J. Carpenter and Donald M. Anderson

The distribution and abundance of motile cells of the toxic dinoflagellate Gonyaulax tamarensis Lebour were monitored in estuarine waters of Long Island, a region with no previous history of shellfish toxicity. The population distribution was patchy, with the species detected in 40% of 115 estuaries examined during the 1983 spring bloom season. More detailed studies in four estuaries indicated that the dinoflagellate was most abundant in the head-water regions, with concentrations falling to undetectable levels at the mouths. G. tamarensis cell concentrations did not exceed $10^5 \text{ cells l}^{-1}$ and often remained an order of magnitude lower. In several instances, population growth and accumulation ceased under seemingly favorable environmental and nutritional conditions. Paralytic shellfish poison (PSP) was never detected in shellfish monitored throughout this study, presumably due to the relatively low intrinsic toxicities of the Long Island strains of G. tamarensis and to the lack of large bloom populations of the dinoflagellate.

In general, the characteristics of G. tamarensis blooms on Long Island are quite

similar to those previously reported for certain regions to the north where toxic populations originate and accumulate within isolated estuaries. The most economical and effective shellfish monitoring program could thus be modeled after those used in Massachusetts or Maine, whereby early-warning sites are used to warn of initial appearance of the motile stage. Satellite stations could be added in nearby areas when PSP begins to reach dangerous levels.

In press: Estuaries.

Supported by: New York State Sea Grant Institute, Grant NA81AAD00027 and NOAA, Sea Grant, Grant NA80AA-D00077 (R/B 41).

WHOI Contribution No. 5641.

THE EFFECT OF ZOOPLANKTON GRAZING ON ESTUARINE BLOOMS OF THE TOXIC DINOFLAGELLATE Gonyaulax tamarensis

Carl J. Watras, Veronique C. Garcon, Robert J. Olson, Sallie W. Chisholm and Donald M. Anderson

A series of short-term in situ experiments was conducted in two Cape Cod embayments to estimate mortality rates of the toxic dinoflagellate, Gonyaulax tamarensis, resulting from grazing by zooplankton. Rates of grazing by the whole zooplankton community and by specific zooplankton populations were measured at various points in the G. tamarensis bloom cycle. The planktonic larvae of the spionid polychaete Polydora ligni and the tintinnid ciliate Favella sp. were important grazers in the systems studied. Gonyaulax-specific clearance rates effected by Polydora ranged from 0.02 to 0.5 $\text{ml individual}^{-1}\text{h}^{-1}$; for Favella the range was about an order or magnitude lower. Peak population densities were close to 900 and 400 $\text{individuals l}^{-1}$ for P. ligni and Favella, respectively. Whether measured directly or predicted as the product of individual clearance rates and numerical abundance, rates of grazing were often higher than estimated algal division rates in years when blooms failed to develop. A simulation model corroborated the result of the field study, demonstrating that grazing can be a significant source of mortality during blooms and can suppress bloom development when grazers are abundant.

Supported by: NOAA Grants NA81AA-D-0069 to the M.I.T. Sea Grant College Program and NA80AA-D-00077 to WHOI.

WHOI Contribution No. 5811.

GENETIC DIFFERENTIATION OF POPULATIONS
OF THE PLANKTONIC COPEPOD
Labidocera aestiva

Ann Bucklin and Nancy Marcus

Planktonic populations of the calanoid copepod, *Labidocera aestiva*, show significant biochemical genetic heterogeneity along the Atlantic coast of the U.S.A. Samples of *L. aestiva* were collected by surface tows at 3 locations on the east coast of the U.S.A.: Vineyard Sound, Massachusetts; Beaufort Inlet, North Carolina; and Fort Pierce Inlet, Florida. Genetic variation in each population and genetic differentiation among latitudinally distinct populations were estimated by assaying gene-enzyme variation by microacrylamide gel electrophoresis. Electrophoretic phenotypes were interpreted for 6 enzyme loci. All 6 were polymorphic when all populations were considered together, but one population (Beaufort Inlet) was monomorphic at 2 loci. Three measures indicated high variability: the number of alleles averaged over all loci was $2.57 \pm \text{s.d.} = 0.26$; the average proportion of loci for which the frequency of the most common allele is no greater than 0.95, $P_{.95}$, was 0.78 ± 0.10 ; and the average frequency of heterozygous individuals, H , was 0.25 ± 0.07 . Allele frequencies at one aminopeptidase-I locus (*Lap-1*) differed significantly among samples of the 3 regions; there were unique alleles of high frequency at this locus in 2 population samples. Values of the statistic of genetic distance, D , averaged 0.29 ± 0.08 . Based on overall average allele frequencies, highly significant heterozygote deficiencies occurred at 5 of the 6 loci, indicating that random mating does not occur across the species range. The observed genetic differentiation of populations of *L. aestiva* may result from differential selection on populations in the 3 regions, restricted gene flow with the extensive geographic range of the species and latitudinal differences in life history, such as seasonal planktonic occurrence and diapause egg production.

In press: Marine Biology.

Supported by: WHOI Postdoctoral
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OCE80-24440 to Nancy Marcus.

WHOI Contribution No. 5810.

Hal Caswell

This chapter attempts to analyze the demographic consequences of clonal reproduction and the way in which those demographic consequences may mold the selection of life history patterns. The classical methods of demographic analysis, which are presented in basic ecology texts, were developed for use on organisms without clonal reproduction; its presence in a life cycle creates complications with which they cannot deal. Thus, the first sections of this chapter will be devoted to a presentation of an appropriately generalized demographic theory. Among the most important of the life cycle characteristics which require such non-classical demographic methods are growth rate plasticity and vegetative reproduction. If growth rates are plastic, individuals of the same age may differ greatly in size. If, as is often the case, individuals of different sizes differ in their survival probabilities and reproductive output, an age classified demographic model may miss much of the demographically relevant variation between individuals. When vegetative reproductive is present, it typically produces offspring which are quite different in size or developmental stage from those produced by sexual reproduction. Lumping the two together as "newborn offspring" obscures potentially important differences in their demographic properties. After presenting an outline of a generalized demographic theory, I go on to apply that theory to three different depictions of the life cycle of a clonally reproducing organism, focusing on the evolution of senescence and the allocation of resources to clonal and sexual reproduction.

In press: Clonal Organisms. J. B. C.
Jackson, L. Buss and R. Cook, eds.
Yale University Press.Supported by: NSF Grants DEB76-19278 and
BSR82-14583.

WHOI Contribution No. 5586.

SLUTSKY'S EQUATION AND THE PERTURBATION
ANALYSIS OF OPTIMAL LIFE HISTORIES

Hal Caswell and Leslie Real

This paper presents a method for predicting the response of optimal life histories to changes in the costs of alternative fitness components or to changes in the overall energy available for allocation to these fitness components. The

mathematical techniques used were developed by Slutsky (1915) to analyze constrained optima in economics. They assume that some measure of fitness λ , which is a function of two variables x_1 and x_2 , is maximized subject to the constraint that $c_1x_1 + c_2x_2 = \epsilon$, where c_1 is the cost of allocation to x_1 and ϵ is the overall available resource budget. Changes in environmental conditions translate into changes in the costs or the overall budget. The response of an optimal life history to these changes is partitioned into two components, a substitution effect and an income effect. The signs of these components, and thus the predicted qualitative response to environmental change, can be predicted from the shapes of the functions relating to λ to the fitness components. Simple life history models with additive and multiplicative fitness functions are analyzed as examples.

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and BSR82-14583.

WHOI Contribution No. 5700.

POPULATION DYNAMICS OF MARINE COPEPODS: THE IMPORTANCE OF GENETIC VARIATION

Nancy H. Marcus

Considerable genetic variation for demographic and other biological traits related to fitness exists in natural populations of marine planktonic copepods. Theory predicts that with large amounts of genetic variation the potential exists for rapid evolutionary change in response to changing environmental conditions. The aim of this research was to evaluate the potential evolutionary (i.e., genetic) response of the calanoid copepod, *Labidocera aestiva*, to environmental change. Major genetic differences were observed between two laboratory lines that were initiated from the same pool of eggs and subsequently reared under similar conditions. The divergence is attributed to the small size of the founding populations and possibly selection. Evidence for seasonal selection occurring in the field is reported and the significance of these findings is discussed in regard to the population dynamics of copepods.

Supported by: NSF Grant OCE83-14882 and
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WHOI Contribution No. 5731.

RECRUITMENT OF INDIVIDUALS INTO THE PLANKTON: THE IMPORTANCE OF BIOTURBATION

Nancy H. Marcus
and Jutta Schmidt-Gengenbach

Eggs of many planktonic copepods occur in the bottom sediments of coastal waters. A large portion of these eggs are buried beneath several centimeters of sediment where they cannot hatch. This laboratory study demonstrates that bioturbation by some benthic polychaete species promotes the hatching of such eggs. Buried eggs can be deposited onto the sediment surface or ejected into the overlying water due to worm activity. Such eggs are viable, and from these new positions can hatch, thereby providing recruits for the planktonic population.

Supported by: NSF Grants OCE80-24440
and OCE83-14882.

WHOI Contribution No. 5774.

LABORATORY EXPERIMENTS ON THE EFFECTS OF A GASTROPOD (*Hydrobia minuta*) ON SURVIVAL OF AN INFAUNAL DEPOSIT-FEEDING POLYCHAETE (*Capitella capitata*, SPECIES TYPE I)

Peter S. Petraitis

Many species which quickly colonize newly disturbed patches have the potential for rapid reproduction and show broad physiological tolerances. Often these species are uncommon in older patches and it is thought predation and/or competition is the primary cause for their disappearance. As a direct test of the sensitivity of an early colonizer to other species, this study examines the effects of the snail, *Hydrobia minuta*, on the early survivorship of the polychaete, *Capitella* (species I). Family effects (i.e., either maternal effects or genetic differences among females) accounts for most of the variation in survivorship from free-swimming larvae to two weeks of age. If family effects are controlled, then survivorship of *Capitella* is always poorer in the presence of *Hydrobia*. There are no detectable density-dependent or time-dependent effects.

In press: Marine Ecology Progress
Series.

Supported by: WHOI Education Office.

WHOI Contribution No. 5640.

SPATIAL AND TEMPORAL ABUNDANCE PATTERNS OF CHAETOGNATHS IN THE WESTERN NORTH ATLANTIC.

I. HYDROGRAPHIC AND SEASONAL ABUNDANCE PATTERNS

Jerry Cheney

Chaetognath abundance was measured from 38 MOCNESS tows collected in the western North Atlantic from August 1975 to November 1977. Twenty-one species were identified from eighteen slope water (SW), eighteen northern Sargasso Sea (NSS), and two Gulf Stream (GS) tows. Three species, *Sagitta elegans*, *S. hispida* and *S. megalophthalma*, were collected in only one or two tows. *Eukrohnia bathypelagica*, *E. fowleri*, *E. hamata*, *Sagitta helenae*, *S. macrocephala*, *S. maxima* and *S. tasmanica* were significantly more abundant in the SW than in the NSS ($p < 0.05$, Mann-Whitney U test). *Krohnitta subtilis*, *Pterosagitta draco*, *Sagitta bipunctata*, *S. decipiens*, *S. hexaptera*, *S. lyra*, *S. minima*, *S. planctonis* and *S. serratodentata* were significantly more abundant in the NSS ($p < 0.05$). *Krohnitta pacifica* and *Sagitta enflata* showed no significant abundance differences between the SW and NSS ($p > 0.05$). Most species showed at least an order of magnitude abundance difference between the SW and NSS, with intermediate GS abundances. A simple mixing model and previous reports of chaetognath distributions in the North Atlantic were used to identify species with expatriate populations in the SW or NSS. Increased temperature and decreased food abundance appear to be of major importance in limiting SW species from the NSS, while decreased temperature and increased predator abundance probably limit NSS species from the SW. Spring abundance peaks were observed for many species in the NSS, but there were no detectable seasonal peaks for species in the SW. The spring abundance peaks in the NSS are probably due to increased food abundance, although temperature and predator abundance could not be ruled out as important factors. The lack of seasonal abundance peaks in the SW may have been due to inadequate sampling frequency.

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WHOI Contribution No. 5775.

SPATIAL AND TEMPORAL ABUNDANCE PATTERNS OF CHAETOGNATHS IN THE WESTERN NORTH ATLANTIC.
II. VERTICAL DISTRIBUTIONS AND MIGRATIONS

Jerry Cheney

Vertical distributions of twenty-one chaetognath species were studied from the upper 1000 m using 38 [eighteen slope water (SW), eighteen northern Sargasso Sea (NSS) and two Gulf Stream (GS)] MOCNESS tows collected on six cruises to the western North Atlantic between August 1975 and November 1977. *Krohnitta pacifica*, *Pterosagitta draco*, *Sagitta bipunctata*, *S. enflata*, *S. helenae*, *S. hexaptera*, *S. minima*, *S. serratodentata* and *S. tasmanica* were classified as epipelagic species; *Eukrohnia hamata*, *Krohnitta subtilis*, *Sagitta decipiens*, *S. lyra*, *S. maxima* and *S. planctonis* were classified as mesopelagic species; *Eukrohnia bathypelagica*, *E. fowleri* and *Sagitta macrocephala* were classified as bathypelagic species; and *Sagitta elegans*, *S. hispida* and *S. megalophthalma* were too rare for adequate analysis. Sixteen of the eighteen abundant species were shallower on average in the SW relative to the NSS, with nine statistically significantly so ($p < 0.05$, Mann-Whitney U test), while *K. subtilis* and *S. lyra* were significantly deeper ($p < 0.05$) in the SW. Few seasonal differences in average vertical distribution were detected in either the SW or NSS for any of these species, and vertical distributions in the two GS tows were similar to those found in the SW and NSS. No diel vertical migrations were detected for any of these species, but ontogenetic vertical migrations were detected for several of the meso- and bathypelagic chaetognaths. Average population depth in thirty-five tows was highly correlated with average individual length in the population ($r = 0.83$, $p < 0.01$, product-moment correlation) for *S. lyra*, indicating that much of the spatial and temporal variation in its average population depth was due to its ontogenetic vertical migrations coupled with spatial and temporal variations in the size structure (or developmental stage structure) of its population. Because most species were shallower on average in the SW, it was hypothesized that many species attempt to follow isotherms in selecting their vertical distributions because isotherm depths are shallower in the SW. This hypothesis was only supported by the *E. hamata* data, and the remaining species appeared to live at higher temperatures in the NSS relative to the SW. Light and/or pressure may also be important for some species. However, many of the observed variations in vertical distribution between the SW and NSS may have been due to ontogenetic vertical migrations combined with regional variations in population develop-

mental stage structure, as was found for S. lyra. Further studies should concentrate on comparing the vertical distributions of developmental stages for each of the species in different hydrographic regions.

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WHOI Contribution No. 5776.

FOOD CONCENTRATIONS ON GEORGES BANK:
NON-LIMITING EFFECT ON DEVELOPMENT AND
SURVIVAL OF LABORATORY REARED
Pseudocalanus SP. AND Paracalanus parvus
(COPEPODA, CALANOIDA).

Cabell S. Davis

Laboratory and field studies were used to show that development rate and survival of the copepods, Pseudocalanus sp. and Paracalanus parvus, are generally not food limited on Georges Bank. Copepods were reared in the laboratory at a series of phytoplankton concentrations (25-200 μg carbon l^{-1}) spanning the range of particulate carbon and nitrogen measured on Georges Bank in October 1978 and February 1979. Pseudocalanus sp. and Paracalanus parvus were reared at 5 and 12°C, respectively. Development rate and survival in both species were not affected at Georges Bank food concentrations but were reduced at lower food levels. Development times from hatching to adulthood was 60-70 d for Pseudocalanus sp. and 25-30 d for Paracalanus parvus.

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WHOI Contribution No. 5709.

INTERACTION OF A COPEPOD POPULATION WITH
THE MEAN CIRCULATION ON GEORGES BANK

Cabell S. Davis

The population structure of the copepod, Pseudocalanus sp., on Georges Bank in February 1975 had distinct shifts from younger to older developmental stages in a clockwise pattern around the bank. It is hypothesized that this spatial pattern resulted from the interaction of copepod population dynamics and the mean circulation of sea water around Georges Bank. To test this idea, a combined physical/biological model is developed which simulates copepod

population dynamics at each of a series of fixed spatial points around a hypothetical gyre. This simple physical scheme incorporates both advection and diffusion of copepods around the gyre. Rates of advection and diffusion are taken from the literature. Environmental influence on life history parameters (development rate, fecundity, and mortality) for Pseudocalanus sp. are found from laboratory experiments and from the literature. Spatial patterns generated by the model agree well with those observed from field samples. The results show that the hypothesis is possible, thus providing a reasonable explanation for mechanisms generating these patterns. It is suggested that such mechanisms may contribute to much of the coarse and meso-scale (50-1000 km) heterogeneity in the distribution of marine zooplankton.

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WHOI Contribution No. 5662.

EVOLUTION OF ZOOPLANKTON SIZE STRUCTURE
AND TAXONOMIC COMPOSITION IN A
WARM CORE GULF STREAM RING

Cabell S. Davis and Peter H. Wiebe

Zooplankton size structure and taxonomic composition in warm-core ring 82-B were examined from a time series (March, April, June) of ring center MOCNESS (1 m) samples. Size distributions of fifteen major taxonomic groups were determined from length measurements digitized from silhouette photographs of the samples. Silhouette digitization allows rapid quantification of zooplankton size structure and taxonomic composition. Length/weight regressions, determined for each taxon, were used to partition the biomass (displacement volumes) of each sample among the major taxonomic groups. Zooplankton taxonomic composition and size structure varied with depth and appeared to coincide with the hydrographic structure of the ring. In March and April, within the thermostad region of the ring, small herbivorous/omnivorous zooplankton, including copepod, crustacean larvae, and euphausiids, were dominant whereas below this region larger carnivores, such as medusae, ctenophores, fish, and decapods, dominated. Copepods were generally dominant in most samples above 500 m. Total zooplankton abundance and biomass increased between March and April due primarily to increases in herbivorous taxa, including copepods, crustacean larvae, and

larvaceans. A marked increase in total zooplankton abundance and biomass between April and June was characterized by an equally dramatic shift from smaller herbivores in April to large herbivores and carnivores in June. Species identifications made directly from the samples suggest that changes in trophic structure resulted from seeding type immigration and subsequent in situ growth of Slope Water zooplankton species.

Supported by: NSF Grant OCE80-17248.

WHOI Contribution No. 5814.

NOT ALL CTENOPHORES ARE HERMAPHRODITES

G. R. Harbison and R. L. Miller

The phylum Ctenophora is considered to be composed entirely of hermaphrodites, but the lobate ctenophores, *Ocyropsis maculata* and *O. crystallina*, are exceptions to this rule. Sex ratios of populations and sex ratios of size classes within populations support the hypothesis that these animals are neither simultaneous nor sequential hermaphrodites. Mature males and females can be easily distinguished and have been successfully mated in the laboratory. That these oceanic ctenophores are dioecious, whereas the far more abundant nearshore species are hermaphroditic, directly contradicts the suggestion that simultaneous hermaphroditism provides a selective advantage in environments where the probability of finding a mate is reduced.

Supported by: NSF Grant OCE82-09341 and an in-house grant from Temple University.

WHOI Contribution No. 5637.

ON THE CLASSIFICATION AND EVOLUTION OF THE CTENOPHORA

G. R. Harbison

Relationships between ctenophores and other lower metazoans are unclear, and there is no compelling evidence that ctenophores are more closely related to cnidarians than they are to platyhelminths. All of the presently recognized orders of the Ctenophora appear to be monophyletic, except for the Cydippida. The families in this group are redefined, in an attempt to incorporate them into a phylogenetic classification. Although conclusions can be drawn concerning interrelationships between the monophyletic groups, present knowledge is inadequate to determine the direction of

important evolutionary changes within the phylum. Two conflicting phylogenetic scenarios are presented, with a preference for the assumption that the common ancestor of the phylum was atentaculate. Although presently accepted classifications of the Ctenophora are clearly not phylogenetic, it seems premature to drastically alter the conventionally recognized taxa until new information is forthcoming. It appears that there is a large undescribed deep-sea fauna, which may clarify our understanding of evolution within the group.

In press: Origins and Relationships of Lower Invertebrates. S. C. Morris, J.D. George, R. Gibson and H. M. Platt, eds. Systematics Assoc. Spec. Vol. 28, pp. 78-100, Oxford Univ. Press, Oxford.

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WHOI Contribution No. 5607.

THE CONCENTRATING OF ORGANISMS AT FRONTS: A COLD-WATER FISH AND A WARM-CORE GULF STREAM RING

Donald B. Olson and Richard H. Backus

Net hauls made in and around a warm-core Gulf Stream ring in April and June 1982 suggest a concentrating of the mesopelagic fish *Benthoosema glaciale* (family Myctophidae) in the frontal zone at the east edge of the ring. In April, *Benthoosema* was found in very small numbers in the two-month old ring, as was to be expected from the temperate-subarctic distribution of this fish and the warm-water origin and age of the ring. By June, age-0 fish had been recruited to the population susceptible to capture by the midwater trawl. These young fish were about five times as abundant at the frontal zone of the ring and about twice as abundant in the ring center as in the adjacent Slope Water. The hypothesis that the increased abundance is tied to the concentrating effect of convergence in the ring front on the original Slope Water population is considered with data and a model. The increase of *B. glaciale* in the center of the ring may be associated with the inwardly spiralling streamers observed in satellite images.

A simple advection/diffusion model for both the fish and a passive tracer of the fluid is used to consider a mechanism that might have concentrated the fish at the ring edge. It is assumed that the fish can counter the vertical flow in order to maintain their preferred depth. Swimming in the

horizontal is assumed to be random. The result of this behavior is that the fish and the passive tracer are affected differently in flow fields such as those in rings. Solutions to the model equations lead to the conclusion that the abundance of fish at the ring front can be accounted for by convergence. The model and the divergence pattern in the ring, calculated from hydrographic data, show the time necessary to effect the hundred-fold increase in abundance that was observed in the ring front between April and June to be on the order of two weeks to a month. We suggest that the concentrating mechanism described is widely applicable to a variety of frontal phenomena and to a variety of planktonic plants and animals.

In press: Journal of Marine Research.

Supported by: NSF Grants OCE80-16991, OCE80-17270 and OCE82-14899.

WHOI Contribution No. 5817.

EVOLUTION OF ZOOPLANKTON BIOMASS STRUCTURE IN GULF STREAM WARM-CORE RINGS

Peter H. Wiebe, Valerie Barber,
Steven H. Boyd, Cabell Davis
and Glenn R. Flierl

Depth stratified collections of zooplankton in warm-core ring 82-B and the Slope Water were made in the upper 1000 m with a MOCNESS in March, April, June and August 1982. Samples were also collected in warm-core ring 81-D in September 1981 and in ring 82-H in September/October 1982. Biomass integrated to 1000 m was lower by a factor of 2 in the ring center during March (25.5 cc/m^2) and April (42.1 cc/m^2) than in the Slope Water (49.0 , 97.4 cc/m^2 , respectively). During this period the depth at which 50% of this biomass occurred was deeper in the ring by 100 to 200 m. In June, following thermal stratification and a surface phytoplankton bloom, the ring's center of zooplankton biomass had shoaled significantly and had increased another 1.5 times. Conversely, in the Slope Water, biomass per m^2 declined to about that found in the ring and the center of biomass was deeper, by 200 to 300 m, than observed previously. Ring biomass was larger in August than in June, but similar in quantity and vertical distribution to the Slope Water. A mixing model was used to show that for the period March through June the increase in biomass at ring center cannot be explained solely by physical exchange with surrounding Slope Water. Model comparison of lateral transport of biomass into the ring versus the transport required

to account for changes in salinity indicated that in situ production was largely responsible for ring biomass increases.

Vertical distributions of biomass in the upper 1000 m of warm and cold-core rings, the Slope Water, and the Sargasso Sea revealed that for most of the year depth of the median biomass was usually at or below 200 m at night and 300 m by day. The depth of median biomass shoaled significantly during periods of high concentrations of near surface plant biomass associated with spring restratification of the upper ocean. While this may be indicative of the classical response of zooplankton to a spring bloom, significant increases in biomass took place in 82-B prior to stratification. Diel shifts in the depth of median zooplankton biomass in the upper 1000 m showed significant regional differences; the order of the values averaged for all cruises was ring 82-B=76 m < Slope Water = 115 m < cold-core rings = 149 m < Sargasso Sea = 212 m.

Contrary to our expectation that warm-core rings should initially have 2 to 3 times less biomass than the surrounding Slope Water, two rings, 82-B and 82-H, appeared to have formed with smaller biomass gradients. Furthermore, zooplankton biomass in warm-core rings reaches levels found in the surrounding Slope Water about 4 times faster than the biomass in cold-core rings reaches levels found in the Sargasso Sea. This is in part due to more frequent interactions between warm-core rings and the Gulf Stream and the effects of winter convective overturn, both of which appear to stimulate rapid in situ changes.

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WHOI Contribution No. 5813.

to account for changes in salinity indi-
cated that in this production was largely
responsible for the biomass increase.
Vertical distribution of biomass in the
upper 1000 m of water and cold-core rings,
the Slope Water, and the Sargasso Sea re-
vealed that for most of the year depth of
the median biomass was usually at or below
300 m at night and 300 m by day. The depth
of median biomass showed significantly
during periods of high concentrations of
near surface plant biomass associated with
spring stratification of the upper ocean.
While this may be indicative of the ap-
parent response of zooplankton to a spring
plankton, significant increases in biomass took
place in 82-83 prior to stratification. This
evident in the depth of median zooplankton
biomass in the upper 1000 m showed slightly
east regional differences; the order of the
values averaged for all cruises was ring
82-83 > Sargasso Sea > 81-82 > cold-core
rings > 100 m > Sargasso Sea > 81-82.
Contrary to our expectation that warm-
core rings should initially have a 1 to 1
ratio of biomass to the surrounding
water, we found that the surrounding
water, cold-core rings, 82-83 and 81-82, ap-
peared to have biomass with smaller biomass
gradients. Furthermore, zooplankton biomass
in warm-core rings reached levels found in
the surrounding Slope Water about 6 times
larger than the biomass in cold-core rings.
These levels found in the Sargasso Sea,
this is in part due to more frequent inter-
actions between warm-core rings and the Gulf
Stream and the effects of winter convective
overturn, both of which appear to stimulate
growth in this region.

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WHOI Contribution No. 2813

horizontal to assume to be random. The
result of this behavior is that the fish and
the passive tracers are affected differently
in flow fields such as those in rings.
Solutions to the model equations lead to the
conclusion that the abundance of fish at the
ring front can be accounted for by conver-
gence. The model and the divergence pattern
in the ring, calculated from hydrographic
data, show the time necessary to effect the
hundred-fold increase in abundance that was
observed in the ring front between April and
June to be on the order of two weeks to a
month. We suggest that the concentrating
mechanism described is widely applicable to
a variety of frontal phenomena and to a
variety of planktonic plants and animals.

In press: Journal of Marine
Research.

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OCE80-11210 and OCE82-14892.

WHOI Contribution No. 2814

STRUCTURE OF BIODIVERSITY IN THE SARGASSO SEA IN THE SARGASSO SEA-CORE RINGS

John E. Meyer, Valerie Smith,
Steven E. Rysgaard, David J. Lavelle,
and Glenn R. Gertzel

Depth stratified collections of zoo-
plankton in warm-core ring 82-83 and the
Slope Water were made in the upper 1000 m
with a 100- μ m mesh in March, April, June and
August 1982. Samples were also collected
in warm-core ring 81-82 in September 1981 and
in ring 82-83 in September-October 1982.
Biomass (averaged to 1000 m) was lower by a
factor of 1 to 100 in the ring center during March
(12.5 g/m³) and April (4.2 g/m³) than
in the Slope Water (42.0 g/m³) and
significantly higher during the depth
at which 50% of the biomass occurred was
deeper in the ring by 100 to 300 m in
June. Following thermal stratification and
a surface phytoplankton bloom, the ring's
center of zooplankton biomass had shifted
significantly and had increased another 1.5
times. Conversely, in the Slope Water,
biomass per m³ declined to about that
found in the ring and the center of biomass
was deeper, by 100 to 300 m, than observed
previously. Ring biomass was larger in
August than in June, but similar in quan-
tity and vertical distribution to the Slope
Water. A mixing model was used to show
that for the period March through June the
increase in biomass at ring center cannot
be explained solely by physical exchange
with surrounding Slope Water. Model trans-
port of lateral transport of biomass in-
to the ring versus the transport required

DEPARTMENT OF CHEMISTRY

Robert B. Gagosian, Department Chairman

CHEMISTRY

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Robert M. Carpenter, Department Chairman

ORGANIC AND
BIOLOGICAL CHEMISTRY

THE RELEASE OF FREE AMINO ACIDS BY
HETEROTROPHIC MARINE MICROFLAGELLATES

Agneta Andersson, Cindy Lee, Farooq Azam
and Ake Hagström

Heterotrophic microflagellates isolated from the Baltic Sea and grown under laboratory conditions were shown to release dissolved free amino acids (DFAA) when grazing bacteria. Flagellates released ^3H -amino acids when fed ^3H -leucine-labelled bacteria, and concentrations of amino acids increased in the experimental medium. Serine showed a strong positive correlation with flagellate feeding. Aspartic acid, glutamic acid, and ornithine also increased more than other amino acids. During consumption of bacteria, the flagellates released 13% of the ingested nitrogen as ammonia and 30% of the ingested phosphorus as phosphate. In a field experiment off Scripps Pier, we measured bacterial production, flagellate abundance, and concentration of DFAA over a 28 hour period. The concentration of DFAA showed a covariation with the flagellate numbers. Results from our field and laboratory experiments suggest that flagellates may be a source of DFAA in the sea.

In press: Marine Ecology Progress
Series.

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C071; NSF Grant OCE83-00018 and
Swedish Natural Science Research
Council Grant NFR B-BU 4452-111.

WHOI Contribution No. 5616.

SCLEROSPONGE GROWTH RATE AS DETERMINED
BY ^{210}Pb AND ^{14}C CHRONOLOGIES

Livia M. Benavides and Ellen R. M. Druffel

Measurements of bomb-produced radio-carbon and ^{210}Pb provide concordant estimates of the growth rate of the sclerosponge *Ceratoporella nicholsoni* collected from the surface waters of northern Jamaica. Radio-carbon measurements of older growth bands in the same specimen were similar to the time history of radiocarbon in coral bands from two other sites in the northwestern Atlantic. Furthermore, ^{210}Pb and stable Pb analyses revealed that the sclerosponge incorporates this element at much higher concentrations than do corals. This is an indication that digestion and retention of

particulate material by the sclerosponge are different from the feeding mechanisms which operate in corals.

Supported by: NSF Grant OCE81-11954.

WHOI Contribution No. 5782.

BIOGEOCHEMISTRY OF PCBs IN INTERSTITIAL
WATERS OF A COASTAL MARINE SEDIMENT

Bruce J. Brownawell and John W. Farrington

Polychlorinated biphenyls (PCBs) were measured in interstitial waters and sediments at a site in New Bedford Harbor, Massachusetts, to study partitioning processes of hydrophobic organic compounds in marine sediments. Pore water concentrations of total PCBs, expressed as Aroclor 1254, increased with depth in the sediments with a maximum concentration of 17.1 $\mu\text{g/L}$ at 9-11 cm. Apparent distribution coefficients of individual chlorobiphenyls decreased with depth and were related to dissolved organic carbon levels. Results from this site suggest that most of the PCBs in interstitial waters are sorbed to organic colloids. A simple three-phase equilibrium sorption model can explain many features of the data. Isomeric changes in the composition of PCBs in the sediments were also apparent. Microbial degradation appears to be responsible for large relative depletions of several PCB isomers with depth in the core.

Supported by: Andrew W. Mellon Foundation; U.S. Dept. of Commerce, NOAA, and National Sea Grant Program Grants NA 83 AA-D-00049 (R/P-13) and NA 84 AA-D-00033 (R/P-17).

WHOI Contribution No. 5839.

SOURCES AND DISTRIBUTION PROCESSES OF
CHEMICAL CONTAMINANTS IN THE COASTAL ZONE

John W. Farrington

A brief review of biogeochemical cycles research - routes of input, rates of movement, reactions, reservoirs of accumulation for several pollutant compounds - is presented. The present status of chemical contamination in coastal areas is illustrated with historical records obtained from sediment cores and from bivalve sentinel organism analyses. Problems of continuing and future concern for environmental quality are presented for: i) the open ocean, ii) developing nations, and iii) analytical chemical methodology.

Published in: The Law of the Sea and Ocean Industry: New Opportunities and Restraints. D. Johnston and N. G. Letalik, eds. Proceedings, Law of the Sea Institute, 21-24 June 1982.

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WHOI Contribution No. 5383.

AROMATIC HYDROCARBONS IN NEW YORK BIGHT
POLYCHAETES: U.V.-FLUORESCENCE
ANALYSES AND GC/GCMS ANALYSES

John W. Farrington, Stuart G. Wakeham,
Joaquim B. Livramento, Bruce W. Tripp
and John M. Teal

Polychaetes collected from New York Bight sediments near sewage sludge and harbor dredge spoil dump sites contained a series of diaromatic-tetracyclic hydrocarbons of apparent triterpenoid origin. These octahydrochrysenes were much more abundant in the polychaetes than were the fossil fuel and combustion-derived polycyclic aromatic hydrocarbons which were found in the sediments. If the polychaetes had been analyzed only by the spectrofluorometric techniques often used for screening samples for petroleum contamination, then grossly inaccurate results for aromatic hydrocarbon content would be obtained. Therefore, U.V.-fluorescence must be used in a hierarchical approach, with more sophisticated procedures available to verify the petrogenic nature of the hydrocarbons.

Supported by: DoE contract DE-AC02-77EV04256 A007 and DoE/U.S. Dept. of Interior AA550-IA7-20.

WHOI Contribution No. 5798.

FIELD AND LABORATORY STUDIES OF THE
ONTOGENY AND ECOLOGY OF Globorotalia
truncatulinoides (d'Orbigny) AND
Globorotalia hirsuta (d'Orbigny)
IN THE SARGASSO SEA

Christoph Hemleben, Michael Spindler,
Ingrid Breitingner and Werner G. Deuser

The life habits of Globorotalia truncatulinoides (d'Orbigny) and Globorotalia hirsuta (d'Orbigny) were investigated. These non-spinose planktonic foraminifers occur in high abundance and reproduce in early spring in the subtropical waters around Bermuda. Samples were obtained from plankton tows and a deep (3200 m) sediment trap.

Test development was traced through size measurements, chamber counts, and stable-isotope measurements. Reproduction and juvenile development take place in the upper 200 m of the water column. Size comparison between tests from surface tows and the sediment trap shows growth due to addition of chambers while these species migrate or settle to deeper waters. Individuals reaching temperatures below 8-10°C in a viable state deposit a calcite crust on top of the primary wall. The boundary of 8-10°C was established in temperature-controlled culture experiments. Oxygen-isotope measurements confirm growth through chamber and crust addition in deeper, colder water. Carbon-isotope data suggest a change in feeding behavior or food source between juvenile and adult stages.

Supported by: NSF Grants OCE76-21280, OCE78-19813, OCE80-24130 and OCE82-19588.

SEASONALITY IN THE FLUXES OF SUGARS,
AMINO ACIDS AND AMINO SUGARS
TO DEEP OCEAN: SARGASSO SEA

Venugopalan Ittekkot, Werner G. Deuser
and Egon T. Degens

The fluxes of sugars, amino acids and amino sugars were determined in the <37µm fraction of samples collected during successive two-month sediment trap deployments in the deep Sargasso Sea (3200±100 m) from April 78 till December 81. All fluxes varied seasonally and in phase with the flux of <37µm fraction, which was shown previously to vary in phase with primary productivity in the surface layers. During the period of investigation the fluxes of sugars, amino acids and amino sugars were in the range of 0.03 to 0.64 mg m⁻²d⁻¹ and 0.12 to 1.7 mg m⁻²d⁻¹ respectively. They contributed 18 to 20% of the measured organic carbon. About 40 to 50% of the measured total nitrogen could be accounted for by amino acids and amino sugars. The distribution pattern of sugars and amino acids were, in general, similar to those reported for biomineralized tissues of carbonate and silica producers and the cell walls of biomineralizing organisms. However, amounts of non-protein amino acids, i.e. β-alanine and γ-aminobutyric acid, relative to aspartic and glutamic acids and those of amino sugars relative to total amino acids varied seasonally. They appear to indicate the nature and source of organic matter arriving at the sediment trap.

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WHOI Contribution No. 5609.

U.S. "MUSSEL WATCH" PROGRAM:
TRANSURANIC ELEMENT DATA FROM
WOODS HOLE OCEANOGRAPHIC INSTITUTION
1976-1983

Julianne M. Palmieri, Hugh D. Livingston
and John W. Farrington

Bivalves (*Mytilus edulis*, *Mytilus californianus*, *Crassostrea virginica*, and *Ostrea equestris*) were collected once per year during 1976, 1977, and 1978 along the United States coast and analyzed for $^{239,240}\text{Pu}$, ^{241}Am , and ^{137}Cs as part of the U. S. Mussel Watch program. Monthly samples were collected during 1976-1980 from Narragansett Bay, Rhode Island, and Bodega Head, California, and analyzed for $^{239,240}\text{Pu}$, ^{241}Am , and ^{137}Cs .

There is no evidence in the data for systematic regional or local elevated concentrations of radionuclides as a result of releases from the nuclear fuel cycle. Elevated concentrations of $^{239,240}\text{Pu}$ in mussels from the central California coast are due to uptake from upwelled water fed by North Pacific water which has elevated $^{239,240}\text{Pu}$ from input of nuclear weapons test fallout.

Monthly fluctuations in radionuclide concentrations in the Narragansett Bay mussels appear to be primarily influenced by spawning. The slight monthly fluctuations in the radionuclide concentrations for the Bodega Head mussels are less coherent from year to year compared to Narragansett Bay, although $^{239,240}\text{Pu}$ may be influenced by upwelling season.

Limited data on transplants of mussels as well as mussel data from the Ebro estuary on the Spanish coast and from the Irish Sea are also reported.

Supported by: U.S. EPA Grants CR-
807181 and 68-03-3193.

WHOI Technical Report 84-28.

METHODOLOGY FOR SAMPLING AND ANALYSIS
OF LIPIDS IN AEROSOLS
FROM THE REMOTE MARINE ATMOSPHERE

Edward T. Peltzer, Jane B. Alford
and Robert B. Gagosian

A procedure is described for the collection of remote marine aerosol samples by high-volume filtration, cascade impaction, dry fallout collection, and rain. Samples were analyzed quantitatively for five

classes of naturally occurring lipids (n-alkanes, wax esters, fatty alcohols, sterols, and fatty acids) and polycyclic aromatic hydrocarbons (PAHs). Air samples (4,000-10,000 m³) were collected on glass fiber filters under automatic control. Rain samples of 1-5ℓ were collected on an event basis. Filters and rain samples were extracted with methylene chloride. The extracts were fractionated into discrete chemical classes by silica-gel adsorption chromatography. The fractions were derivatized if necessary and analyzed by HRGC and HRGC/MS. A second filter extraction was required for fatty acid salt analysis. Internal standards were used to quantify recoveries and concentrations. Mean recoveries relative to the internal standards were 96.5±2.8% for C₁₈-C₃₆ n-alkanes, 96.4±5.3% for C₂₀-C₃₀ n-fatty acids, 92.5±4.5% for C₁₄-C₃₀ n-fatty alcohols, and 93.3±1.4% for cholesterol. Typical blanks and concentrations for remote marine aerosol and rain samples are described and compared with other methods used in coastal marine, rural, and suburban sampling locations.

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and OCE81-11947.

WHOI Technical Report 84-9.

PARTICLE SIZE DISTRIBUTION OF LIPIDS
IN AEROSOLS OFF THE COAST OF PERU

Jürg K. Schneider and Robert B. Gagosian

Lipid components in aerosols were characterized as a function of particle size from samples collected in spring 1981 off the coast of Peru as part of the Sea/Air Exchange Program (SEAREX). The investigation was designed to determine (i) the particle size distributions for different terrestrial and marine source marker organic compounds, (ii) the importance of the atmosphere as an input source to the sea for terrestrial compounds, and (iii) the significance of recycling of these compound classes from seawater back into the atmosphere.

The terrestrially-derived components of three compound classes (fatty alcohols, wax esters, and n-alkanes) were found to have similar particle size distributions. They are relatively evenly distributed over the whole particle size range, suggesting (i) little modification of the wide spectrum of plant and soil derived particles by short range transport offshore, and (ii) insignificant gas-particle partitioning for these materials. On the other hand, the terrestrially-derived fatty acid salts show a different particle size distribution probably due to their very different physico-

chemical properties.

The atmospheric flux to the sea surface via both wet and dry deposition is not significant relative to the flux through the euphotic zone of the water column for two lipids of terrestrial origin, octacosanoic acid and 24-ethylcholest-5-en-3 β -ol. No significant recycling from the sea surface back into the atmosphere was observed for lipid compounds of terrestrial origin.

Marine-derived sterols, fatty alcohols, and fatty acid salts were found in high concentrations in surface microlayer samples. The enrichment of these compound classes is about 2-4 orders of magnitude relative to bulk sea water.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 5707.

USING SENTINEL ORGANISMS TO MONITOR CHEMICAL CHANGES IN THE COASTAL ZONE: PROGRESS OR PARALYSIS

B. W. Tripp and J. W. Farrington

Contamination of coastal waters by synthetic organics, petroleum, trace metals, and radionuclides has been monitored in recent years through the use of bivalve filter-feeding molluscs as sentinel organisms. While no single approach is perfect, sentinel organisms have proven to be a good tool for monitoring chemical contamination.

Over the past decade several international, regional, and national monitoring programs have been established based on the sentinel organism concept, including the U.S. Mussel Watch program, funded by EPA in the mid-1970's. The results of these national and regional programs now permit a more comprehensive assessment of the sentinel organism concept and its application to other coastal areas. In November of 1983 an international workshop was held to discuss the detection and measurement of chemical changes in the coastal environment and to assess the concepts and methodologies used in obtaining monitoring data. Fifty-three representatives from twenty-eight countries met and the results of their discussion are now being edited for publication.

Ideally, we need data on the concentrations of pollutants in all segments of the ecosystem, pathways and rates of transfer of pollutants between these segments, and the adverse effects of these pollutants from the subcellular to the ecosystem level. The com-

plexity of nature is a recognized reality and will inherently introduce some uncertainty into monitoring data. Decisions that have environmental, economic, and social impacts will be made, and we cannot permit the uncertainty caused by the complexity of natural systems to paralyze research, environmental assessment, and resource management in coastal areas.

An operational monitoring program can be designed and implemented now, even with our imperfect understanding of natural systems. Part of the success of previous efforts has been the recognition that complexity exists and that monitoring programs must be designed and operated within that context. The sentinel organism concept can be an effective component in a well-designed monitoring program.

Supported by: Andrew W. Mellon Foundation and a U.S. EPA Contract.

WHOI Contribution No. 5830.

WAX ESTERS AND TRIACYLGLYCEROLS IN SINKING PARTICULATE MATTER IN THE PERU UPWELLING AREA (15°S, 75°W)

Stuart G. Wakeham

The flux and composition of wax esters and triacylglycerols were measured in particulate matter collected by free-drifting sediment traps in the Peru upwelling area. The purpose was to assess diurnal variations in sources and vertical transport of these lipids. Traps were deployed for periods of 8-12 hr during both day and night at the base of the euphotic zone (10-15 m) and at about 50 m. Although the flux of total particulate organic carbon varied by 4x, the flux of wax esters varied by 84x and triacylglycerols by 30x. POC, wax esters, and triacylglycerols also showed different temporal patterns. The highest wax ester flux was measured in shallow traps at night and is attributed to increased inputs from zooplankton which feed near the surface at night. Triacylglycerol flux was high in both shallow and deep nocturnal traps, consistent with inputs of both phytoplankton and zooplankton lipids. The composition of these lipids was also quite variable and attests to the complex nature of the lipid sources.

In press: Marine Chemistry.

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WHOI Contribution No. 5783.

THE BIOGEOCHEMISTRY OF TOLUENE IN
COASTAL SEAWATER: RADIOTRACER EXPERIMENTS
IN CONTROLLED ECOSYSTEMS

Stuart G. Wakeham, Elizabeth A. Canuel,
Peter H. Doering, John E. Hobbie and
John V. K. Helfrich

The fate of toluene in coastal seawater was investigated in controlled ecosystems using ^{14}C - and ^3H -toluene as tracers. Under winter-like conditions, 80% of the toluene volatilized from the water column in 2 months. Microbial degradation was less important than volatilization and sorption onto particulate matter with resultant loss to the sediments was minor. During summer most of the toluene was degraded by microbes. Nearly 80% of the toluene was converted to CO_2 within 1 week and the label remained in the water column as dissolved CO_2 . The experimental results were applied to estimate the removal rates and the residence time of toluene in adjacent Narragansett Bay, Rhode Island. In winter, volatilization would dominate the loss of toluene and a residence time of 6 d would be predicted. However, rapid biodegradation in summer would result in a residence time of <1 d.

In press: Biogeochemistry.

Supported by: NOAA Grant NA81RAD00015.

WHOI Contribution No. 5799.

VARIABILITY IN LIPID FLUX AND
COMPOSITION OF PARTICULATE MATTER
IN THE PERU UPWELLING REGION

Stuart G. Wakeham, John W. Farrington
and Robert B. Gagosian

Particulate matter samples were collected with free-drifting sediment traps and in situ filtration systems in the Peruvian upwelling area to study the organic geochemistry of particulate organic matter in the water column and its relationship to source organisms and sediments. A variety of lipids - fatty acids, wax esters, sterol esters, triacylglycerols, sterols, fatty alcohols, stanones, unsaturated C_{37} - and C_{38} -methyl ketones, and hydrocarbons - were analyzed by capillary gas chromatography and gas chromatography-mass spectrometry. Diel and depth-related variations in lipid composition and flux of an order of magnitude were not uncommon in the sediment trap samples. Two samplings of a single site four days apart produced significantly different results. Flux and composition patterns varied depending on lipid class, collection time and depth, and source. The

lipid composition of the suspended particles collected by in situ filtration was quite different from that of sinking particles collected in sediment traps, reflecting complexities in differentiating between source, transport, and transformation processes affecting the two particle size fractions.

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Geochemistry, 1983.

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WHOI Contribution No. 5610.

DIMETHYLSULFIDE IN A STRATIFIED
COASTAL SALT POND

Stuart G. Wakeham, Brian L. Howes
and John W. H. Dacey

Dimethylsulfide (DMS) is the major volatile reduced organic sulfur compound in open ocean and coastal waters, and its emission from surface water represents a major flux of biogenic reduced sulfur to the atmosphere. It is an algal natural product as well as a product of microbial decomposition of organic matter. In the open ocean, the distribution of DMS is correlated with primary productivity. In a study of a stratified coastal salt pond reported here, DMS was the predominant volatile sulfur compound in the oxic epilimnion throughout the year. There was consistently a peak in DMS concentration just above the oxic-anoxic interface at low oxygen tensions, probably arising from a combination of physiological stress and decomposition of algal material. During winter and early spring, a second DMS peak was present in the epilimnion, probably associated with algal production. Elevated DMS concentrations did not seem to be related to strict anoxia, as the lowest concentrations were always found in the anoxic hypolimnion where H_2S (a volatile reduced inorganic sulfur compound) dominates.

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770-772.

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and BSR81-04701.

WHOI Contribution No. 5639.

ATMOSPHERIC TRANSFORMATIONS OF FLUXES
OF LIPIDS AT ENEWETAK ATOLL

Oliver C. Zafiriou, Robert B. Gagosian,
Edward T. Peltzer, Jane B. Alford
and Theodore C. Loder

We report data for the Enewetak site of the SEAREX program from the rainy season in 1979. The concentrations of n-alkanes, n-alkanols, sterols, n-alkanoic acids and their salts, and total organic compounds in rain are reported, as well as the apparent gaseous hydrocarbon concentrations. These data and information on the particulate forms are analyzed in conjunction with ancillary chemical and meteorological data to draw inferences about sources, fluxes, and chemical speciations.

While the higher molecular weight lipid biomarker components are exclusively terrestrial, the organic carbon in rain appears to derive from atmospheric transformations of terrestrial carbon. Distinctively marine components are nearly absent.

Comparison of the scavenging ratios of the organic components in rain vs. those for clays reveals that the alkanolic acids and the higher molecular weight alkanols behave as exclusively particulate materials, whereas lower alkanols and most hydrocarbons show much higher scavenging ratios, probably due to the involvement of a gaseous phase. Vaporization in the atmosphere and scavenging of a gas phase would lead to higher scavenging ratios; vaporization during sampling would give low aerosol concentrations and high gas-phase concentrations leading to high scavenging ratios. Physico-chemical estimates of vapor pressures under relevant conditions support the reasonableness of this suggestion, particularly for the alkanes.

The major fluxes at Enewetak result from rain rather than dry deposition, and extrapolating the measured values to meaningful annual averages requires adjustments for seasonally varying source intensity and rain dynamics. Aerosol data for other seasons and other substances are used to correct for source-strength intensity variations, and a 210-Pb/organic compound correlation is established and extrapolated to adjust for rainfall volume effects. These corrections, assumed independent and applied together, yield inferred fluxes that are 2.5 to 9-fold larger than the fluxes calculated from mean concentrations.

The inferred fluxes to the ocean, while small compared to primary production, are large enough to have potential impacts in the cycle of dissolved organic carbon and the sedimentary geochemistry of refractory lipid components.

In press: Journal of Geophysical
Research.

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WHOI Contribution No. 5638

S E A W A T E R A N D

G E O C H E M I S T R Y

ASPECTS OF THE AROMATIC HYDROCARBON
GEOCHEMISTRY OF RECENT SEDIMENTS
IN THE GEORGES BANK REGION

Paul D. Boehm and John W. Farrington

Polynuclear aromatic hydrocarbon (PAH) concentrations and compositions were determined seasonally over one year at a series of 22 sampling stations on and adjacent to Georges Bank off the northeastern U.S. Coast. PAH concentrations are directly related to the total organic carbon (TOC) content of the sediments and to the silt/clay content of these sediments. Several groupings of two-ringed to five-ringed PAH compounds were quantified with concentrations of these groups ranging from 1 to 100 ppb. The overall compositions of the PAH compounds indicate that pyrogenic (combustion) PAH dominate the assemblage at higher levels while lower levels are often associated more with a fossil fuel PAH origin. The relationship of PAH to TOC, the ratio of fossil fuel to combustion PAH, and the absolute concentrations of PAH form a useful set of monitoring parameters in these and other continental shelf regions.

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Commerce (NOAA) Contract No. NA81
SRC-00098.

WHOI Contribution No. 5576.

MEASUREMENTS OF TOTAL CARBON DIOXIDE
AND ALKALINITY IN THE
NORTH ATLANTIC OCEAN IN 1981

Peter G. Brewer, Alvin L. Bradshaw
and Robert T. Williams

During the Transient Tracers in the
Ocean (TTO) North Atlantic study in 1981

several thousand measurements of the alkalinity and total carbon dioxide concentration of sea water were made. These data provide fundamental information on the ocean's capacity to absorb fossil fuel CO₂ and reveal the natural oceanic carbon cycle. The measurements were made by potentiometric titration at sea. In this paper we report the details of standardization, the measurement of the blank values, and our investigations of overall data quality. Comparisons with samples stored for shore-based measurements show that the alkalinity determinations agree to within 0.8±9.5µeq/kg; stored total carbon dioxide determinations deviate from shipboard measurements by +21.3µmoles/kg, probably due to imperfections in storage.

The surface ocean chemical properties we measure are correlated with temperature and salinity. The surface alkalinity is described by $\text{Surf. Alk.} = 547.05 + (50.560 \times S^{\circ}/\text{oo})$, with a correlation coefficient of 0.990 and a standard deviation of 9.14µeq/kg. Surface total carbon dioxide, normalized to a constant salinity of 35‰ can be more crudely represented by $\text{Total CO}_2 (35^{\circ}/\text{oo}) = 2158 (8.169 \times t^{\circ}\text{C})$ with a correlation coefficient of -0.885 and a standard deviation of 30µmol/kg. Regional variability in this relationship exists.

In press: "The Global Carbon Cycle: Analysis of the natural cycle and implications of anthropogenic alterations for the next century." Proceedings of the Sixth Oak Ridge National Laboratory Life Sciences Symposium. Springer-Verlag, New York.

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WHOI Contribution No. 5598.

RARE EARTH ELEMENTS IN THE PACIFIC AND ATLANTIC OCEANS

Hein J. W. de Baar, Michael P. Bacon, Peter G. Brewer and Kenneth W. Bruland

The first profiles of Pr, Tb, Ho, Tm, and Lu in the Pacific Ocean, as well as profiles of La, Ce, Nd, Sm, Eu, Gd and Yb, are reported. Concentrations of REE (except Ce) in the deep water are two to three times higher than those observed in the deep Atlantic Ocean. Surface water concentrations are typically lower than in the Atlantic Ocean, especially for the heavier elements Ho, Tm, Yb, and Lu. Cerium is strongly depleted in the Pacific water column, but less so in the oxygen minimum zone. Lanthanum acts somewhat independently from the other elements. The distributions of the REE as a group, best represented by the suite

Pr-Lu, are controlled by two simultaneous processes: (1) cycling similar to that of opal and calcium carbonate, with circumstantial evidence in support of the latter as a possible carrier, and (2) adsorptive scavenging by settling particles and possibly by uptake at ocean boundaries. The observed fractionations of the REE in seawater relative to shales appear to be controlled largely by the latter process.

In press: *Geochimica et Cosmochimica Acta*.

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WHOI Contribution No. 5750.

ANOMALIES IN RARE EARTH DISTRIBUTIONS IN SEA WATER: Gd AND Tb

Hein J. W. de Baar, Peter G. Brewer and Michael P. Bacon

We have measured profiles of the rare earth elements (REE) in Atlantic and Pacific Ocean waters. The data, normalized versus shales, exhibit a pronounced anomaly in Gd relative to its neighbors Eu and Tb in the REE series such that the Gd concentrations are high by 30-50%. Closer inspection reveals that the anomaly is made up of both elevated Gd and depressed Tb concentrations, likely associated with solution chemistry shifts in the transition from an exactly half-filled 4f electron shell. Anomalies in Gd and Tb solution complexation are also indicated by the Turner-Whitfield-Dickson speciation model. The overall trend of heavy REE(III) enrichment in seawater and the Gd/Tb anomaly described here tend to support scavenging as an important removal mechanism for the REE from seawater.

In press: *Geochimica et Cosmochimica Acta*.

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WHOI Contribution No. 5751.

SEA SURFACE TEMPERATURE ANOMALIES IN THE TROPICAL PACIFIC OCEAN AS RECORDED IN BANDED CORALS: IMPLICATIONS FOR THE CARBON DIOXIDE CYCLE

Ellen R. M. Druffel

Stable oxygen isotope ratios from an-

nually-banded corals are correlated with historical records of sea surface temperature in the mid- and eastern tropical Pacific Ocean. El Niño events between 1929 and 1976 can be detected using this method, but there are discrepancies between the records of El Niños from corals and those determined using historical sea surface temperature (SST) measurements along the coast of South America. Depletion of $\Delta^{18}\text{O}$ during El Niño events is greater at the Galapagos Islands sites ($.45^\circ/\text{oo}$) than at the Fanning and Canton Island sites in the Mid-Pacific ($.20^\circ/\text{oo}$ and $<.2^\circ/\text{oo}$, respectively). Of prime importance is the evidence of decade timescale variations in SST in the tropical Pacific. In particular, SST appears to have been 1°C higher in the eastern tropical Pacific during the 1930s than during subsequent years. A significant net flux of CO_2 from the surface ocean to the atmosphere is envisioned during these periods of higher SST.

In press: AGU Monographs, Proc. AGU Chapman Conference, Jan. 1984.

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WHOI Contribution No. 5735.

PETROLOGICAL AND GEOCHEMICAL VARIATIONS
ALONG THE MID-ATLANTIC RIDGE BETWEEN
46°S AND 32°S: INFLUENCE OF THE
TRISTAN DA CUNHA MANTLE PLUME

Susan E. Humphris, Geoffrey Thompson,
Jean-Guy Schilling and Richard H. Kingsley

Basalts from a section of the Mid-Atlantic Ridge close to the active volcanic island of Tristan da Cunha in the South Atlantic have been analyzed to investigate the influence of the mantle plume on the geochemistry of basalts being erupted at the spreading center. Although petrographically the rocks show only limited variation, two basaltic types were determined to be erupting in this region based on their major, trace and REE compositions. One group shows depletion in the large ion lithophile and LRE elements, and can be characterized as N-type mid-ocean ridge basalts. The second group shows "enriched" geochemical characteristics and is similar to T-type MORBs.

Mixing hyperbolae for the incompatible element and REE ratios suggest that extensive mixing of an end-member characteristic of a plume region with an end-member of normal depleted MORB can account for the occurrence of the T-type MORBs in this region. Based on the nature and development of the Tristan da Cunha mantle plume over the past 100 Ma, a composite model of evolution is suggested in which a ridge-centered hotspot progressed to a near ridge hotspot and finally to a totally intra-plate situation. The fact that Tristan da Cunha is highly alkalic now, but that an irregular geochemical anomaly is also present on the Mid-Atlantic Ridge at this latitude, would suggest an intermediate stage between the near-ridge and totally intra-plate situation. This model leads to the conclusion that, as the hotspot migrated away from the Mid-Atlantic Ridge, a preferential sublithospheric flow towards the Ridge was established. This discontinuous feature can explain the geochemical variations seen along the Mid-Atlantic Ridge by providing a mechanism for mixing of a depleted N-type MORB component with an enriched component originating through processes active at the Tristan da Cunha mantle plume.

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In press: *Geochimica et Cosmochimica Acta*.

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WHOI Contribution No. 5636.

GENERATION AND MIGRATION
OF LIGHT HYDROCARBONS

John M. Hunt

Light hydrocarbons are formed from disseminated organic matter in sediments at the ppb level by biological and low temperature ($<50^\circ\text{C}$) chemical reactions and at the ppm level by high temperature ($>50^\circ\text{C}$) reactions. The cooler reactions produced mainly branched hydrocarbons while the hotter reactions yield more straight chains. Generation zones in the subsurface can be recognized by hydrocarbon distribution patterns. The best source rocks show characteristic cracking patterns of long chain hydrocarbons from laboratory pyrolysis. Hydrocarbons with tertiary carbon atoms form at lower temperatures than those with quaternary carbons. Methane and ethane migrate vertically through fine-grained shales by diffusion and solution whereas many of the C_{3+} hydrocarbons such as the C_7 alkanes and cycloalkanes show little or no vertical migration. Light hydrocarbon concentrations, including methane, in fine-grained source rocks decrease to low values in deep, high temperature ($>200^\circ\text{C}$) sediments. This is coincident with the observation that no oil or gas production exists deeper than 27,000 ft (8.2 km) despite more than 100 ultradeep exploration wells being drilled annually.

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WHOI Contribution No. 5678.

GEO-MICROBIOLOGY OF DEEP SEA HYDROTHERMAL VENTS

Holger W. Jannasch and Michael J. Mottl

During the cycling of seawater through the earth's crust along the mid-ocean ridge system, geothermal energy is transferred into chemical energy in the form of reduced inorganic compounds. They are derived from the reaction of seawater with crustal rocks at high temperatures. Emitted from warm ($<25^{\circ}\text{C}$) and hot ($\sim 350^{\circ}\text{C}$) submarine vents, this chemical energy is used by chemolithotrophic bacteria for the reduction of CO_2 (assimilation) to organic carbon. Thus, bacteria form the base of the food chain which permits copious populations of certain adapted invertebrates to grow in the immediate surroundings of the vents. Reduced sulfur compounds appear to represent the major electron donor for aerobic microbial metabolism, while methane-, hydrogen-, iron- and manganese-oxidizing bacteria have also been observed. Methanogenic and sulfur respiring isolates are representatives of anaerobic chemosynthesis. Bacteria grow abundantly in the shallow crust where upwelling hot, reducing waters mix with downwelling cold, oxygenated waters. The predominant production of biomass, however, is based on hitherto unknown symbiotic associations between chemolithotrophic bacteria and certain invertebrates, which have also been found as fossils in Cretaceous sulfide ores of ophiolite deposits.

Supported by: NSF Grants OCE82-14896, OCE83-08631 and OCE-10175.

WHOI Contribution No. 5764.

THE USE OF TRACERS AND WATER MASSES TO ESTIMATE RATES OF RESPIRATION

William J. Jenkins

One method of estimating oxygen utilization rates in the sea is to infer them from the spatial distributions of dissolved oxygen and other properties. That is, one obtains some measure of the "age" or velocity of a given parcel of water, and combining this with an observed deficit or gradient in dissolved oxygen concentration, one obtains an apparent oxygen utilization rate. The advantage of such an approach is

that it represents a true in situ measurement; there is no experimental perturbation of the system. The disadvantage of such an approach is that it is often a rather model-dependent calculation and is therefore subject to potential ambiguities, inaccuracies and even fallacies due to the model used. However, in all fairness it should be noted that even quite unrealistic models may in fact give rather good estimates of oxygen utilization, largely due to the degree of similarity between the boundary conditions of oxygen and the tracer used to calibrate the model. Such "metaphoric" models have proven very powerful in this regard and in large part form the basis of our quantitative understanding of the rates of chemical and biological processes in the oceans.

Published in: Heterotrophic Activity in the Sea. J. E. Hobbie and P. J. LeB. Williams, eds. Plenum Publishing Corp., 1984.

SEASONAL OXYGEN CYCLING AND PRIMARY PRODUCTION IN THE SARGASSO SEA

W. J. Jenkins and J. C. Goldman

The hydrographic record at Station S in the Sargasso Sea shows the development of a subsurface oxygen maximum within the euphotic zone which must be of photosynthetic origin. Consideration of insolation, heat budgets and available $^3\text{He}/^3\text{H}$ data yields an estimate of the order of $5 \text{ Mm}^{-2}\text{y}^{-1}$ for the vertically integrated oxygen production rate. Gas exchange calculations reveal a similar oxygen flux leaving the surface, and examination of respiration cycles below the euphotic zone yields consistent results. Such results point to new production of the order of $50 \text{ g C m}^{-2}\text{y}^{-1}$. By using a more realistic mixed layer-thermocline model (Klein and Coste, 1984), it appears that the flux of nutrients into the euphotic zone is sufficient to support such a production. The pulse-like nature of nutrient injection implied by this model raises the possibility of a spatially variable efficiency of recycling which may account for the disparity between the above observations and the level of new production inferred from ^{14}C and ^{15}N incubation techniques.

In press: Journal of Marine Research.

Supported by: NSF Grants OCE81-17998 and OCE83-08578

WHOI Contribution No. 5824.

HIGH RESOLUTION ISOTOPE STUDY OF THE LAST
DEGLACIATION BASED ON BERMUDA RISE CORES

Lloyd D. Keigwin and Ellen R. M. Druffel

We report stable isotope and ^{14}C results on carbonates from three Late Quaternary cores with high rates of sedimentation from the northeastern Bermuda Rise. These cores contain the highest resolution record of glacial maximum to Holocene stable isotope change yet produced from an open ocean location. Details of this record include a three step "termination" and the first direct evidence of an early deglacial melt-water "spike" in the open sea.

In press: Quaternary Research.

Supported by: NSF Grant OCE83-15260.

WHOI Contribution No. 5422.

HELIUM ISOTOPIC SYSTEMATICS WITHIN
THE NEOVOLCANIC ZONES OF ICELAND

Mark D. Kurz, Peter S. Meyer
and Haraldur Sigurdsson

Helium isotopic compositions have been measured in a suite of sub-glacial basaltic glasses from the neovolcanic zones of Iceland. The $^3\text{He}/^4\text{He}$ ratios vary between 8 and $26.2 \times$ atmospheric; the higher ratios are generally consistent with a relatively primitive undegassed mantle source for the helium. Several sampling tests indicate that sub-glacial basaltic glasses retain a representative sample of magmatic helium, much like mid-ocean ridge basalts. The overall variations, high observed helium concentrations (up to 1.6×10^{-6} STP/g), and young age of Icelandic crust argue against crustal contamination as a primary control of helium isotopes in the basaltic lavas. Each volcanic zone has a distinctive basaltic $^3\text{He}/^4\text{He}$ isotopic signature: $18\text{--}26.2 \times$ atmospheric in the eastern volcanic zone, $12\text{--}16 \times$ atmospheric in the western volcanic zone, and $8\text{--}11$ in the northeastern volcanic zone. Each volcanic zone is also relatively homogeneous with respect to helium isotopes. The homogeneity within zones, variability between volcanic zones in $^3\text{He}/^4\text{He}$, and temporal aspects of Icelandic volcanism are interpreted within the framework of a plume model for the mantle beneath Iceland. The preferred model involves variable contributions from a plume source (i.e. undegassed) to each of the Icelandic volcanic zones.

In press: Earth and Planetary Science
Letters.

Supported by: NSF Grant OCE83-15270.

WHOI Contribution No. 5786.

CHEMISTRY OF HOT WATERS SAMPLED FROM
BASALTIC BASEMENT IN HOLE 504B,
DEEP SEA DRILLING PROJECT LEG 83,
COSTA RICA RIFT

M. J. Mottl, E. M. Druffel, S. R. Hart,
J. R. Lawrence and E. Saltzman

Seawater which has been altered by reaction with basaltic basement has been sampled from Deep Sea Drilling Project Hole 504B, located on 5.9 m.y.-old crust on the southern flank of the Costa Rica Rift. Fourteen water samples have been collected on Legs 69, 70, and 83, both before and after renewed drilling on the latter two legs, at temperatures from 69° to 133°C and pressures from 390 to 425 bars.

The water sampled prior to renewed drilling on Leg 83 had occupied the hole for nearly two years since it was last flushed with surface seawater at the end of Leg 70. Despite some contamination by seawater during sampling, the composition of two of these waters has been determined by using nitrate as a tag for the contaminant. Both the 80°C and the 115°C waters have seawater chlorinity but have lost considerable Mg, Na, K, sulfate, and O_2 , and have gained Ca, alkalinity, Si, NH_3 , and H_2S . The loss of sulfate is due to anhydrite precipitation, as indicated by the $\delta^{34}\text{S}$ value of the remaining dissolved sulfate. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio has been lowered to 0.7086 for the 80°C water and 0.7078 for the 115°C water, while the Sr concentration is nearly unchanged. The changes in major element composition relative to seawater are also larger for the 115°C water, indicating that the basement formation water at this site probably varies in composition with depth. Based on their direction relative to seawater, the compositional changes for the 80° and 115°C waters do not complement the changes inferred for the altered rocks from Hole 504B, suggesting that the bulk composition of the altered rocks, like their mineralogy, is largely unrelated to the present thermal and alteration regime in the hole.

The exact nature of the reacted seawaters cannot yet be determined. During its two-year residence in the hole, the surface seawater left there at the end of Leg 70 would have reacted with the wall rocks and exchanged with their interstitial formation waters by diffusion and possibly convection. How far these processes have proceeded is not yet certain, although calculations suggest that diffusion alone could have largely exchanged the two waters. The $\delta^{18}\text{O}$ of the samples is indistinguishable from seawater, however, and the $\Delta^{14}\text{C}$ of the

80°C sample is similar to that of ocean bottom water. While the interpretation of these species is ambiguous, that of tritium should not be. Tritium analyses, which are in progress, should clarify the nature of the reacted seawaters obtained from the hole.

In press: Initial Reports of the Deep Sea Drilling Project, Vol. 83.

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WHOI Contribution No. 5577.

**CaCO₃ SOLUBILITY IN MARINE SEDIMENTS:
EVIDENCE FOR EQUILIBRIUM AND
NON-EQUILIBRIUM BEHAVIOR**

F. L. Sayles

Studies of the ion concentration product (ICP) $[Ca^{2+}] \times [CO_3^{2-}]$ in the pore waters of marine sediments have been carried out using in situ sampling techniques. For sediments near the sediment-water interface the ICP of the pore waters is indistinguishable from that predicted from laboratory studies of calcite solubility at 1 atm. The pressure dependence of calcite solubility is also consistent with laboratory studies.

At depths greater than ten to fifteen cm enhanced solubility is almost always seen. In some instances ICP gradients occur in the upper 15 cm. The ICP increases indicate that calcite solubility cannot be adequately described by a single thermodynamic equilibrium constant.

In press: *Geochimica et Cosmochimica Acta*.

Supported by: NSF Grant OCE81-24447.

WHOI Contribution No. 5652.

**THE DISTRIBUTION OF ^{239,240}Pu, ¹³⁷Cs,
AND ⁵⁵Fe IN CONTINENTAL MARGIN SEDIMENTS:
RELATION TO SEDIMENTARY REDOX ENVIRONMENT**

F. L. Sayles and H. D. Livingston

A series of sediments from the East and West Coasts of the U.S. have been analyzed for fallout nuclides in conjunction with redox-sensitive parameters in the pore waters of the sediments. Depth distributions show correlation with redox conditions. In particular, depths of penetration of Pu, ¹³⁷Cs and ⁵⁵Fe are greater under more oxidized conditions than in reduced sediment. Modelling of distributions indicates that in a number of sediments dispersion of nuclides at depth is enhanced above that pertaining to the uppermost 2-5

cm of sediment. Comparison of ^{239,240}Pu with ²¹⁰Pb indicates that migration of Pu independent of particle mixing occurs. Modelling of distributions indicates that the occurrence of enhanced migration at depth (below 2-5 cm) may be widespread. A simple model of the migration of a small soluble fraction of the sedimenting nuclides produces distributions consistent with those observed in the sediments.

In press: *Wastes in the Ocean Series*, Vol. 8.

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WHOI Contribution No. 5755.

**HOTSPOT-MIGRATING RIDGE INTERACTION
IN THE SOUTH ATLANTIC**

J.-G. Schilling, G. Thompson,
R. Kingsley and S. Humphris

We report here that short wavelength geochemical anomalies in the basaltic layer 2A occur along the South Atlantic mid-ocean ridge opposite Ascension, St. Helena and Tristan hotspots. This provides further evidence that preferential subcrustal flow channels develop between mantle upwelling zones (hotspots) and migrating ridge axes. Observed geochemical variability suggests that the plume flow along these channels would be schlieren-like in form rather than continuous.

In press: *Nature*.

Supported by: NSF Grant OCE82-09582.

WHOI Contribution No. 5797.

**HEAT-TRANSFER EXPERIMENT IN MARINE PELAGIC
CLAY: IMPLICATION FOR SUBSEAED DISPOSAL
OF HIGH-LEVEL RADIOACTIVE WASTE AND CONTACT
METAMORPHISM OF SEDIMENTS IN THE GUAYMAS
BASIN, GULF OF CALIFORNIA**

W. E. Seyfried, Jr. and F. L. Sayles

A heat transfer experiment has been conducted in marine pelagic clay to provide data to model geomechanical and geochemical properties of seabed sediment exposed to a relatively large thermal gradient and seafloor pressure. This experiment entailed emplacement of a resistance-type heat source in the center of a tank of sediment (1 m³) from the central North Pacific and overlain by a reservoir (2 m³) of artificial seawater. The system was pressurized to 500

bars. Pore fluid samples extracted from sediment at 5° to 150°C and samples of sediment altered at temperatures from approximately 30° to 270°C yield information on mass transport and sediment alteration processes.

Sediment alteration in the vicinity of the heat source caused an increase in sediment shear strength, water and Na₂O contents, and formation of hydrated analcime at the expense of kaolinite and quartz. This so-called "baked" zone consisted of sediments altered at temperatures >170°C. The high Na₂O contents of baked-zone sediments require additions of Na⁺ in amounts exceeding that available in pore fluid alone and suggest convective circulation of sea-salt solution along the relatively permeable boundary between the sediment and the heat probe. Quartz dissolution and removal of SiO₂ by convectively circulating sea-salt solution, moreover, played an important role in microcrack extension and permeability enhancement in the baked zone itself. Mineralogic and chemical changes in baked zone sediment provide useful insight into the mechanism of alteration of hemipelagic sediments in contact with dolerite sills in the Guaymas Basin, Gulf of California.

Sediment exposed to temperatures <170°C remained unconsolidated even though important mineralogic and chemical changes occurred. Sediments from the highest temperature portion of this zone contained chlorite and calcite (?) and had lost Na and K-rich phases. In situ sampled pore fluids were characterized by distinct compositional gradients including a large decrease in Na⁺, Cl⁻, Mg⁺⁺, Ca⁺⁺ and SO₄⁼ concentrations with increasing temperature. These changes are consistent with thermomass transport (so-called Soret effect) and rock-water interaction. Cl⁻ was the only component to respond only to thermal diffusion and correspondingly was unaffected by rock-water interaction. That a Cl⁻ flux reflective of convection near the heat source was not apparent from the pore-fluid chemistry of unconsolidated zone sediment suggests that mass transport from the baked zone to the unconsolidated zone was insignificant.

Application of results from the heat transfer experiment to the subseabed disposal concept shows that thermal diffusion will dominate near field mass transport provided sediments remain relatively unconsolidated and impermeable and are not affected by convection. Assuming convection does not occur, or if it does, is localized and closed to recharge pathways, pH at temperatures >250°C will most probably be mildly acidic. The redox intensity (fO₂) will be constrained by sediment chemistry and mineralogy.

In press: Chemical Geology.

Supported by: Sandia National
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WHOI Contribution No. 5800.

PERIDOTITES FROM THE MID-ATLANTIC RIDGE AT 43°N AND THEIR PETROGENETIC RELATION TO ABYSSAL THOLEIITES

Tsugio Shibata and Geoffrey Thompson

Whole-rock, major and trace element analyses and microprobe mineral analyses were conducted on the serpentinized peridotites recovered from the walls of the MAR (Mid-Atlantic Ridge) 43°N fracture zone. These peridotites are extensively serpentinized; serpentine usually makes up 30-100 vol.% of the bulk rocks. The relict minerals observed consist mainly of olivine and orthopyroxene with subordinate amounts of clinopyroxene and brown spinel. The range in olivine composition is very limited (Fo₉₁₋₉₂). Orthopyroxene forms large, anhedral crystals with clinopyroxene exsolution lamellae and shows undulose extinction with banded cleavages and lamellae. Broad beam microprobe analyses indicate that the composition range of orthopyroxene is also limited (En_{89.1-87.6} Fs_{8.2-8.0} Wo_{2.7-4.4}; Al₂O₃=1.82-2.64 wt%; Cr₂O₃=0.63-0.88 wt%). Clinopyroxene tends to fringe large orthopyroxene crystals or fills the interstices between them. The Mg/Fe ratios of clinopyroxene are practically constant; however, the Ca/(Ca+Mg+Fe) ratios range from 0.48 to 0.45. The Cr/(Cr+Al) and Mg/(Mg+Fe²⁺) ratios of brown spinel ranges from 0.57 to 0.36 and 0.69 to 0.56, respectively. The geothermometers utilizing coexisting spinel lherzolite mineral assemblages suggest that the MAR 43°N peridotites attained equilibrium at temperatures from 1100° to 1250°C.

The peridotites recovered from the ocean floor are generally considered to have been subjected to partial melting processes and regarded as residues left after primary magma was removed. Major element chemistry of the MAR 43°N peridotites are compared with those of the ocean floor ultramafic tectonites reported previously and used together with those published data to demonstrate that the major element abundances of the ocean floor peridotites define an average trend which is compatible with removal of primary magma from these peridotites at moderate pressures (10-15kb). Then, the most primitive abyssal tholeiite glasses could be produced by ca. 10% olivine fractionation of such primary magma. Extensive fractionation of olivine and/or orthopyroxene from picritic liquids which are in equilibrium with the lherzolitic or harzburgitic mantle sources at higher pressures (>20kb) could not yield the majority of the most primitive abyssal tholeiite glasses.

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WHOI Contribution No. 5840.

MIGRATION OF C₁-C₈ HYDROCARBONS IN MARINE SEDIMENTS

Jean K. Whelan, John M. Hunt, John Jasper
and Alain Huc

Light hydrocarbon (C₁-C₈) profiles are compared for three wells of varying maturities: two immature DSDP wells (Site 397 near the Canary Islands and site 530A near the Walvis Ridge in the Southeast Atlantic) and a mature well, the East Cameron well in the Texas Gulf Coast. Primary migration of C₁ and C₂ appear to be occurring in all of the sedimentary rocks examined. Primary migration of C₃+ components becomes important only as fine-grained sedimentary rocks enter the catagenetic hydrocarbon generation zone or over short distances in more permeable sections. Lateral migration along bedding planes was more important than vertical migration in sedimentary rocks of all maturities. The lightest (methane, ethane, and propane gases) hydrocarbons show greater fractionation than do the C₄-C₈ alkanes which generally show minimal fractionation during the migrational process. Subsurface diffusion coefficients for these ppb quantities of C₂-C₅ alkanes from immature sediments from DSDP site 530 are estimated to be several orders of magnitude less than values reported in the literature for diffusion of much larger amounts of these compounds from mature water wet sediments into air or sandstones. Since our calculations suggest light hydrocarbons are present in amounts less than their reported solubilities in pure water at 25°C, we postulate that the sediment organic matter has a substantial effect on retarding the movement of these light hydrocarbons.

In press: Organic Geochemistry.

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and DoE Contract EG-77-02-4392.

WHOI Contribution No. 5634.

PHOTOCHEMISTRY OF NATURAL WATERS

O. C. Zafiriou, J. Joussot-Dubien,
R. G. Zepp and R. G. Zika

Many compounds and environments are affected by sunlight-induced photochemistry.

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Technology, 18, 12, 358A-371A.

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RADIOCHEMISTRY

A PORE WATER STUDY OF PLUTONIUM IN A SEASONALLY ANOXIC LAKE

Ken O. Buesseler, Gaboury J. Benoit
and Edward R. Sholkovitz

Data are presented here on the distribution and seasonal variability of ^{239,240}Pu in the pore waters of a seasonally anoxic lake. The pore water ^{239,240}Pu profile exhibits a strong subsurface activity maximum of 230±30 μBq/kg in the 3-6 cm interval in June. This is in contrast to the overlying water ^{239,240}Pu activity of 5±3 μBq/kg. The pore water ^{239,240}Pu profile in June appears to follow the solid phase distribution pattern of ^{239,240}Pu and also the pore water distributions of Fe and Mn. Under more reducing conditions in August, pore water ^{239,240}Pu drops off to undetectable levels at all depths in the sediments. We feel that this rapid change in the pore water ^{239,240}Pu activity reflects the dynamic nature of Pu diagenesis in these sediments. Potential diffusional fluxes of ^{239,240}Pu into the lake's hypolimnion in June are calculated to be on the order of 2.5 μBq/cm²yr. This flux would not be significant in altering the solid phase ^{239,240}Pu inventory (2.8×10⁴ μBq/cm²), but may be responsible for ^{239,240}Pu enrichments in the anoxic hypolimnion of lakes, such as seen by Sholkovitz et al. at this site.

In press: Journal of Environmental
Radioactivity.

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83ER60172.

WHOI Contribution No. 5604.

RADIOCESIUM AND OTHER NUCLIDES IN THE NORWEGIAN-GREENLAND SEAS 1981-1982

Susan A. Casso and Hugh D. Livingston

This report contains data obtained from measurements of various artificial radio-tracers in seawater samples from the Norwegian-Greenland Seas and adjacent seas during 1981-82. The radionuclides measured include ¹³⁷Cs, ¹³⁴Cs, ⁹⁰Sr, and ³H. The sampling and analytical work result from the efforts of several laboratories, viz. Deutsches Hydrographisches Institut,

Germany; Ministry of Agriculture, Fisheries and Food (Fisheries Laboratory), U.K.; Riso National Laboratory, Denmark; University of Miami Tritium Laboratory, USA; and Woods Hole Oceanographic Institution, USA.

The data set includes a large number of measurements in surface water in the region and a substantial number of vertical profiles in the various water masses. The radiotracers in the region originate from nuclear fallout from atmospheric nuclear weapons tests and from low level releases of liquid waste to European coastal waters in association with the reprocessing of nuclear fuel. The data represent a comprehensive series of measurements suitable for gaining new insight in respect to the rates and routes of the regional circulation and to the dispersal pattern of pollutants introduced to European shelf waters.

Supported by: NSF Grants OCE83-00491 and OCE84-02849.

WHOI Technical Report 84-40.

RADIOMETRIC DETERMINATION OF THE GROWTH RATE OF Nautilus IN NATURE

J. Kirk Cochran and Neil H. Landman

Nautilus is the sole surviving genus of externally shelled cephalopods and, therefore, determination of its rate of growth is important for understanding the life histories of a host of related fossil forms. However, because direct observations of its growth rate are difficult, we have used naturally occurring radionuclides. We employed the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio as a chronometer to estimate the growth rates of seven specimens of Nautilus belauensis Saunders. Our analyses have shown that in three immature animals the age of the last septum ranged from 10-52 days and, based on the age difference between the last two septa, the rate of septal formation ranged from >120-~230 days. In four animals near or at maturity the age of the last septum ranged from 110-240 days and the rate of septal formation ranged from 100->290 days. Based on these rates the time to maturity is >10 years. Rates of septal formation translate approximately into rates of <0.12 and <0.08 mm of ventral circumference/day for immature and mature animals respectively and agree well with mark-recapture observations of this species in Palau.

In press: Nature.

Supported by: National Geographic Society Grant No. 2526-82.

WHOI Contribution No. 5589.

WOODS HOLE OCEANOGRAPHIC INSTITUTION RADIOCARBON LABORATORY: SAMPLE TREATMENT AND GAS PREPARATION

Ellen R. M. Druffel and Sheila M. Griffin

This paper presents the methodology used for sample preparation at the Woods Hole Oceanographic Institution Radiocarbon Laboratory. The WHOI lab is dedicated to oceanographic research supported for the most part by the National Science Foundation. The methods used for the production of samples are based on those developed previously. Subsequent changes and refinements to these methods are described. Also presented are detailed descriptions of how various samples are collected and sectioned, then converted to CO_2 and to C_2H_2 , the primary counting gas used for most of the samples.

In press: Radiocarbon.

Supported by: NSF Grants OCE83-15260 and OCE81-11954.

WHOI Contribution No. 5787.

VERTICAL PROFILE OF ARTIFICIAL RADIONUCLIDE CONCENTRATIONS IN THE CENTRAL ARCTIC OCEAN

H. D. Livingston, S. L. Kupferman,
V. T. Bowen and R. M. Moore

The artificial radionuclides ^{90}Sr , ^{137}Cs , ^{238}Pu , $^{239,240}\text{Pu}$, and ^{241}Am have been measured in eight water samples collected in 1979, at intervals from surface to bottom, through the ice at the LOREX satellite camp SS near the North Pole. Differences in the concentrations and ratios of these nuclides compared with values measured over time in the various water masses that flow into the Arctic Ocean, can be used as semi-independent checks on rates of flow to the LOREX stations and on residence times in the Arctic Ocean. An unexpected finding was that water labelled with low-level liquid waste from the Wind-scale plant on the Irish Sea is a major component of the 1500 m LOREX sample and has reached there in no more than eight to ten years. Even from this one station in the Polar Ocean, estimation of the inventories of the various radionuclides is good enough to emphasize the importance of horizontal advection of the various supply terms to the Arctic.

In press: Geochimica et Cosmochimica Acta, 48, 2195-2203.

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WHOI Contribution No. 5704.

ARTIFICIAL RADIONUCLIDE TRACER SUPPLY
TO THE DENMARK STRAIT OVERFLOW
BETWEEN 1972 AND 1981

Hugh D. Livingston, James H. Swift
and H. Gote Östlund

Measurements of the concentrations of the artificial radionuclides ^3H , ^{137}Cs , and ^{90}Sr in the northern Irminger Sea in 1972 and 1981 are reported. The sampling location was south of Denmark Strait and the stations were occupied there during the GEOSECS cruise in 1972 and the Transient Tracers in Oceanography/North Atlantic Study (TTO/NAS) in 1981. In both years, tracer measurements from this area included data from samples of the dense overflow water from the north through Denmark Strait. The data, set in context of the observed hydrographical regimes, are discussed in terms of the historical input of these radio-tracers to the Norwegian/Greenland Sea and of the current understanding of the regional circulation and water mass definition.

In both 1972 and 1981, all three tracers were strongly correlated inversely with salinity in the dense outflows -- the tracer maxima being related directly to the salinity minimum. When the tracer characteristics in the outflows in 1972 and 1981 were compared, concentrations of all in 1981 were observed to be about double the 1972 values. The individual tracer concentrations -- on a decay corrected, density normalized basis -- were higher in increasing order ^{90}Sr (+93%) < ^3H (+111%) < ^{137}Cs (+139%). The relatively greater increases for ^3H and ^{137}Cs were attributed to contributions of new sources of these tracers in northern surface waters. The ^3H source is argued to derive from atmospheric hydrological recycling, whereas the ^{137}Cs source is identified as the input to the Norwegian/Greenland Seas of advected European nuclear fuel reprocessing wastes.

Both the tracer and hydrographic data are used to identify northern locations of intermediate water formation capable of supplying the observed dense overflow water properties. It is argued from the time taken for the overflow water to reflect the new surface ^{137}Cs source that transport is quite rapid (>2 years).

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and OCE79-25889.

WHOI Contribution No. 5698.

REMOVAL OF BIAS FROM THE SELECTION OF
SAMPLES OF MATERIAL FOR CHEMICAL ANALYSIS

Donald C. Bankston

To insure that analytical results provide sufficient information, an analyst must apply the statistical theory of sampling. From a given population, the analyst draws a sample, calculates some statistics to describe it, and draws inferences about their corresponding population parameters.

A population may have either one or more than one set of descriptive parameters. In the former case, the population is classified as homogeneous; in the latter case, as heterogeneous.

Populations encountered in experimental design are usually heterogeneous. The investigator always tries to segregate a heterogeneous sample into subdivisions, or strata, each of which represents a homogeneous population.

A sample is considered representative of a population, by standards that differ according to the goals of the sampling process, which must include either: 1) estimating the mean and/or variance of the population or 2) approximating expected values for the population as accurately and economically as possible.

Published in: American Laboratory,
16, 43.

Supported by: NSF Grant OCE81-19056.

WHOI Contribution No. 5687.

AN AUTOMATED CRYOGENIC CHARCOAL TRAP
SYSTEM FOR HELIUM ISOTOPE
MASS SPECTROMETRY

D. E. Lott and W. J. Jenkins

An automated sea water sample processing line employing a two stage activated charcoal trap system cooled by a closed cycle helium refrigerator is described. All dissolved gases except neon and helium are adsorbed on the first stage operating at 55°K with neon and helium quantitatively adsorbed on the second stage at 10°K. The second stage trap is heated to 40°K to release virtually 100% of the helium isotopes (^3He , ^4He) for mass spectrometer measurement followed by heating to 70°K to release the neon component. Performance data for helium isotope measurements on sea water samples and

air standards ($^4\text{He} \sim 10^{-6}\text{cm}^3(\text{STP})$ and $^3\text{He} \sim 10^{-12}\text{cm}^3(\text{STP})$) are presented.

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Instruments, 55, 1982-1988.

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WHOI Contribution No. 5736.

DEPARTMENT OF GEOLOGY AND GEOPHYSICS

Richard P. Von Herzen, Department Chairman

DEPARTMENT OF REVENUE AND FINANCE
Richard F. Van Nieuwen, Department Director

G E O L O G Y

RECENT SEA LEVELS FROM TIDE GAUGES: PROBLEMS AND PROGNOSIS

D.G. Aubrey

Changes in relative sea level play an important role in human affairs, with future increased importance if the anticipated global warming due to higher levels of atmospheric carbon dioxide causes significant melting of ice sheets. Throughout geologic history, relative sea level has been changing, encompassing a full spectrum of space and time scales. The rich spectra complicate the unraveling of recent relative sea-level trends, making prediction a complex task. Recent studies are helping to define the space and time scales of relative sea-level rise of the past century over the world's oceans, separating regional patterns of relative sea level from global patterns, using tide gauge records. We will test the hypothesis that rate of eustatic sea-level rise is increasing, or will increase in the near future, as a result of thermal expansion and addition of glacial meltwaters. Because of the non-uniform distribution of sea-level observations in both space and time, new statistical techniques beyond simple regressions have been developed and applied, resulting in definition of space and time scales of change with appropriate error estimates.

In press: National Research Council,
National Academy of Science.

Supported by: Coastal Research Center;
NOAA Sea Grant NA83-AA-D-00049
(R/B-54) and NA80-AA-D-0077
(R/B-54).

WHOI Contribution No. 5845.

RELATIVE SEA LEVELS OF JAPAN FROM TIDE-GAUGE RECORDS

D.G. Aubrey and K.O. Emery

We attempted to separate tectonic, oceanographic, and eustatic components of change in relative sea levels derived from the many tide-gauge records of Japan acquired over the past fifty years. A modified eigenanalysis was introduced to permit use of station data having unequal lengths. Both regression analysis and eigenanalysis reveal systematic spatial differences in relative sea-level rise that reach about 20 mm/year. This is far

too much to be solely eustatic in origin, but the data are insufficient to permit accurate separation of tectonic and eustatic effects on relative sea levels. The low-frequency patterns (periods longer than 50 years) are those expected from subduction of the Pacific and Philippine plates beneath Japan. Higher frequencies (12-, 6-, and 2-year periods) are correlated with oceanographic factors such as shifts in the position of the Kuroshio. The contours of relative change in sea levels provide convincing evidence that neither a single nor several Japanese tide-gauges can be selected to authentically denote present or past eustatic sea level rise.

Supported by: NOAA Sea Grants NA80-AA-D-00077 (R/B-54) and NA83-AA-D-00049 (R/B-54); Coastal Research Center; and Ocean Industry Program.

WHOI Contribution No. 5816.

NORTHWESTERN EUROPEAN PALEOGENE MAGNETO-BIOSTRATIGRAPHY AND PALEOGEOGRAPHY: CALCAREOUS NANNOFOSSIL EVIDENCE

Marie-Pierre Aubry

Calcareous nannofossil biostratigraphy allows correlations between the Paleogene chronostratigraphic units of northwestern Europe and the standard calcareous nannofossil biozones. Such biostratigraphic correlations allow interpretation of the paleogeography of northwestern Europe during the Paleogene and evaluation of the influence of global sea-level (eustatic) changes on NW European stratigraphy. A well-documented unconformity occurs near the lower/middle Eocene boundary in the Paris Basin. This unconformity, which also can be traced in the London-Hampshire Basin and in Belgium, correlates with a presumed sea-level event of Vail et al. (1977). On the basis of magnetobio-stratigraphic correlations, the duration of the hiatus associated with this unconformity can be estimated at about 0.6-1.5 my in the Hampshire Basin and at 2 to 4 my in the Paris Basin.

In press: Geology.

Supported by: A consortium of oil companies.

WHOI Contribution No. 5843.

MAGNETO- AND CALCAREOUS NANNOFOSSIL
STRATIGRAPHY OF THE LOWER PALAEOGENE
OF THE HAMPSHIRE-LONDON BASIN

M-P. Aubry, E.A. Hailwood
and H.A. Townsend

In recent years the development of integrated magneto-biostratigraphy has become a strong tool in regional stratigraphic correlation and has resulted in significant improvements to the geological time-scale. Associations between biostratigraphic events and geomagnetic polarity reversal sequences have been documented in deep sea sediment cores and in bathyal deposits exposed in land sections. Correlation of these polarity reversals with the sequence of marine magnetic anomalies has facilitated the development of magneto-biostratigraphic time scales in which successive geological stages and/or biostratigraphic zones, are related to corresponding marine magnetic anomalies. This provides a basic stratigraphic framework in which biostratigraphic data can be used to 'calibrate' magnetic polarity zones ('magneto-zones') observed in discontinuous sedimentary sequences, in terms of the appropriate marine magnetic anomaly or magnetic chron. Once properly identified, these magneto-zones and, in particular, their upper or lower boundaries can often provide much tighter stratigraphic constraints on the sequence under study.

In press: Nature.

Supported by: A consortium of oil companies.

WHOI Contribution No. 5844.

THE PLIO/PLEISTOCENE BOUNDARY
IN DEEP SEA SEDIMENTS

W.A. Berggren and Lloyd Burckle

Recent studies suggest that the Pliocene/Pleistocene boundary (as stratotyped in the Vrica section in the Croton-Sparticento basin, SW Italy) is situated a short distance above the Olduvai chron with an estimated age of ca. 1.6-1.65 Ma. In deep sea sediments this level may be recognized and correlated on a global basis by means of biostratigraphic events (FADs, LADs, abundance changes) in calcareous and siliceous plankton, stable isotope stratigraphy, and carbonate stratigraphy. The Pliocene/Pleistocene boundary is slightly subsequent to the FAD of Globorotalia truncatulinoides and the LAD of Discoaster brouweri (and its triradiate varieties). It is within an (isotopic) interglacial

interval, within the carbonate minimum (M15) just above the pronounced minimum (M17) at the top of the Olduvai Event, and within the interval of low carbonate values corresponding to oxygen isotope stage "Mb" of Gardner (1982).

In press: Paleogeography, Paleoclimatology and Paleoecology, Spec. Vol. Elsevier Publishing Company.

Supported by: American Geological Institute.

WHOI Contribution No. 5675.

SEISMIC STRATIGRAPHY OF THE OCEANIC
MOHO BASED ON OPHIOLITE MODELS

Thomas M. Brocher, Jeffrey A. Karson
and John A. Collins

Synthetic seismograms which model vertical incidence seismic reflections from the oceanic MOHO were calculated from detailed laterally-varying, velocity-depth models of several ophiolite complexes. The synthetics reproduce the rapid lateral variability of waveforms, amplitudes, and two-way travel times of reflections from the oceanic MOHO which are observed in existing MCS data. The large variations observed in the synthetics were caused solely by the complexity of the geologic structure along the crust/mantle boundary because focusing/defocusing of seismic energy by the upper crustal units were not modeled. The petrologic contrast producing the strongest reflector from the oceanic crust/mantle transition is highly variable so it is difficult to identify what particular MOHO reflections represent geologically, although with broad-band data velocity gradients may be distinguished from laminated zones. More important, however, is our finding that the seismic refraction oceanic MOHO and the seismic reflection oceanic MOHO usually do not coincide, and that either or both may cross major geologic contacts.

In press: Geology.

Supported by: NSF Grants EAR80-26445, EAR83-9535 and OCE80-25206.

WHOI Contribution No. 5672.

GEOMORPHOLOGY, SHALLOW STRUCTURE AND
GEOLOGICAL HAZARDS IN THE EAST CHINA SEA

Jorge Butenko, John D. Milliman
and Ye Yincin

The inner shelf of the East China Sea is covered with a lens of fine-grained modern sediment derived from the adjacent Chang-jiang; modern sediments north of the Chang-jiang came from the Huangho. Rapid accumulation results in a featureless seafloor, except where escaping biogenic gases cause vents. The modern mud thins towards the mid-shelf and sediment becomes increasingly sandy and locally rippled, indicative of its relict age and present-day mixing and transport. The outer shelf, particularly south of Cheju Island, is covered with fine-grained sediment that apparently reflects modern Huangho-derived sedimentation.

Shallow seismic profiles show that the Holocene sediment overlies an eroded late Pleistocene surface, dominated by a number of well-defined buried river channels formed (and filled) during the last low stand of sea level; some channels may be associated with recent faulting. These filled channels and depressions probably represent the single most important geological hazard for future emplacement of man-made structures (such as drilling platforms) on the seabed. Other potential hazards include methane gas vents on the inner shelf, possible vents of deeper gas on the mid-shelf, outcrops or near-surface expressions of the Fukien-Reinan Massif, and possibly migrating sand waves.

In press: Continental Shelf Research.

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WHOI Contribution No. 5646.

METAMORPHISM IN THE BAY OF ISLANDS OPHIOLITE COMPLEX

J.A. Karson, D.L. Elthon,
J.F. Casey and M. Titus

Deformation and metamorphism occur in several distinct geological settings within the Bay of Islands Ophiolite Complex of western Newfoundland. Detailed studies of the internal structure of the ophiolite provide a geometric framework within which these metamorphic assemblages may be related to specific tectonic events. At least five metamorphic assemblages are present and are distinguished on the basis of: a) relative age determined by cross-cutting field relationships; b) style of recrystallization relative to deformation; c) assemblage of metamorphic facies present; d) protolith(s); and e) distribution of metamorphic rocks and implied thermal gradients with respect to the ophiolite structure.

In order of formation, the five assemblages are related to: 1) high-temperature, solid-state, anhydrous deformation of residual upper mantle and some cumulate rocks during mantle upwelling and spreading; 2) static hydrothermal metamorphism and extensional tectonics in the upper crustal units during seafloor spreading; 3) asymmetric deformation and metamorphism across a steeply dipping shear zone that transects the ophiolite allochthon and was produced by transform faulting; 4) thrust faulting and metamorphism forming a basal metamorphic aureole during obduction of the ophiolite; and 5) late static serpentinization of the ultramafic units after obduction and transportation.

In press: Ophiolite. Special Volume of Proceedings of 1983 Annual Meeting, Florence.

Supported by: NSF Grants EAR80-26445 and EAR83-09535.

WHOI Contribution No. 5647.

DEFORMED AND METAMORPHOSED OCEANIC CRUST ON THE MID-ATLANTIC RIDGE

J.A. Karson and H.J.B. Dick

Highly deformed and metamorphosed gabbroic rocks were collected during detailed mapping of a portion of the median valley wall of the Mid-Atlantic Ridge at 24°N with a camera sled and the manned submersible ALVIN. The area investigated occurs at the lithosphere plate corner bounded by the MAR and the transform segment of the Kane Fracture Zone. Steep, ridge-parallel (NS) faults and fissures were observed in the neovolcanic zone of the median valley, but at the margins of the valley, steep normal fault scarps up to ~150 m high expose mainly subvolcanic lithologic units. The basaltic carapace has apparently been stripped away by back-tilting, mass wasting and erosion. The subvolcanic rocks are mainly metadiabases and metagabbros and are cut by numerous faults and shear zones that are spaced at intervals of a few centimeters to a few meters and that dip toward the spreading axis at 30 to 70 degrees. These inclined shear zones have down-dip lineations and slickensides indicating normal fault displacements. Some vertical transform-parallel (EW) faults and antithetic (west-dipping) normal faults were also observed. The assemblage of basement structures may be interpreted as the result of low-angle slip on the soles of listric normal faults that flatten beneath the median valley floor or as the result of slip during progressive tilting

of planar faults prior to their uplift, truncation, and exposure along steep active faults of the median valley walls.

Rocks recovered from between the fault zones are fresh to slightly fractured and veined gabbros and minor diabbases. Rocks from the faults and shear zones include a wide variety of cataclastites, mylonites, and amphibolites with petrographic evidence of recurrent tectonic deformation and hydrothermal alteration. Relatively lower temperature vein fillings occur in fractures cutting the deformation fabrics. Talus derived from volcanic and plutonic rocks locally overlies the faulted rocks.

This study suggests that obducted oceanic crust from such a setting will not necessarily have a complete ophiolite stratigraphy. In this setting we expect a relatively thin crustal section in which the volcanics would be very thin and locally absent; sheeted dikes would be highly fractured and possibly absent; much of the gabbroic section would be pervasively deformed and metamorphosed; and underlying peridotites would occur at shallow levels (<2 km) and might be subject to early serpentinization along fault zones. A variable thickness of breccias with clasts of basalt, diabase, gabbro, and possibly serpentinite would cap this sequence. Despite the proximity to a transform fault, there would be little evidence of strike-slip deformation. This type of structure probably forms due to extensive crustal extension in an area with very little magmatism during seafloor spreading.

In press: Ophiolite. Special Volume of Proceedings of 1983 Annual Meeting.

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WHOI Contribution No. 5648.

PROPERTIES OF SUSPENDED SEDIMENT OVER THE HEBBLE AREA ON THE NOVA SCOTIAN RISE

I.N. McCave

Twenty samples from 20, 40, 250, and 1000 m above bottom were analyzed by Coulter Counter for size using three overlapping tubes giving a size range of 1.59 to 296 μm . The principal features are a fine mode in the region 2-8 μm and a coarser one between 20 and 60 μm . Aperture shear was probably responsible for lack of particles counted over 100 μm . Log-log cumulative particle number distributions are mainly wavy or curved but have segments (particularly 1.6 to 10 μm) with a slope approaching -3 signifying equal

particle volumes in logarithmic size grades. If waviness and coarse-end truncation are ignored there is a rough overall fit to -3 in many cases. The samples were also filtered to determine weight concentration and examined by scanning electron microscope. Aggregates were common in most samples, particularly with associated mucus. Blobs and strings of mucus were common with and without particles. Apparent density of particles a) increases with overall concentration but b) decreases with increasing concentration when only larger particles are included. This probably reflects a) aggregation during aging of a suspension and b) presence of more mucus in larger coarse mode populations.

In press: Marine Geology (Special HEBBLE Volume).

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5671.

ANALYSIS OF A LONGITUDINAL RIPPLE FROM THE NOVA SCOTIAN CONTINENTAL RISE

I.N. McCave, C.D. Hollister,
D.J. DeMaster, C.A. Nittrouer,
A.J. Silva and J.Y. Yingst

A longitudinal ripple was obtained in a box core taken from the Nova Scotian Continental Rise in July 1982. Soft brown mud comprising 1.5 to 10% sand, ~60% silt and ~35% of <2 μm clay forms the 5 cm high and ~40 cm wide ripple. A maximum thickness of 8 cm of this mud under the crest, thinning to 2 cm on the ripple's flank, overlies stiff muddy foram ooze. The vane shear strength of the brown mud is ~0.4 kPa whereas that of the ooze is ~4 kPa. X-radiographs show the mud to contain many fine burrows and a few larger ones as well as winnowed horizons rich in foraminifera of both benthonic and planktonic origin. Gentle wet sieving of the sand fraction on board ship showed the sand fraction to contain very few faecal pellets. Thus it appears unlikely that bedload movement played a large part in formation of the ripple. Rapid initial deposition from a concentrated suspension is suggested to have formed the structure, but this was followed by periods of erosion to yield winnowed horizons and further rebuilding with material deposited from suspension. Radiochemical data (^{234}Th and ^{210}Pb) and X-radiographs suggest rapid particle mixing ($D_b \sim 90 \text{ cm}^2 \text{ yr}^{-1}$) and rapid sediment deposition ($\sim 1.5 \text{ cm month}^{-1}$). Thus it is possible that the bedform (and

associated structures) are destroyed and recreated on a time-scale of a few months.

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82-C-0019.

WHOI Contribution No. 5613.

OLIGOCENE GLACIO-EUSTACY AND EROSION ON THE MARGINS OF THE NORTH ATLANTIC

Kenneth G. Miller, Gregory S. Mountain
and Brian E. Tucholke

Oxygen isotopic studies of Oligocene foraminifera provide evidence for the development of significant continental ice (= inferred glacio-eustatic sea-level lowstands) at ca. 35-36 Ma, 28-31 Ma, and 24-25 Ma. Biostratigraphic analyses of continental margin boreholes and wells from the east coast of the U.S. and the Irish continental margin reveal a consistent chronostratigraphic pattern, with upper Oligocene sediments lying above a diachronous erosional surface. In the most complete record, upper Oligocene (Zone P21a) overlies lower Oligocene strata (*Pseudohastigerina micra* Zone), constraining the hiatus to ca. 30 and 34 Ma. We speculate that erosion during a glacio-eustatic sea-level fall near the early/late Oligocene boundary (in Zone P21a; ca. 31-32 Ma) developed an unconformity on these margins of the North Atlantic. These events may correlate with the "middle" Oligocene event noted by Vail et al. (1977). Using oxygen isotopic data, we are able to apply a model for eustatic sea level change and margin response that explains the relationships of sea level, unconformities, and coastal onlap events of the "Vail curve."

In press: Geology.

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C-0019.

WHOI Contribution No. 5673.

THE NORTHERN RED SEA: CONTINENTAL RIFTING AND SALT TECTONICS

Elazar Uchupi and David A. Ross

The Red Sea can be divided into at least five provinces having various styles of tectonic activity (from rifting to incipient spreading to actual spreading). These provinces are further subdivided into 10-50 km long cells by fracture zones. The

transition of these tectonic provinces from south to north along the Red Sea may reflect the evolution of spreading in this relatively young oceanic basin.

Multichannel seismic reflection profiles recorded in the Red Sea northern rift segment show that the structure in this region is due to plastic flow of latest Miocene salt. We believe that the evaporites rest on attenuated continental crust and that the flow is due either to sediment loading or to faulting in the basement. No evidence of oceanic crust is shown on any of the profiles.

In press: American Association of
Petroleum Geologists Bulletin.

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0003.

WHOI Contribution No. 5861.

G E O P H Y S I C S

GRAVITY FIELD OF VENUS AT CONSTANT ALTITUDE AND COMPARISON WITH EARTH

Carl Bowin, Geoffrey Abers
and Loren Shure

The acceleration (gravity) anomaly estimates by spacecraft tracking, determined from Doppler residuals, are components of the gravity field directed along the spacecraft-earth line-of-sight (LOS). These data constitute a random set of vector components of a planet's gravity field, depending upon where the earth happened to be at the time of the measurement, and they are at varying altitudes above the planet surface. We have solved for the gravity field using the method of harmonic splines which imposes a smoothness criterion to select a gravity model compatible with the LOS data. Maps of geoid and gravity at spacecraft and at constant altitudes are presented for the planet Venus. For Venus, the major geoid and gravity anomalies each coincide with the locations of positive topographic features. These anomalies at 300 km altitude have significantly greater magnitude than anomalies that are on earth coincident with topographic features. Another striking difference is that most of the major geoid anomalies on the earth do not coincide with locations of its largest topographic features, including continents, but may be due to deep sources.

On Venus, major mass anomalies appear to be restricted principally to the surficial 200 km of the planet. The substantially thicker crust on Venus, compared to the earth's explains its greater range of gravity anomaly and the positive correlation of gravity anomaly with topographic height. Four regions with high gravity to topography response functions are interpreted to be due to crustal loading by recent volcanism.

In press: Proceedings of 15th Lunar and Planetary Science Conference to be published by Journal of Geophysical Research.

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WHOI Contribution No. 5643.

RESIDUAL GEOID ANOMALIES IN ATLANTIC OCEAN BASIN: RELATIONSHIP TO MANTLE PLUMES

Carl Bowin, Geoffrey Thompson and J.G. Schilling

The relations of geoid data from radar altimeter measurements (GEOS-3) to water depth and geochemical variations along the Mid-Atlantic Ridge are investigated. Eight geophysical lines across the ridge in the Atlantic Ocean were constructed approximately normal to the local ridge trend. Slopes of geoid per kilometer of topographic relief show an asymmetry between the two sides of the ridge that generally is not matched by topography, which has better symmetry between the two flanks. Subtracting a regional field, based on previous work, produces residual geoid anomalies whose source must be in the earth's outer 600 km. The residual geoid anomalies of the North Atlantic show striking correlation with the axis of the Mid-Atlantic Ridge, but those in the South Atlantic do not. Instead, major positive residual geoid anomalies appear over the Rio Grande and Walvis Ridges. Determination of slope, S , residual geoid per million years crustal age, reveals that S increases with greater residual geoid anomaly with higher (shallower) crestal ridge topography. The slope of 0.27 m/Ma over the Azores high suggests that the anomalously high crestal residual geoid and depth anomalies are not of thermal origin, which normally appears to produce slopes of about 0.9 m/Ma. Correlation of residual geoid anomalies with depth, geochemical variations along the length of the Mid-Atlantic ridge and the chemistry of the Rio Grande Rise and Walvis Ridge suggest that the regions of anomalous residual geoid and crestal depth values are largely a

function of crustal thickness and density variations induced by plume volcanism.

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WHOI Contribution No. 5614.

ANOMALOUSLY THIN CRUST IN OCEANIC FRACTURE ZONES: NEW SEISMIC CONSTRAINTS FROM THE KANE FRACTURE ZONE

Marie-Helene Cormier, Robert S. Detrick and G. Michael Purdy

Three detailed and carefully positioned seismic refraction experiments have recently been carried out along the Kane fracture zone near 24°N, 44°W in order to place better geophysical constraints on the extent and origin of the anomalously thin crust reported from parts of this and other large Atlantic fracture zones. These three experiments, when combined with earlier studies, result in reversed structural control along about a 300 km long segment of the Kane fracture zone extending from the ridge-transform intersection out onto crust about 25 Myr old. An analysis of refraction lines obtained along the fracture zone trough using both travel time modeling and delay time function techniques reveal large variations in crustal thickness and/or velocity. However, along most of the eastern fracture zone trough, upper mantle-type velocities are found at depths of only 2 to 3 km below the sea floor, less than half the typical depth to Moho in the ocean basins. This anomalous fracture zone crust is generally characterized by unusually low compressional wave velocities, relatively high velocity gradients throughout most of the thinned crustal section (about 1 to 2 s-1) and a distinct crust-mantle boundary. The very thin crust appears to be confined to the deepest parts of the Kane fracture zone trough (<10 km wide), although a more gradual crustal thinning may extend up to several tens of kilometers from the fracture zone. A specially designed delay time experiment at the intersection of the Kane fracture zone and Mid-Atlantic Ridge also revealed the presence of a thinned crustal section of a relatively uniform thickness (about 3 km), except beneath the nodal basin where the crust may be less than one kilometer thick. The anomalous crust in the intersection area appears to extend at least part way down the median valley. We interpret this anomalous fracture zone crust as a primary accretionary feature

that forms as a result of a restricted magma supply near ridge-transform intersections, although tectonic processes may also play a part, at least locally, in thinning the crust. Our results support a "ribbon" model of the gross seismic structure of the ocean basins in which bands of relatively homogeneous, so-called normal crust 50-100 km wide extend away from spreading centers, each formed at a discrete ridge crest segment and each separated by the thin crust underlying the fracture zone trough.

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WHOI Contribution No. 5747.

HEAT FLOW IN THE BALEARIC AND TYRRHENIAN BASINS, WESTERN MEDITERRANEAN

I. Hutchison, R. P. Von Herzen, K. E. Loudon, J. G. Sclater and J. Jemsek

We present the results of three detailed heat flow surveys which are used to investigate the variations of heat flow and age of the Balearic and Tyrrhenian basins in the Western Mediterranean. Analysis of 12 measurements within a 10 km radius from 40°01'N, 4°55'E in the Balearic abyssal plain show a mean heat flow of $92 \pm 10 \text{ mWm}^{-2}$. After correction for the effects of sedimentation, this value agrees well with the predictions of plate cooling and high extension stretching models for crust of the late Oligocene age proposed for the basin. A similar survey with 18 measurements around 40°16'N, 11°19'E in the Western Tyrrhenian gives a flux of $134 \pm 8 \text{ mWm}^{-2}$, while the third survey of 26 measurements in the southern Tyrrhenian abyssal plain at 37°17'N, 12°58'E yields a slightly higher heat flow of $151 \pm 10 \text{ mWm}^{-2}$. These values are within the range predicted by simple plate cooling models for the late Miocene ages of the deep Tyrrhenian basin. Thus, our observations suggest that although the mode of crustal formation of these deep marginal basins is less well defined than that of the major ocean basins, the thermal signature is similar. Also, the trend of increasing heat flow from west to east through the Balearic and Tyrrhenian basins is in agreement with models of the formation of the Western Mediterranean behind an eastwardly migrating trench system. In all three areas, the measured flux shows significant local variability. In the two westernmost surveys, this can be attributed to the presence of buried, high conductivity salt structures, but in the third area

(S.E. Tyrrhenian) the magnitude of the variations is several times greater than can be attributed to steady-state thermal refraction alone. Instead, evidence exists for localised hydrothermal activity linked to the small topographical relief within the survey area.

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WHOI Contribution No. 5745.

COSTA RICA RIFT BOREHOLE SEISMIC EXPERIMENT, DSDP HOLE 504B

S. A. Little and R. A. Stephen

An Oblique Seismic Experiment (OSE) was carried out down DSDP Hole 504B, located south of the Costa Rica Rift (crustal age: 6my).

A velocity-depth function with upper crustal velocities of greater than 4 km/s was determined using linear travel-time inversion, forward modelling and amplitude analysis. Considerable lateral variability in shallow upper crustal seismic velocity and thus rock porosity is suggested by the misfit between forward models of the sonic logging results obtained on leg 83 and the data obtained from this OSE.

Travel-time analysis of this data set reveals the presence of horizontal anisotropy of magnitude 4-4.8 km/s with the higher velocity in the east-west direction, parallel to the ridge axis, and the lower velocity north-south, perpendicular to the ridge axis. Large scale fractures with preferred orientation probably cause the seismic anisotropy.

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WHOI Contribution No. 5779.

MESOZOIC AND CENOZOIC GEOLOGY OF THE U.S. ATLANTIC CONTINENTAL SLOPE AND RISE

Gregory S. Mountain and Brian E. Tucholke

We have studied single-channel and multi-channel seismic reflection profiles to identify and trace key reflecting horizons and seismic sequences from the North American Basin into the U.S. Atlantic continental rise and slope. Using seismic facies analyses and isopach maps of seismic

sequences together with available borehole data, we interpret the geologic history of the continental margin seaward of the shelf break. This area has a complex geologic record because deposition was controlled by interaction of a variety of sedimentary processes. These processes had their origins in both shallow-water (e.g. sea-level) and deep-ocean (e.g. abyssal-current) impulses. Unfortunately, our interpretations are constrained by bore-hole data only along the continental slope and the lowermost continental rise. Until the necessary samples are recovered in intervening areas, this report serves as a preliminary analysis.

From the time of initial sea-floor spreading in the Middle Jurassic until the end of the Eocene, the sedimentary record was shaped principally by cross-slope processes such as turbidity currents and debris flows. The sedimentary prism that formed along the margin in the Middle Jurassic probably was carbonate-rich and it had a relatively uniform thickness with respect to the strike of the adjacent continental hinge zone. It is not clear whether the margin was a carbonate ramp or had a fringing reef. In contrast, by Late Jurassic time a shelf-edge reef was present and it controlled seaward dispersal of sediment. Abyssal fans formed at the foot of the continental slope below gaps in the reef trend, notably seaward of Baltimore Canyon Trough and northeast of the Blake Plateau Basin. Extensive construction of fans occurred throughout the Early Cretaceous as segments of the reef gradually died or were overstepped by prograding shelf sediments. Seismic reflection profiles show cut-and-fill structures and presumably coarse-grained channel fill within the abyssal fans, but boreholes have sampled only the distal, fine-grained edges of these deposits. The boreholes do show the dominant effect of deep-ocean processes on the outermost margin, namely a sharp rise in the calcite compensation depth at the end of the Neocomian with subsequent deposition of carbon-rich black shales beneath intermittently anoxic bottom water. During the Late Cretaceous the basin again became oxygenated and high eustatic sea level caused flooding of the shelf. This restricted offshore transport of sediment, and a conformable drape facies was deposited across most of the continental rise. In the Paleocene and especially during the Eocene, seaward transport of sediment in turbidity currents reached its zenith. High productivity in surface waters, shelf erosion during sea-level lowstands, and rapid sediment accumulation on the continental slope all contributed to mass wasting that carried sediments up to 1100 km across the broad continental rise and into the

deep basin.

The dominance of cross-slope sedimentation processes was dramatically curtailed at the beginning of the Oligocene. Global cooling and the opening of the Greenland Sea to the Arctic Ocean allowed cool, strongly circulating bottom water to enter the North Atlantic at this time. The abyssal western boundary current that was formed along the U.S. margin deeply eroded the continental rise and oversteepened the continental slope. Current speeds probably decreased during the Oligocene. However, the flow remained swift enough that the only sediment retained on the continental rise accumulated from large mass movements off the slope and during a period of accelerated shelf erosion caused by a major sea-level lowstand in the mid-Oligocene (29 Ma). In the early to middle Miocene bottom-current speeds decreased further, the Gulf Stream swept sediment off the Blake Plateau, and a large clastic wedge prograded across the shelf of Baltimore Canyon Trough. These factors led to rapid deposition that formed the cores of the Blake Outer Ridge and another large sediment drift (Chesapeake Drift) beneath the upper continental rise off New Jersey. These drifts continued to develop under the influence of gradually decreasing current speeds during the late Miocene and Pliocene. At the same time, growth of two secondary sediment drifts, the Hatteras and Bahama Outer Ridges, was accelerated and very well developed sediment waves were formed there. The trend of generally decreasing bottom-current speeds was interrupted by short pulses of intense deep circulation in the late middle Miocene (12 Ma) and the late Pliocene (3 Ma). These erosional pulses locally truncated beds on the flanks of sediment drifts, and they formed recognizable seismic boundaries (reflectors Merlin and Blue, respectively) between seismic sequences. The pulses are primarily responsible for modern seafloor outcrops of Miocene and Pliocene sediments in ridge-flank locations. When northern hemisphere glaciation began in the late Pliocene (3 Ma), down-slope sedimentary processes again assumed an important role, particularly by incising submarine canyons and channels into the continental slope and rise. The Quaternary sedimentary record has been shaped under the combined influence of these downslope processes and of contour-following bottom currents.

In press: Geologic Evolution of the U.S. Atlantic Margin. C.W. Poag, ed. Van Nostrand Reinhold, Stroudsburg, PA.

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WHOI Contribution No. 5608.

GRAVITATIONAL AND MAGNETIC FIELDS OF SOME SIMPLE SOLIDS OF REVOLUTION

Robert L. Parker and Loren Shure

Exact spherical harmonic expansions are given for calculating the gravitational and magnetic fields associated with certain uniform solids of revolution. The figures are those made by rotating a conic section about one of its principal axes. The coefficients in the expansions can be computed accurately and efficiently and this approach leads to a very satisfactory method for calculating the fields of geological bodies with approximate circular symmetry about a vertical axis. A complete theory of convergence is given for the expansions. Somewhat unexpectedly, the sphere of convergence is determined by the location of a number of equivalent point or line sources that lie within the body or on its edges.

In press: Geophys. Journal of Roy. Astron. Soc.

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WHOI Contribution No. 5690.

DEVELOPMENT OF NEW TECHNIQUES: DEEP SEISMIC STUDIES BY REFRACTION METHODS

G.M. Purdy

Since the early sixties a revolution has occurred in the methods of both acquisition and interpretation of seismic refraction and reflection data in the world's oceans. The discipline has shifted from purely exploratory efforts almost exclusively to the solution of tightly defined process oriented problems. Whereas twenty years ago the community's data collection capability was limited by technology, now the extent to which we can use seismology to probe the earth's interior is restricted only by our data processing and interpretation methods. New data collection and interpretation techniques have most frequently been developed independently of one another, progress being made in a set of apparently unrelated steps with first the technology of acquisition restricting the quality of the experiments and then the capabilities for processing and interpretation limiting the information that can

be extracted from the data. This interesting chronology requires too much detail to be described in this brief review. The primary goal here will be to describe the four or five landmarks in each of data interpretation and data collection development during the last twenty years.

In press: Geological Geophysical Atlas of the Atlantic and Pacific Oceans.

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WHOI Contribution No. 5792.

SEISMIC STRUCTURE OF THE OCEAN CRUST

G.M. Purdy and J.I. Ewing

This paper will emphasize the evaluation of the resolving power of existing seismic data in the Western Atlantic Ocean and will compare this evaluation with the scale of the local and regional variations in crustal structure predicted by reasonable geological models. We shall not focus attention on the relationship between the seismic and petrological structure of the crust and will use the terms Layer 2, Layer 3 and Moho only in their true seismic sense. Layer 2 is a region of high velocity gradients (perhaps as high as 3 s^{-1} at its upper surface), with velocities in the range 3 to 6.5 km/s that extends from the seafloor to depths of 2-3 km. (We neglect sediments in this chapter restricting ourselves only to the igneous crustal column.) Layer 3 is typically about 4 km in thickness, has velocities of 6.7 to 7.2 km/s, and is characterized by low velocity gradients generally less than 0.1 s^{-1} . The Mohorovicic discontinuity ('Moho') is actually a transition zone which varies in thickness from a few hundred meters (or less) to 1-2 km and is almost always the most prominent seismic characteristic of the ocean crust. Velocities increase by about 1 km/s across this transition to the typical values of about 8 km/s found in the upper mantle. The uppermost 5-10 kilometers of oceanic upper mantle can be defined as a homogeneous (but sometimes recognizably anisotropic) region with velocities within a few tenths of a kilometer per second of 8 km/s, and low velocity gradients that are certainly less than 0.1 s^{-1} and are perhaps negative in some locations.

The way forward in studies of the oceanic crust now lies with substantial experiments or sets of experiments of widely differing scales designed specifically to test and refine models of formational and

evolutionary processes. The days of exploration have essentially passed and sufficient knowledge and understanding have been gained so that reasonably detailed hypotheses can be posed and tested. Such is not the case for the sub-crustal lithosphere. Our knowledge of the structure of the upper several tens of kilometers of the earth's mantle is extremely poor. As it is the interaction between lithospheric plates and not only the thin crustal skin that shapes the major features of the earth's surface, then ignorance of this structure is especially serious. This is an area where exploration is needed; a critical mass of data needs to be collected and structural interpretations determined before substantial progress can be made.

Studies of the crust and upper mantle cannot be separated from those of mid-ocean ridges, fracture zones and continental margins. They constitute a single system with processes and controlling variables that are intimately interwoven. There can be no complete understanding of one without the understanding of the whole. Research in the future should be balanced in its progress to optimize the cross flow of ideas and understanding between studies of ridges, fracture zones, margins and the oceanic lithosphere.

In press: G.S.A. DNAG Synthesis.

Supported by: ONR Contract N00014-82-C-0019 and NSF Grants OCE79-24174 and OCE80-25206.

WHOI Contribution No. 5730.

A PRELIMINARY HARMONIC SPLINE MODEL FROM MAGSAT DATA

L. Shure, R.L. Parker and R.A. Langel

We present a preliminary main field model for 1980 derived from a carefully selected subset of Magsat vector measurements using the method of harmonic splines. This model is the smoothest model (in the sense that the rms radial field at the core surface is minimum) consistent with the measurements (with an rms misfit of 10 nT to account for crustal and external fields as well as noise in the measurement procedure). Therefore the harmonic spline model is more suitable for studies of the core than models derived with the traditional least-squares approach (e.g. GSFC (9/80)). We compare characteristics of the harmonic spline spectrum topology of the core field and especially the null-flux curves (loci where the radial field is zero) and the flux through patches bounded by such

curves. The harmonic spline model is less complex than GSFC (9/80) and is therefore more representative of that part of the core field that the data constrain.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5847.

THE DIRECT WAVE ROOT IN MARINE SEISMOLOGY

R. A. Stephen and S.T. Bolmer

The "direct wave root" is an evanescent wave which is observed below the sea floor when the direct water wave is incident on the sea floor from above at super-critical angles. For shallow borehole receivers it is the largest amplitude arrival on large offset seismograms. The wave has been studied and observed in electromagnetics and acoustics but this paper is the first report of the "direct wave root" in marine seismology.

Theoretically, an expression for the "direct wave root" can be obtained from a branch line integral in the complex ray parameter plane for the transmission problem between two acoustic half-spaces. Synthetic seismogram analysis based on the discrete wavenumber (or reflectivity) method can be applied to study the more realistic cases of elastic bottom gradients beneath the sea floor and intrinsic attenuation. Steep gradients below the sea floor gave amplitude-depth relations which are not exponential. Attenuation ($Q=40$) affects amplitudes less than 1 dB.

Observations of the "direct wave root" have been made at the Deep Sea Drilling Project Site 504B in the Costa Rica Rift area and the observed properties are consistent with theory. It is proposed that more detailed measurements of the decay of the direct wave root amplitude with depth can be used to obtain high resolution measurements of upper crustal elastic properties at seismic frequencies.

In press: Bulletin of the Seismological Society of America.

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WHOI Contribution No. 5713.

R.A. Stephen, F.K. Duennebieer
and D.R. Bellows

This report describes a test of a wireline re-entry system designed to emplace packages into holes on the seafloor without the use of drill pipe. In this initial test, no re-entry was attempted, but a passive sled with an acoustic beacon and side scan sonar was lowered to 3000 m below the surface and its tracking capability was monitored. The test is unique from other bottom package experiments because the drill ship was able to remain stationary within a 100 m radius during the experiment. The results are thus applicable to a "hovering" rather than a "towing" mode. The conclusions are that: 1) the bottom package remained within 100 m of the ship's position; 2) bottom package motion lags the ship's motion by 10 to 15 minutes; and 3) controlling the bottom package position to within 3.0 m (the accuracy required for re-entry) was not possible by maneuvering the ship alone. It appears necessary to have propulsion on the bottom package.

In press: DSDP Initial Reports,
Volume 88.

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WHOI Contribution No. 5781.

MICROEARTHQUAKE BENEATH THE MEDIAN VALLEY
OF THE MID-ATLANTIC RIDGE NEAR 23 N:
HYPOCENTERS AND FOCAL MECHANISMS

Douglas R. Toomey, Sean C. Solomon,
G.M. Purdy and Mark H. Murray

We report hypocenters and focal mechanisms of microearthquakes located by an ocean-bottom seismic network deployed in the median valley of the Mid-Atlantic Ridge near 23°N during a three-week period in early 1982. The network consisted of 7 ocean-bottom hydrophones and 3 three-component ocean-bottom seismometers. The instrument coordinates were acoustically determined to within 25 m at the one-standard-deviation level of confidence. The hypocentral parameters of the 26 largest microearthquakes are reported; 18 of these events have epicenters and focal depths which are resolvable to within ±1 km at the 95% confidence level. Microearthquakes occur beneath the inner floor of the median valley and have focal depths generally between 5 and 8 km beneath the sea floor. Composite fault plane solutions for two spatially related groups of microearthquakes beneath the inner floor

indicate normal faulting along fault planes that dip at angles of 30° or more; these solutions are similar to the mechanisms of nearby large earthquakes. Microearthquakes also occur beneath the steep eastern inner rift mountains. The rift mountain earthquakes have nominal focal depths of 5 to 7 km and epicenters as distant as 10 to 15 km from the center of the median valley, but these hypocenters have larger uncertainties because of the possible effects of large topographic relief and associated lateral heterogeneity in velocity structure. We interpret the depth distribution and source mechanisms of these microearthquakes to indicate that this segment of ridge axis is undergoing active extension and has been cooled to temperature within the brittle field of behavior to a depth of at least 7-8 km.

In press: Journal of Geophysical
Research.

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WHOI Contribution No. 5836.

TESTING MODELS OF CONTINENTAL RIFTING
AND EXTENSION: THE LIGURIAN BASIN
(W. MEDITERRANEAN)

R. Von Herzen, J.-P. Rehault, J. Jemsek,
D. L. Williams and J. Sclater

Evidence suggests that the western Mediterranean basin was formed in recent geological time (20-30 Ma) as a result of rifting of adjacent continental blocks. Detailed investigations of the relationships between structured and thermal and tectonic history of such basins and their adjacent margins can provide the data needed to improve models of the rifting process. New corrected heat flow values in the Ligurian basin, with a systematic spatial variation ranging between about 70 to 150 mWm⁻² support a simple model of substantial lithospheric thinning, including creation of oceanic crust, beginning about 21 Ma.

Supported by: NSF Grants OCE80-24287
and OCE80-25181.

WHOI Contribution No. 5761.

A MECHANISM FOR MAGMATIC ACCRETION
UNDER SPREADING CENTERS

J.A. Whitehead, Jr., H.J.B. Dick
and H. Schouten

Laboratory model experiments, fluid dynamical considerations, and geological and geophysical observations of mid-ocean spreading centers, are consistent with a three-dimensional gravitational instability (a modified Rayleigh-Taylor instability) occurring in the zone of partial melt formation beneath the sea-floor spreading axis.

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1984.

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Systems, W.H.O.I.

WHOI Contribution No. 5668.

P A L E O C E A N O G R A P H Y

THE EOCENE/OLIGOCENE EVENT
IN THE DEEP SEA

Bruce H. Corliss, Marie-Pierre Aubry,
William A. Berggren, Julianne M. Fenner,
Lloyd D. Keigwin, Jr. and Gerta Keller

Analysis of middle Eocene to early Oligocene calcareous and siliceous microfossils shows gradual biotic changes with no massive extinction event across the Eocene/Oligocene boundary. The mid-Paleogene biotic changes are suggested to reflect changing paleoclimatic and paleoceanographic conditions and do not support previous interpretations of a catastrophic biotic event caused by a bolide impact event at the Eocene/Oligocene boundary.

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WHOI Contribution No. 5612.

STABLE ISOTOPIC RESULTS ON UPPER
MIOCENE AND LOWER PLIOCENE FORAMINIFERA
FROM SITE 552A

Lloyd D. Keigwin, Jr.

This report summarizes preliminary stable isotopic results on benthic and

planktonic foraminifera from the Upper Miocene and Lower Pliocene sections of DSDP Site 552A. Stratigraphically higher in the section at Site 552A (middle Pliocene-Pleistocene), Shackleton (this volume) has provided considerable isotopic detail. Grazzini (this volume) has results from lower in the section (upper Eocene to Middle Miocene). Study of this site was undertaken as part of a general study of Neogene stable isotopic change in open ocean North Atlantic sites. Blanc et al. (1980) published results from the only previous North Atlantic location, DSDP Site 116. Other studies concentrated on the isotopic records from marginal seas (Gulf of Mexico, Brunner and Keigwin, 1981; Caribbean, Keigwin, 1982; Mediterranean Sea, Keigwin and Thunell, 1979) or from nearshore locations (Continental Margin off W. Africa, Shackleton and Cita, 1979). Results from Blanc et al. (1980) reveal general trends in Neogene isotopic history of the North Atlantic, but since Site 116 was only spot-cored, detailed study of specific isotopic features is difficult.

Within Upper Miocene and Lower Pliocene sections of other DSDP sections, previous studies have revealed changes in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of foraminifera which may have resulted from changing oceanographic or climatic conditions. For example, Kennett et al (1979) noted small $\delta^{18}\text{O}$ changes in Pliocene sediments of ~3.5 m.y. age and in latest Miocene sediments at southwest Pacific DSDP Site 284. Several increases and decreases of ~0.5‰ in $\delta^{18}\text{O}$ were found in Upper Miocene sediments at eastern equatorial Pacific DSDP Site 158 (Keigwin, 1979), and an enrichment in ^{18}O of planktonic foraminifera at DSDP 502 was thought to be the result of an increase in Caribbean salinity in the early Pliocene (Keigwin, 1982). A decrease in $\delta^{13}\text{C}$ of latest Miocene foraminifera has been found throughout the Indo-Pacific region (for example, Keigwin, 1979; Bender and Keigwin, 1979; Vincent et al., 1980) but has not yet been clearly identified in open ocean North Atlantic sediments.

It is important to know if these Late Miocene and Early Pliocene isotopic events are local, basin-wide, or ocean-wide in extent. Site 552A was sampled at coarse intervals (on the order of meters, equal to time-spacing of hundreds of thousands of years) to determine the general nature of oxygen and carbon isotopic variation in foraminifera for comparison with other locations. The results of this preliminary study are being used as a framework for a detailed study now in progress.

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WHOI Contribution No. 5602.

CARBON ISOTOPES IN DEEP-SEA BENTHIC
FORAMINIFERA: PRECESSION AND CHANGES IN
LOW-LATITUDE BIOMASS

Lloyd D. Keigwin and Edward A. Boyle

Detailed carbon isotope records have been obtained from benthic foraminifera in the North Atlantic (CHN 82 Sta 24 Core 4PC, 42°N, 32°W, 3427 m, 244 kyr) and central Equatorial Pacific (KNR 73 Sta 4 Core 3PC, 0°S, 106°W, 3606 m, 410 kyr). These data demonstrate that the North Atlantic site has always been nutrient-depleted relative to the Pacific site. Although down-core carbon isotope data in the Atlantic and Pacific reflect changes in deep-ocean circulation patterns, a larger fraction of $\delta^{13}\text{C}$ variability in both oceans is due to changes in the inventory of continent-reduced carbon. The magnitude of this carbon isotope biomass signal is nearly twice as large during oxygen isotope stages 4 and 6 as it is during stage 2. Carbon isotope variability in both oceans contains significant power at the 23 kyr frequency band which is coherent with insolation changes caused by precession of the earth's rotational axis. We propose that this correlation is due to orbitally-driven variations in low-latitude biomass and that the lower amplitude of the carbon isotope signal during the last 60 kyr is due to the reduction in precession parameter amplitude during this period.

In press: Natural Variations in CO_2
and the Carbon Cycle, AGU Series.

Supported by: NSF Grant OCE82-17644.

WHOI Contribution No. 5837.

P A L E O N T O L O G Y

NEOGENE BENTHIC FORAMINIFERA OF THE
HATTON-ROCKALL BASIN

Paul E. Belanger and William A. Berggren

A quantitative analysis is presented of the benthic foraminifera from twenty-five samples from the Miocene and Pliocene section of DSDP Site 116 (eastern margin of the Hatton-Rockall Basin in the northeast Atlantic). Taxonomic turnover was gradual; however, abundance changes (dominance) are more dramatic. Results show that this

major abundance change of assemblages to modern taxonomically dominated assemblages occurred in the early middle Miocene. This change appears to be associated with major stabler isotopic changes documented at this time and suggests a benthic foraminiferal response to a major reorganization of oceanic circulation. The causes of subsequent assemblage dominance fluctuations are more ambiguous; an increase in the Uvigerina fauna in the early Pliocene can be associated with more negative $\delta^{13}\text{C}$ values and a decreased contrast in $\delta^{13}\text{C}$ between the Atlantic and Pacific, possibly indicative of reduced circulation in that part of the Atlantic.

In press: Micropaleontology.

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WHOI Contribution No. 5746.

MICROHABITATS OF BENTHIC FORAMINIFERA
WITHIN DEEP-SEA SEDIMENTS

Bruce H. Corliss

Analysis of living (stained) benthic foraminifera within the upper 15 cm of deep-sea sediments reveals vertical stratification of four dominant species with species-specific microhabitat preferences. Hoeglundina elegans, Cibicidoides kullenbergi, Oridorsalis tener and Planulina wuellerstorfi are found in the 0-1 cm interval and are suggested to have epifaunal habitats, whereas Melonis barleeanum, found within the 1-6 cm interval, and Chilostomella oolina and Globobulimina affinis, found from 6-15 cm, are suggested to have infaunal habitats. The epifaunal species have plano-convex or biconvex shapes with surface pores absent or present only on the umbilical side, in contrast to infaunal species which are rounded or cylinder-shaped with pores found evenly distributed over the entire test. The morphological features of the infaunal species are suggested to be adaptations to low-oxygen conditions within the sediments. The existence of infaunal habitats indicates that certain foraminifera may not be directly controlled by overlying bottom-water conditions, but by physical-chemical conditions within the sediment. The microhabitats of the individual species may also explain interspecific carbon isotopic differences, since existing carbon isotopic data show that species with infaunal microhabitats generally have lighter carbon isotopic values than epifaunal species.

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WHOI Contribution No. 5729.

EVIDENCE FOR CONTROL OF ABYSSAL
AGGLUTINATED FORAMINIFERAL COMMUNITY
STRUCTURE BY SUBSTRATE DISTURBANCE:
RESULTS FROM THE HEBBLE AREA

Michael A. Kaminski

Deep-sea agglutinated foraminifera have been quantitatively examined from 28 core-top samples from 7 box cores collected in June 1983 at the HEBBLE (High Energy Benthic Boundary Layer Experiment) Site [40°27'N, 62°20'W, 4815-4825 m depth] and HEBBLE Shallow Site [40°53'N, 63°44'W, 4185 m depth] on the Nova Scotian lower continental rise.

Samples from the relatively tranquil HEBBLE Shallow Site can be distinguished from the HEBBLE Site on the basis of their microfauna. A Q-mode VARIMAX factor analysis of species-frequency data delineates 3 major faunal assemblages: (1) A faunal assemblage dominated by *Ammobaculites* sp. cf. *A. americanus*, with 2 species of *Reophax* being of secondary importance. This assemblage exhibits lowest species diversity (suggesting a disturbed community) and is found in one box core from the northern corner of the HEBBLE Site containing fine-grained, laminated sediments with high water content; (2) An assemblage associated with remaining box cores from the HEBBLE Site (HEBBLE Meadow) dominated by *Saccammina tubulata*, *Psammosphaera* sp. cf. *P. fusca* and a coarse-grained species of *Psammosphaera* with subdominant *Recurvoides contortus*; and (3) An assemblage occurring at the HEBBLE Shallow Site (BC-01), dominated by *Hormosinella distans* and *Reophax* sp., with *Reophax bacillaris* and *Ammobaculites agglutinans* being unique to the assemblage. This fauna displays a higher ratio of calcareous/agglutinated species, significantly higher species diversity, lower variability and a greater proportion of hormosinids and fine-grained species than samples from the HEBBLE Site, which reflects the stability of the physical environment in accordance with the Stability-Time Hypothesis.

Marked heterogeneity exists among agglutinated foraminiferal assemblages within box cores. At the HEBBLE Meadow, within-box core faunal variability exceeds between-box core variability, suggesting that environmental factors influencing the distribution of species are patchy on a scale of approximately 40 cm.

In press: Journal of Marine Geology.

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WHOI Contribution No. 5600.

SPECIES FORMATION THROUGH PUNCTUATED
GRADUALISM IN PLANKTONIC FORAMINIFERA

Bjorn A. Malmgren, William A. Berggren
and G.P. Lohmann

Detailed analysis of evolutionary changes in a 10-million-year long Late Neogene lineage of planktonic foraminifera has revealed a pattern that is not consistent with either the gradualistic or the punctuational model of evolution. The lineage was in stasis over a considerable part of its total duration but underwent relatively rapid, but not geologically instantaneous, gradual morphologic change that did not lead to lineage splitting. The term "punctuated gradualism" is suggested for this evolutionary modality.

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and OCE82-14930.

WHOI Contribution No. 5815.

OLIGOCENE-MIOCENE BIOSTRATIGRAPHY,
MAGNETOSTRATIGRAPHY, AND ISOTOPIC
STRATIGRAPHY OF THE WESTERN NORTH ATLANTIC

Kenneth G. Miller, Marie-Pierre Aubry,
M.J. Khan, A.J. Melillo, D.V. Kent and
William A. Berggren

Magnetostratigraphic records from western North Atlantic Deep Sea Drilling Project (DSDP) Sites 563 and 558 are correlated with the geomagnetic polarity time scale (GPTS; Berggren et al., 1984a,b) using marine magnetic anomalies and selected biostratigraphic datum levels. The magneto-chronology established is used to make direct magnetobiostratigraphic correlations which agree with previous Oligocene-early Miocene studies. However, we show that Zones NN8 partim and NN9 and associated Epoch 11 correlate with Magnetic Anomaly 5 (= Chron C5n). This contrasts with previous indirect correlations of Epoch 11 with Anomaly 5A and requires an upward adjustment of 1.5-2.0 m.y. for middle-late Miocene calcareous nannofossil zones. We correlate the middle-late Miocene boundary with Zone NN8 and earliest Chron C5n (10.4 Ma).

In press: Geology.

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and OCE83-00356.

WHOI Contribution No. 5850.

P E T R O L O G Y

MINERALOGIC VARIABILITY OF THE UPPERMOST MANTLE ALONG MID-OCEAN RIDGES

Henry J.B. Dick, Robert L. Fisher
and Wilfred B. Bryan

Modal analyses of 273 different peridotites representing 43 dredge stations in the Atlantic, Caribbean, and Indian Oceans define 3 separate melting trends. Peridotites dredged in the vicinity of "mantle plumes" or hot spots have the most depleted compositions in terms of basaltic components, while peridotites dredged at locations removed from such regions are systematically less depleted. The modal data correlate well with mineral compositions, with the peridotites most depleted in pyroxene also having the most refractory mineral compositions, which would appear to demonstrate that they are the residues of variable degrees of mantle melting. Further, there is a good correlation between the modal compositions of the peridotites and the major element composition of spatially associated dredged basalts. This demonstrates for the first time that the two must be directly related, as is frequently postulated. The high degree of magmatic depletion of the peridotites in the vicinity of so-called mantle plumes provides direct evidence for a thermal anomaly in such regions -- justifying their frequent designation as "hot spots." The high incompatible element concentrations in these basalts are contrary to what is expected for high degrees of melting, and thus require an unusually enriched mantle source or selective contributions from enriched veins and/or a volatile-rich metasomatic front in the upper mantle.

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WHOI Contribution No. 5601.

S E D I M E N T O L O G Y

THE QUANTITATIVE DESCRIPTION OF BEACH CYCLES

David G. Aubrey and Robert M. Ross

A quantitative method is developed to describe sequential changes in beach profile morphology. Dominant cycles in temporal eigenfunctions (computed by empirical eigenfunction analysis and rotary component analysis) are defined and used to construct a sequence of profiles representing the energetic portions of beach cycles. Five sets of beach profile data from Torrey Pines Beach in southern California were analyzed with these techniques. Because the first and second eigenfunctions account for between 65% and 90% of the variability of the data, the beach profiles are accurately described with only these two variables and the mean profile. Using rotary component analysis, beach changes represented by the two dominant eigenfunctions can be separated into many elliptical components, each representing a particular frequency associated with cycles in beach state. Profiles are reconstructed using points from the perimeter (latera recta) of these beach state ellipses.

A frequency of 1 cpy is the most energetic frequency in the first and second eigenfunctions, corresponding to the cyclic onshore-offshore sediment movement associated with 'bar' and 'berm' profiles. Profiles constructed from points on the elliptical path associated with annual cycles graphically depict the sequential development of bar and berm during the beach cycle. Beach cycles corresponding to a frequency of 2 cpy are also significant, primarily due to the energy of the second eigenfunction. No other frequencies are consistently found to be as significant as the annual and semi-annual cycles at this beach. In particular, monthly beach cycles have little energy associated with them.

The method described provides a uniform way to objectively discriminate energetic beach cycles and yields a concise representation for beach modeling and prediction. It should be a valuable tool for uniform, quantitative intercomparison of beaches and beach cycles.

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WHOI Contribution No. 5859.

A STUDY OF NON-LINEAR TIDAL PROPAGATION
IN SHALLOW INLET/ESTUARINE SYSTEMS
PART I: OBSERVATIONS

D.G. Aubrey and P.E. Speer

The offshore tide becomes strongly distorted as it propagates into shallow estuarine systems. Observations of sea surface elevation and horizontal currents over periods ranging from three days to one year at nine stations within Nauset inlet/estuary, document the non-linear interaction of the offshore equilibrium tidal constituents. Despite strong frictional attenuation within the estuary, the overtides and compound tides of M_2 , S_2 and N_2 , in particular, reach significant amplitude, resulting in strong tidal distortion. High frequency forced constituents in sea surface are phase-locked, consistently leading the forcing tides by 60° - 70° , resulting in a persistent distortion such that falling tide is longer than rising tide. Forced constituents in currents are more nearly in phase with equilibrium constituents, producing flood currents which are shorter but more intense than ebb currents. A compound fortnightly tide, MSF, modulates the mean water level such that lowest tides occur during Neap phase instead of Spring phase. This fortnightly tide can be contaminated by storm surge, changing the phase characteristics of this constituent. Implications of the over-tides, compound tides, and lower frequency tides on near-bed and suspended material transport are profound.

In press: Estuarine, Coastal and Shelf Science.

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WHOI Contribution No. 5674.

KINEMATIC AND DYNAMIC ESTIMATES FROM
ELECTROMAGNETIC CURRENT METER DATA

David G. Aubrey and John H. Trowbridge

The dynamic response of spherical electromagnetic current meters has been clarified through a comprehensive laboratory measurement program. Since flow past a spherical body with three-dimensional roughness elements has considerable complexity under various hydrodynamic conditions, a careful laboratory study of current meter response was carried out for

pure steady, pure oscillatory (horizontal plane), and combined steady/oscillatory motion. Preliminary tests were also performed on the effects of free-stream turbulence and biofouling on current meter response. Flowmeter response under pure steady flow in the absence of high levels of free-stream turbulence shows an r.m.s. error of only 1-2 cm/sec, derived from a simple linear regression. Pure oscillatory response shows a sensitivity which not only differs by 5-8% from the pure steady case, but which is strongly correlated with oscillatory Reynolds number and Keulegan-Carpenter number. Combined steady/oscillatory flows result in larger residual errors and significant differences in meter sensitivity compared with either pure steady or pure oscillatory tests. This behavior is interpreted in dynamical terms and qualitatively related to published studies of flow behavior past spherical bodies with varying types of super-imposed roughness. Results from these measurements have been applied to error analyses for several distinct common uses of electromagnetic flowmeter data in the inner continental shelf (including the surf zone). The analysis shows surf zone measurements of currents using electromagnetic current meters to be not generally appropriate for estimation of higher order velocity moments for sediment transport calculations, estimates of near-bed shear stress using logarithmic or eddy correlation techniques, and must be used with care in calculations of directional wave properties.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 5626.

DYNAMIC RESPONSE OF SPHERICAL
ELECTROMAGNETIC CURRENT METERS

David G. Aubrey, John H. Trowbridge
and Wayne D. Spencer

The dynamic response of spherical electromagnetic current meters has been clarified through a comprehensive laboratory measurement program. Studies of current meter response for pure steady, pure oscillatory (horizontal plane), and combined steady/oscillatory motion were carried out. Flow-meter response under pure steady flow and pure oscillatory flow in the absence of high levels of free-stream turbulence shows an r.m.s. error of only 1-5 cm/sec. Com-

bined steady/oscillatory flows result in larger residual errors and significant differences (up to 20%) in meter sensitivity compared with either pure steady or pure oscillatory tests. Horizontal cosine response showed systematic deviations from pure cosine behavior. The analysis shows electromagnetic current meters to be accurate for certain kinematic estimates, but could be erroneous when used to estimate dynamical quantities such as Reynolds stress, bottom friction, and log-layer friction velocities. A careful error analysis must precede any use of the meters for estimating dynamical quantities.

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WHOI Contribution No. 5749.

CARBON DEPOSITION RATES AND DEEP WATER RESIDENCE TIME IN THE EQUATORIAL ATLANTIC OCEAN THROUGHOUT THE LAST 160,000 YEARS

W. B. Curry and G. P. Lohmann

In the deep, silled basins of the equatorial Atlantic Ocean, large changes have occurred in the rates of carbonate production and dissolution, deep water residence time, and rates of organic carbon accumulation over the last 160,000 years. Accumulation of carbonate in shallow, relatively undissolved sediments decreased by one half during glacial maxima, reflecting reduced surface water production of carbonate. The most severe dissolution occurred during stage 4 (64,000 to 75,000 yrs BP) when carbonate accumulation decreased abruptly below 3750 m. Benthic foraminiferal $\delta^{13}\text{C}$ decreased below 3750 m during all glacial maxima, reflecting greater remineralization of organic carbon and reduced dissolved oxygen concentrations below sill depth (~3750 m) within the eastern Atlantic. While the reduced $[\text{O}_2]$ inferred during stage 2 (13,000 to 32,000 yrs BP) can be attributed predominantly to increased residence time of the deep water, the lower $[\text{O}_2]$ during stage 4 resulted largely from increased delivery of organic carbon to the deep eastern basins. No bathymetric gradient in benthic foraminiferal $\delta^{13}\text{C}$ is detectable during stage 5e (115,000 to 125,000 yrs BP), implying that the eastern Atlantic was as well ventilated with deep water during the last interglacial period as it is today. During stages 1 and 5, organic carbon accumulation was constant below 3000 m. During stages 2, 3 and 4, the accumulation of organic carbon increased below 3750 m, reflecting

in part better preservation because of reduced oxygen conditions.

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WHOI Contribution No. 5807.

SEAFLOOR ZONATION IN SEDIMENT TEXTURE ON THE NOVA SCOTIAN LOWER CONTINENTAL RISE

Mavis L. Driscoll, Brian E. Tucholke
and Nick McCave

Grain-size analyses of surface sediment samples from the continental rise below 4000 m off Nova Scotia clearly show a slope-parallel zonation in textural parameters. Zones of sediment with high sand content (>20%) are located between 4800 and 4900 m and below 5000 m. A zone rich in clay (>40%) occurs between 4000 and 4800 m. The silt/clay ratio increases steadily with depth between 4000 and 5100 m. These textural trends suggest predominantly slope-parallel sedimentary processes on the modern sea floor and, conversely, little evidence of downslope processes.

The textural zonations are thought to result from a zonation of bottom currents which are weak at 3500 m but increase regularly to peak speeds greater than 50 cm/sec on the lower rise at 5000 m. The mean position of the northern edge of the Gulf Stream lies across the southern part of the continental rise over the 4600 to 4900 m depth contours. The clay-rich band lies upslope from the Gulf Stream edge beneath a weak to moderate mean abyssal flow toward the southwest. In contrast, the sand rich zone lies beneath the region of stronger mean southwest flow and beneath the 'cold filament' of Weatherly and Kelly (1982). This region is also intermittently occupied by the Gulf Stream, and episodic reinforcement of flow in the mean southwest current by bottom-sensing eddies from the Gulf Stream probably creates intermittent high-velocity currents that account for the coarse surface texture.

In press: Marine Geology.

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WHOI Contribution No. 5738.

THEORETICAL AND OBSERVATIONAL ESTIMATES
OF NEARSHORE BEDLOAD TRANSPORT RATES

M. R. Goud and D. G. Aubrey

Theoretical predictions of net sediment transport rates based solely on asymmetrical tidal flows underestimate transport rates as calculated from migration of sand waves over a 10 year period. The study area is a shallow (<3 m) nearshore region located in Nantucket Sound, Mass., in a region of strong, shore-parallel tidal currents and weak background wave energy. A series of long wave- and crest-length (tens to hundreds of m), low amplitude (tens of cm), shore-normal sand waves migrate 10 to 20 m/year, as measured from vertical aerial photographs. Predicted bedload transport rates, calculated using current velocity measurements with the methods of Bagnold and Meyer-Peter and Muller, are as low as one-sixth the average observed sand wave migration transport rate. Estimates which include the effects of storm-generated surface gravity waves on the transport bring predictions into better agreement with observations. Even in tidally-dominated, protected regions with low background wave energy, infrequent storm events significantly modify sand transport rates and patterns.

In press: Marine Geology.

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WHOI Contribution No. 5669.

OCEANIC PARTICLES AND PELAGIC SEDIMENTS
IN THE WESTERN NORTH ATLANTIC OCEAN

Susumu Honjo

Deep sea sediment is formed by the accumulation of oceanic particles originally generated elsewhere. A large part of oceanic sedimentation is accomplished by biological activities in the overlying surface layers before the particles are advected for long distances. Some lithogenic particles, however, are transported for a long distance from the interior and edge of continents toward the pelagic environment. The transportation pathways of oceanic particles is usually complex, involving biological, chemical, and physical processes. The time necessary to complete such pathways varies from instantaneous to hundreds of years. Not all oceanic particles settle as permanent members of the

deep sea sediment. They are dissolved, decomposed, or may change their properties. Some particles are refractory and increase their relative content in the pelagic sediment as a result of such altering processes through time. The object of this report is: 1) to review the genesis of oceanic particles by listing the variabilities which are known to us, 2) to discuss the pathways and mechanisms of transportation, and 3) to estimate the fate of particles while they are settling and advecting in pelagic ocean-water layers.

In press: DNAG Series.

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WHOI Contribution No. 5664.

STUDY OF OCEAN FLUXES IN TIME AND SPACE
BY BOTTOM-TETHERED SEDIMENT TRAP ARRAYS:
A RECOMMENDATION

Susumu Honjo

In order to produce a predictable model of the linkage between ocean surface productivity and the material flux at the interior of the ocean, it is essential to gather and comprehend numerous oceanic parameters collected in a time series manner. Bottom-tethered, multi-depth ocean flux experiments, applying state-of-the-art automated sediment traps with large apertures and operating on a synchronized time series schedule at Ocean Station P, provided preliminary but crucial information on 1) micro- and meso-cyclicity of ocean fluxes, 2) pathways and general residence time of settling particles, and 3) relationship of fluxes to the oceanographic parameters. Similar results have been gained from the Black Sea and other stations. We believe the technology of bottom-tethered sediment traps is ready for large-scale experiments. Recommendations are made, based upon these on-going programs, to apply this method for the longest possible continuous interannual duration coupled with the shortest possible sampling time-unit in three-dimensional spatial expanse, such as throughout an entire oceanic basin, together with time series assessments of ocean productivity related parameters.

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Study, Proceedings of a Workshop.
National Academy Press,
Washington, D.C., 305-324.

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WHOI Contribution No. 5846.

MICRITIC CEMENT IN MICROBORINGS IS NOT
NECESSARILY A SHALLOW-WATER INDICATOR

James E. Hook, Stjepko Golubic
and John D. Milliman

Intragranular, micritic cement has been observed in microborings from deep sea sedimentary particles (pteropod shells), depths 528 m to 871 m. It is particularly conspicuous in non-depositional environments such as the Blake Plateau. Such cementation may be concurrent and analogous to the formation of intergranular deep sea cement. It can occur at such energy levels where particle-to-particle contacts do not persist for sufficient time to allow intergranular cementation.

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WHOI Contribution No. 5628.

EROSION, TRANSPORT AND DEPOSITION OF
FINE-GRAINED MARINE SEDIMENTS

I.N. McCave

Fine-grained marine sediments are cohesive but their degree of cohesion is not simply determined by grain size. Cohesion controls erodibility and water content, mineralogy, cation exchange capacity, salinity of interstitial and eroding fluid, organic mucus content and Bingham yield strength. All are parameters relating to cohesion that have been proposed. No unique relation to erodibility has emerged and for erosion of slowly deposited sediment, modified by biota, it seems that measures of surface properties such as aggregate strength should be more relevant than bulk properties such as yield strength. The latter may be more appropriate for rapidly deposited estuarine muds. Once eroded, suspended sediment is subject to flocculation and biological aggregation, which alters size and settling velocity distributions, thereby controlling distribution in the flow and rate of deposition. Disaggregation may also occur through turbulent straining of particles, but in most marine situations this will permit stable particles over 1 mm in diameter, though under higher shear close to the bed the upper limit may be 100-200 μm . For deposition where $\tau_0 < 0.1$ Pa the maximum stable aggregate size is probably $\geq \mu\text{m}$. Deposition of fine sediment on smooth beds probably occurs by entrapment in, and settling through, the viscous sublayer. On

rough beds particles are trapped in the interstices between roughness elements. We have only a rough idea of critical deposition conditions but can give a fairly good estimate of deposition rate in given conditions. The longer term net deposition rate as measured by radiometric methods over weeks to months probably owes as much to frequency of erosion as to frequency and rate of deposition and is not yet well predicted from fluid and sediment parameters.

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Deep-sea processes and facies.
D.A.V. Stow and D.J.W. Piper, eds.
Spec. Publication, Royal Geol.
Soc., London, May/June 1984.

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WHOI Contribution No. 5727.

SEDIMENTOLOGY AND STRATIGRAPHY OF
BOX-CORES FROM THE HEBBLE SITE ON
THE NOVA SCOTIAN CONTINENTAL RISE

I.N. McCave

Fifty box cores were obtained from the 2 x 4 km site of the High Energy Benthic Boundary Layer Experiment (HEBBLE) on the lower Nova Scotian continental rise at 4820 m. The oldest unit (occurring in two gravity cores) is a pre-Holocene dark grey gravelly mud, probably of debris flow origin. Above this is a soft grey mud overlain by brown sandy mud whose sand is largely foraminiferal with some terrigenous material from interbedded turbidites. In some places this unit has a stiff brown gravelly mud at its base which is always overlain by sandy mud containing dispersed gravel. It is suggested that the dispersed gravel originated from the underlying gravelly mud and has been dispersed upwards by the action of burrowing organisms. Foraminifera indicate a Holocene age down to about 65 cm and thus a net accumulation rate of about 6 cm ky⁻¹.

The surface unit of brown mud, named the HEBBLE Mud, is spatially variable in both thickness and sand content which average about 4 cm and 6% respectively. Sand percentage is not related to silt size or percentage but varies inversely with deposition rate and thickness, suggesting a relation to local winnowing. The size and peak height of the main silt mode (10-17 μm) are closely correlated and the peak height is inversely related to the percentage of clay. This is attributed to fractionation during deposition of the mud wherein fine silt and clay deposition is

suppressed at flow speeds from 10 to 18 cm s⁻¹ leaving coarser silt. There is more clay on the upstream and downstream sides of a low spur suggesting spatial variation of shear stress that may be due to a standing internal wave added to the mean flow. Silt mode size is variable down core, although clay percentages are similar to those at the surface. The overall silt size is probably controlled by turbidite input, thus silt size is likely to be an unreliable indicator of current speeds down core, though peak height of the silt mode may be satisfactory.

In press: Marine Geology (Special Hebble Volume).

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WHOI Contribution No. 5742.

SEDIMENTATION UNDER DEEP-SEA CURRENT SYSTEMS: PRE-HEBBLE IDEAS

I.N. McCave and C.D. Hollister

Studies of the interaction of deep ocean current systems with the sea bed are briefly traced from their beginnings in the decade of the mid-1950s to mid-1960s. Subsequent lines of study in physical oceanography, suspended sediment measurement, echo-character mapping, microphysiography, sedimentology and developments of instrumentation are noted up to 1978 when the High Energy Benthic Boundary Layer Experiment started.

In press: Marine Geology (Special Hebble Volume).

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WHOI Contribution No. 5748.

TRANSPORT OF RIVER SEDIMENT IN THE CHANGJIANG ESTUARY AND ADJACENT SHELF

John D. Milliman, Shen Huang-ting, Yang Zuo-sheng and Robert H. Meade

Hydrographic observations, suspended-sediment measurements, and historic data point to transport paths and sinks within the Changjiang estuary and adjacent shelf. Most of the sediment transported by the Changjiang to the ocean is carried through the North Channel of the Southern Branch. Sediment transport is directly related to river stage, but tidal phase (spring versus neap tides) also plays an important role.

An estimated 40 percent of the river load is deposited in the estuary, mostly in and seaward of the South Channel. The remaining sediment is deposited directly offshore during flood seasons, but much is re-suspended and carried southward by subsequent winter storms.

In press: Continental Shelf Research.

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WHOI Contribution No. 5841.

MODERN HUANGHE-DERIVED MUDS ON THE OUTER SHELF OF THE EAST CHINA SEA: IDENTIFICATION AND POTENTIAL TRANSPORT MECHANISMS

John D. Milliman, Robert C. Beardsley, Yang Zuo-sheng and Richard Limeburner

Outer shelf muds south of Cheju Island contain calcite in their clay fraction derived from the Huanghe (Yellow River), not the Changjiang (Yangtze River). Radiometric dating suggests that at least the surface of this mud deposit is contemporaneous, although the rate of accumulation may be slow. Part of the sediment may be derived from present-day erosion of the ancient Huanghe submarine delta off Jiangsu Province.

Suspended matter, light transmission and hydrographic measurements indicate a south-southeast transport of sediment in the East China Sea during winter when frequent storms can resuspend sediment and force Yellow Sea water to the southeast along the Chinese coast. The spatial distribution of maximum bottom stress associated with the dominant M₂ and M₄ tides also suggests that tidal currents could resuspend and transport fine-grained material from the inner shelf as well as from the eastern side of the Yellow Sea. Thus the present accumulation of modern sediment south of Cheju Island probably is the result of two separate transport mechanisms acting in concert.

In press: Continental Shelf Research.

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WHOI Contribution No. 5842.

RHYTHMIC BEACH CUSP FORMATION: A CONCEPTUAL SYNTHESIS

Richard J. Seymour and David G. Aubrey

Observations of a sandy beach at Santa

Barbara, California, during February 1980 documented the sequence of beach cusp formation, replacement by a second set of rhythmic cusps obliterating the first set, and finally complete planation of all rhythmic cusps during a major storm. Although neither cusp-building event was observed during its initiation, the wave and tide conditions during formation were well documented by in situ instrumentation. Based on these field observations and those by other investigators, a coherent conceptual theory of beach cusp formation is proposed, including formative, maintenance and destructive phases. This theory proposes: rhythmic cusp formation during relative stillstands of sea level of sufficient duration to permit initial perturbation of beach geometry; regularly spaced cusps acquire their initial spacing from subharmonic edge waves (such that spacing derives from the incident wave period); growth of the initial perturbation continues until cusps reach a limiting value, not necessarily with continuation of edge wave motion; the cusp spacing persists until a change in wave conditions either destroys the cusps, or establishes a radically different spacing; and, finally, that large storms will destroy the rhythmic cusp field, leaving either a planar beach or a beach with arrhythmic cusp-like features.

In press: Marine Geology.

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WHOI Contribution No. 5627.

SEA-FLOOR MORPHOLOGY OUTSIDE A GROUNDED, SURGING GLACIER: BRASVELLBREEN, SVALBARD

Anders Solheim and Stephanie Pfirman

Acoustical profiling and bottom photography reveal several different sea floor morphological features adjacent to the grounded Brasvellbreen glacier on Svalbard, northwestern Barents Sea. Some of the features and their distribution are closely related to a major glacial surge in 1936-38, and as such are valuable in identifying former surges in other locations. A continuous end moraine with a characteristic asymmetrical cross-section runs subparallel to the present glacier front and defines the maximum extent of the surge. Part of this moraine was probably pushed up in front of the glacier as it advanced, and part was deposited from meltwater during the surge. Subsequent slumping down the distal flank of the moraine modified the

surface topography. A rhombohedral pattern of 5 m high discontinuous ridges inside the end moraine probably reflects sediment accumulation in crevasses formed at the base of the glacier at the end of the surge. Discontinuous arcuate ridges and swales within 1 km of the modern ice front define local, minor readvances and retreats of an active glacier. Iceberg plough marks are most frequent seaward of the end moraine; their orientation is controlled by a combination of a longshore current, offshore katabatic winds, and sea-floor topography. Superimposed on the plough marks are secondary features such as a "washboard pattern" and striae, most likely caused by push-up of overconsolidated material during gouging, and multi-keel icebergs, respectively. Bottom sediments observed in photographs and cores are composed of normally consolidated pebbly mud with a high variability in clast content, resting on overconsolidated material, probably basal till. Cores obtained up to 40 km from the ice front coarsen upwards, perhaps because ice rafting increased during the surge. Mud deposition from meltwater outflows presently prevails close to the glacier.

In press: Marine Geology.

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WHOI Contribution No. 5743.

A STUDY OF NON-LINEAR TIDAL PROPAGATION IN SHALLOW INLET/ESTUARINE SYSTEMS PART II: THEORY

Paul E. Speer and David G. Aubrey

The generation of tidal asymmetries is clarified via numerical integration of the one-dimensional equations for channel geometries characteristic of shallow estuaries. Channels without tidal flats develop a time asymmetry characterized by a longer falling than rising tide. This behavior is enhanced by strong friction and large channel cross-sectional area variability over a tidal cycle. Resulting tidal currents have a shorter, intense flood and a longer, weak ebb (flood dominant). Addition of tidal flats to the channels can produce a longer rising tide and stronger ebb currents (ebb dominant), if the area of tidal flats is large enough to overcome the effects of time-variable channel geometry. Weaker friction with flats can also produce this asymmetry. The general features of tidal channels in shallow estuaries can be represented with simple geometries. Despite the physical complexity of these systems, essential features of the estuarine tidal

response can be recovered from one-dimensional models. Shallow estuaries are shown to have a system response leading to stable, uniform senses of tidal asymmetry (due to phase-locking of forced tidal constituents), with down-channel development in magnitude of asymmetry. These concepts are illustrated by modeling idealized representations of tidal channels at Nauset Inlet, MA, and Wachapreague Inlet, VA, which have flood- and ebb-dominance, respectively.

In press: Estuarine, Coastal and Shelf Science.

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WHOI Contribution No. 5691.

LATE PLEISTOCENE SEDIMENTATION ON THE WESTERN NOVA SCOTIAN SLOPE AND RISE

Stephen A. Swift

Reflectivity patterns in echograms recorded from relatively smooth continental slope and rise off Nova Scotia can be grouped into four depositional associations. The shallowest association corresponds to gravelly sand on the outer shelf that spills over the shelf edge and mixes with mud down to 500 m water depth. A sharp boundary near 62°30'W, extending from 500 m down to the abyssal plain, separates associations further seaward. Sediments transported downslope by near-bottom gravity processes accumulated west of the boundary; hemipelagic sediments accumulated east of the boundary from 500 to 4300 m. Below 4300 m, sediment waves are common in a contourite-fan association.

These associations indicate that during the late Pleistocene radically different sedimentation processes were juxtaposed across a sharp boundary down the slope and rise. West of 62°30'W small-scale slope failure occurred over a wide area due to relatively rapid accumulation of fine-grain glacial debris. The slope prograded seaward; the lower rise received distal turbidity current and debris flows deposits. East of 62°30'W relatively less failure occurred in hemipelagic sediment. Lower on the rise seaward of the hemipelagics turbidity currents and contour currents carried sediment, originating in deep canyons to the east of 61°30'W, along the lower rise towards the south and west. In the west the primary depocenter was the

slope and upper rise; in the east the depocenter was on the lower rise. A glacial sediment source on land and relict shelf morphology probably controlled sedimentation processes and, thus, the location of depocenters seaward of the shelf edge.

In press: Bulletin of the Geological Society of America.

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WHOI Contribution No. 5741.

CLOSE-UP STEREO PHOTOGRAPHS OF ABYSSAL BEDFORMS ON THE NOVA SCOTIAN CONTINENTAL RISE

Stephen A. Swift, Charles D. Hollister and Richard S. Chandler

Close-up, stereo photographs of the seafloor were taken at five stations on the Nova Scotian Rise. Stereo viewing reveals abundant relief with heights in the range 1-50 mm which are not apparent in oblique monoscopic pictures. Photogrammetric contour mapping at one millimeter intervals of longitudinal ripples gives in situ dimensions of 12 cm height, 90 cm full width, and 410 cm² cross-sectional area. A field of ripples spaced at 5 m with a sediment density of 0.7 gm/cm³ contains 5.7 kg dry sediment per m².

Seafloor roughness on the scale of centimeters in abyssal, high-energy boundary layers reflects both recent sedimentary and biological processes. The spatial density of eight classes of bed relief varies on scales of tens of kilometers downslope and is consistent with downslope trends in the occurrence of larger bedforms, texture of surface sediments, and bottom boundary layer conditions. Most relief is biogenic, directly or indirectly, and most is stream-lined.

In press: Marine Geology.

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WHOI Contribution No. 5591.

PLANKTONIC FORAMINIFERA: FACTORS CONTROLLING SINKING SPEEDS

Kozo Takahashi and Allan W.H. Be

Sinking speeds of 330 specimens belonging to 10 extant species of planktonic foraminifera were determined in a sinking column device filled with 3°C seawater. The sinking speed is governed primarily by

shell weight and presence/absence of spines. For example, preserved planktonic specimens of *Orbulina universa*, whose shell weight ranged from 2 to 21 μg , sank 122 to 583 m day^{-1} , with a correlation coefficient of 0.92 on log-log scale. Progressive shell thickening during foraminiferal growth accounts for some of the higher sinking speeds. In addition, shells from sediment on the average sink about three times faster than shells (of equivalent size and species) of planktonic foraminifera collected in near-surface waters. These high values are in part due to the shells often being encrusted with clay and nannoplankton remains. In contrast, the sinking speeds of the spinose species are approximately 3-fold slower than those of the nonspinose species. Based on data from plankton tows, most planktonic foraminifera $>150\mu\text{m}$ reach the mean ocean depth of 3800 m in 3 to 12 days depending upon shell weight and presence or absence of spines.

Estimated Reynolds numbers range from 0.05 to 24.85 and most exceed a value of 0.5 which is an upper limit for Stokes' Law range, suggesting that foraminifera are out of Stokes' sinking range. The Reynolds number and drag coefficients are negatively well correlated, indicating that drag is one of the important controlling factors in the sinking regime. The presence of spines is significant in increasing drag, decreasing the Reynolds number, and hence reducing the sinking speed.

In press: Deep-Sea Research.

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WHOI Contribution No. 5801.

W A V E D Y N A M I C S

PERFORMANCE OF BOTTOM-MOUNTED DIRECTIONAL WAVE GAGES

David G. Aubrey and Winfield Hill

The bottom-mounted directional wave gages (Sea Data models 635-9 and 635-12) have been field and laboratory tested to determine accuracies of the directional information. To obtain high precision directional spectral estimates desirable for inshore use, mounting errors must be minimized and both prevention of fouling and periodic calibration checks of the electromagnetic current sensor in the system are required; in nearshore field use EM sensor gain has been observed to vary by 5%

and more between calibrations, not uniformly between axes. With these maintenance procedures, the instruments have proven reliable and accurate.

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WHOI Contribution No. 5793.

DYNAMIC RESPONSE OF ELECTROMAGNETIC CURRENT METERS

David G. Aubrey, Wayne D. Spencer
and John H. Trowbridge

The dynamic response of electromagnetic current meters (manufactured by Marsh-McBirney, Inc.) has been clarified through a comprehensive laboratory measurement program combined with a thorough literature review. Elucidation of the behavior of these flow-meters under a variety of dynamic conditions has been neglected in the past. Since flow past a spherical body has considerable hydrodynamic complexity for different dynamic conditions, a careful laboratory study was carried out for pure steady, pure oscillatory (horizontal plane), and combined steady/oscillatory conditions at two test facilities. Test results indicate that flow-meter behavior under pure steady flow is excellent in the absence of high levels of free-stream turbulence, with an r.m.s. error of 1-5 cm/sec. These errors could be reduced with a higher-order polynomial regression fit. Pure oscillatory response was also excellent, with r.m.s. errors of 1-2 cm/sec, and sensitivity which is correlated with the oscillatory Reynolds number, $(Re)_o$, and the Keulegan-Carpenter number, (A/d) . Combined steady/oscillatory flows degraded current meter performance with larger residual errors (1-6 cm/sec) and significant differences in sensitivity (up to 20%). Horizontal cosine response showed systematic deviations from pure behavior, with a notable inter-cardinal undersensitivity and cosine "shoulder" at lower Reynolds numbers. Error analysis shows these current sensors are adequate for many kinematic measurements, but may lead to excessive errors when using velocity to calculate dynamical quantities (such as bottom friction, Reynolds Stress, or log-layer friction velocities). A careful error analysis must precede any use of these meters for estimating dynamical quantities. These studies pointed out a potential difficulty in using these meters in areas of large ambient turbulence levels (20% turbulent intensities), which are characteristic

of many near-bottom shallow water environments. Further study is needed to clarify this behavior.

Supported by: NOAA Sea Grant NA80-AA-D-00077 and Coastal Engineering Research Center Contract DACW/2-82-C-0014.

W.H.O.I. Technical Report 84-20.

INNER SHELF SAND TRANSPORT WAVE
MEASUREMENTS: POINT SAPIN,
NEW BRUNSWICK, CANADA

David G. Aubrey and Wayne D. Spencer

As part of the Canadian Coastal Sediment Study at Pointe Sapin, New Brunswick, Canada, a Sea Data Corp. model 635-9 directional wave gage was deployed in a mean water depth of 6.15 m. Over the period 19 September to 9 November, 1983, the predominant wave period was three-to-ten seconds, with direction confined to two well-defined corridors related to directions of maximum fetch. The more energetic propagation direction is towards 269° TN, corresponding to the maximum fetch from the northeast across the Gulf of St. Lawrence. The less dominant direction is towards 330° TN, corresponding to the fetch from the south-east out of Northumberland Strait. Lower frequencies (longer periods) are associated with the fetch over the Gulf of St. Lawrence (periods up to 7 to 10 seconds), while higher frequencies (3-4 second periods) are associated with the fetch from Northumberland Strait.

This distinctly bimodal wave character is reflected in storm occurrence as well. During the first month of deployment (19 Sept. - 21 Oct., 1983), many small storms reached the study site, emanating from the southeast in all but one instance. Significant wave heights from these storms were 0.75 m or less in 6 m water depth. The second deployment interval (21 Oct. - 9 Nov., 1983) showed more energetic events. In particular, storms on 25-26 October and 3-5 November, 1983, had significant wave heights of 1.25 m, propagating from the northeast across the greater fetch. Peak wave frequencies were 0.1 hz (10 seconds). Whereas the first deployment was characterized by less energetic, high frequency storm waves emanating from Northumberland Strait, the second deployment was characterized by more energetic, lower frequency storm waves out of the Gulf of St. Lawrence.

The directional wave instrumentation worked flawlessly during the experiment, with nearly 100% data recovery.

Supported by: The National Research Council of Canada Contract S/N OSX8300084.

National Research Council of Canada
Technical Report.

DEPARTMENT OF OCEAN ENGINEERING

Robert C. Spindel, Department Chairman

OCEAN ENGINEERING

DEPARTMENT OF OCEAN ENGINEERING
Robert C. Spindel, Department Chairman

ACOUSTIC SIGNAL

PROCESSING

ON THE MAXIMUM ENTROPY SPECTRUM FOR A CERTAIN CLASS OF CORRELATION FUNCTIONS

Ehud Weinstein

The Maximum Entropy Method (MEM) for spectral analysis, given a finite set of correlation lags, is analyzed when the correlation function of the underlying random process is circular (e.g., when the observed segment of the time series corresponds to a sum of sinusoids in additive white noise). For this class of correlation functions, the solution to the maximum entropy problem can be expressed in terms of the Discrete Fourier Transform (DFT) of the correlation data (i.e. the power spectrum of the corresponding finite segment of the observed time series at the Fourier frequencies). This result can be used to establish and confirm several experimental observations which appear in the recent literature.

Supported by: ONR Contract N00014-80-C-0381.

WHOI Contribution No. 5645.

PERFORMANCE ANALYSIS OF TIME DELAY ESTIMATION SYSTEMS

Ehud Weinstein

This is the second part of a study which deals with the problem of a passive time delay estimation. The focus here is on systems employing wideband signals and/or arrays of very widely separated receivers. A modified (improved) version of the Ziv-Zakai lower bound (ZZLB) is used to analyze the effect of additive noise and signal ambiguities on the attainable mean square estimation errors. When the lower bound is plotted as a function of signal-to-noise (SNR) one observes two distinct threshold phenomena dividing the SNR domain into three disjointed segments: at high SNR the lower bound coincides with the Cramer-Rao lower bound (CRLB). This is the ambiguity-free mode of operation where differential delay estimation is subject only to local errors. At moderate SNR (between the two thresholds), the lower bound exceeds the CRLB by a factor of $12(\omega_0 W)^2$ where ω_0 and W are, respectively, the center frequency and signal bandwidth. In this region the ambiguities in the received signal phases cannot be resolved; however, a useful estimate of the

differential delay can still be obtained using the received signal envelopes. At low SNR, the lower bound approaches a constant level depending only on the variance of the a priori search domain of the unknown delay parameter. In this region signal observations are subject to envelope ambiguities as well, thus essentially useless for the delay estimation.

Supported by: NUSC Contract
N00140-83-C-KA35.

WHOI Technical Report No. 84-32.

SOME RELATIONS BETWEEN THE VARIOUS CRITERIA FOR AUTOREGRESSIVE MODEL ORDER ESTIMATION

Ehud Weinstein and David Borenstein

The problem of model order determination in autoregressive (AR) modeling of a given time series is considered. It is shown analytically that the model order selected using the Final Prediction Error (FPE) criterion never exceeds the model order selected using the Akaike Information Criterion (AIC). It is further shown that, under certain conditions, the model order selected using the Criterion Autoregressive Transfer function (CAT) never exceeds the model order selected using the FPE criterion. These relations give some indication to what should be the preferred criterion, at least for the extreme cases when the model order is likely to be underestimated or overestimated.

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Acoustics, Speech and Signal
Processing.

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WHOI Contribution No. 5719.

ON THE FINITE MAXIMUM ENTROPY EXTRAPOLATION

Ehud Weinstein and Meir Feder

It is shown that an autoregressive (AR) extrapolation of a given set of correlation lags by any finite number maximizes the entropy (i.e. the determinant of the correlation matrix) of the corresponding segment of the times series.

Published in: Proceedings of the IEEE,
1660-1662, November 1984.

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WHOI Contribution No. 5502.

CONVERGENCE ANALYSIS OF LMS FILTERS WITH UNCORRELATED GAUSSIAN DATA

E. Weinstein and A. Feuer

Statistical analysis of the Least Mean Squares (LMS) adaptive algorithm with uncorrelated Gaussian data is presented. Exact analytical expressions for the steady state mean square error (m.s.e.) and the performance degradation due to weight vector misadjustment are derived. Necessary and sufficient conditions for the convergence of the algorithm to the optimal (Wiener) solution within a finite variance are derived. It is found that the adaptive coefficient, μ which controls the rate of convergence of the algorithm must be restricted to an interval significantly smaller than the domain commonly stated in the literature. The outcome of this paper, therefore, places fundamental limitations on the m.s.e. performance and rate of convergence of the LMS adaptive scheme.

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Acoustics, Speech and Signal
Processing.

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WHOI Contribution No. 5483.

FUNDAMENTAL LIMITATIONS IN PASSIVE TIME DELAY ESTIMATION: Part II - WIDEBAND SYSTEMS

Ehud Weinstein and Anthony J. Weiss

This is the second part of the study which deals with the problem of time delay estimation between noise-like Gaussian signals radiated from a common point source and observed at two spatially separated receivers, each of which also receives uncorrelated Gaussian noise. A modified (improved) version of the Ziv-Zakai lower bound (ZZLB) is used to analyze the attainable mean square estimation errors. In Part I we concentrated on narrowband signals. The outstanding observed feature was a distinct threshold phenomenon whereby below a certain signal-to-noise ratio (SNR) the lower bound increases suddenly and precipitously. In Part II we concentrate on wideband signals. If we relax the assumption concerning signal bandwidth, we discover a second threshold phenomenon oc-

curing at a lower SNR. The two threshold effects separate the entire SNR domain into three disjointed segments indicating three distinct modes of operation; at high SNR the attainable mean square error (m.s.e.) is characterized by the Cramer-Rao lower bound (CRLB). At moderate SNR (between the two threshold points) the modified ZZLB coincides with the Barankin lower bound, which exceeds the CRLB by a factor of the order of $(\omega_0/W)^2$ where W and ω_0 are, respectively, signal bandwidth and center frequency. At low SNR the attainable m.s.e. is bounded only by the variance of the a priori search domain of the delay parameter.

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Acoustics, Speech and Signal
Processing, ASSP-32, 5, October
1984.

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WHOI Contribution No. 5472.

LOWER BOUNDS ON THE MEAN SQUARE ERROR IN RANDOM PARAMETER ESTIMATION

Ehud Weinstein and Anthony J. Weiss

A generalization of the Bobrovsky-Zakai lower bound on the mean square error (m.s.e.) in random parameter estimation is presented. The results can be applied to a wide class of parameter estimation problems. An additional variable is introduced into the formulation of the bound which may yield a significantly tighter lower bound. The lower bound is also extended to vector parameters and any given function of the parameters.

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Information Theory.

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C-0199.

WHOI Contribution No. 5737.

LOWER BOUNDS ON THE MEAN SQUARE ESTIMATION ERROR

Ehud Weinstein and Anthony J. Weiss

A general class of lower bounds on the mean square error (m.s.e.) in random parameter estimation is formulated. These lower bounds are generated by using functions of the parameter and the data that are orthogonal to the observed data. Members of the class, among others, are the

Cramer-Rao lower bound, Bhattacharyya lower bound, and the Bobrovsky-Zakai lower bound.

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WHOI Contribution No. 5791.

SUPER RESOLUTION OF ACOUSTIC TOMOGRAPHY MULTIPATH DATA

Jules S. Jaffe

This paper describes the application of a super resolution (bandwidth extrapolation) technique that has been applied to acoustic tomography data. Using this algorithm, we have been able to achieve better resolution of the incoming arrival times.

Initial implementation of a technique was aimed at exploring its effect on noiseless data. In this case, the algorithm succeeded quite well in obtaining a factor of three in resolution enhancement for a typical acoustic tomography transfer function. Additional experiments which included noise indicated that this factor of three was obtainable in the presence of S/N ratios down to 4:1.

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International Conference on
Acoustics, Speech and Signal
Processing.

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WHOI Contribution No. 5852.

C O A S T A L D Y N A M I C S

RIPPLED SCOUR DEPRESSIONS ON THE CONTINENTAL SHELF OFF CENTRAL CALIFORNIA

D.A. Cacchione, D.E. Drake,
W.D. Grant and G.B. Tate

Side-scan sonar records taken during the recent Coastal Ocean Dynamics Experiment (CODE) show elongate, shore-normal rippled depressions of low relief on the inner continental shelf off central California between Bodega Bay and Point Arena. These features extend up to 2 kilometers from the coast into water depths to 65 meters. The proposed mechanism for their generation is storm-generated bottom currents associated with coastal downwelling during the late fall and winter

which scour the surficial fine sand sediment and expose the coarser sand substrate in the depressions. The zones of most intense erosion and the irregular spacing of the features may be controlled by submerged rock ledges and other prominent coastal features. The large straightcrested ripples within the depressions (heights to 40 cm; wave lengths to 1.7 m) are probably formed by large amplitude, long-period surface waves generated by winter storms.

In press: Journal of Sedimentary
Petrology.

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WHOI Contribution No. 5469.

BOTTOM STRESS ESTIMATES AND THEIR PREDICTION ON THE NORTHERN CALIFORNIA CONTINENTAL SHELF DURING CODE-1: THE IMPORTANCE OF WAVE-CURRENT INTERACTION

W.D. Grant, A.J. Williams
and S.M. Glenn

High quality near-bottom boundary layer measurements obtained at a mid-shelf location (90 m water depths) in the CODE region off Northern California are described. Bottom tripod velocity measurements and supporting data obtained during typical spring and early summer conditions (June 1981 during CODE-1) are analyzed to obtain both velocity profiles and mean bottom stress and bottom roughness estimates. During the time period described, the mean near-bottom ($< 2\text{m}$) velocity profiles are highly logarithmic ($R > 0.997$) approximately 30 percent of the time. Effects induced by unsteadiness from internal waves result in some degradation of the profiles ($0.96 \leq R \leq 0.997$) the rest of the time. Mean stress profiles indicate the logarithmic layer is approximately a constant stress layer. The near bottom flow field is composed of mean currents and oscillatory currents due to swell. Typical mean u_* values estimated from measurements greater than 30 cm above the bottom have magnitudes of 0.5-1.0 cm/sec; mean stress values are three to seven times larger than expected from predictions using a typical smooth bottom drag coefficient and one-and-one-half to three-and-one-half times larger than expected for predictions using a drag coefficient based on the observed rough bottom. Corresponding z_0 values have magnitudes of approximately 1 cm; an order of magnitude larger than the observed physical bottom roughness. These values are demonstrated to be consistent

with those expected from theoretical models for combined wave and current flows. The u_x values estimated from the CODE-1 data and predicted by the Grant and Madsen (1979) model typically agree within 10-15 percent. The waves influencing the mid-shelf bottom stress estimates are 12-20 second swell associated with distant Pacific storms. These waves are present over most of the year. The results demonstrate that waves must be taken into account in predicting bottom stress over the Northern California Shelf and that these predictions can be made using existing theory.

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Oceanography, 14, 1984.

Supported by: NSF Grant OCE80-14938.

WHOI Contribution No. 5432.

G E O L O G Y

PROJECT CYATHERM: DETAILED INVESTIGATION OF HYDROTHERMAL ACTIVITY AT 12°48'N ON THE EAST PACIFIC RISE

R.D. Ballard

In 1980, the French Government began a long-term investigation of the East Pacific Rise (EPR) between the Orozco (15°N) and Clipperton (10°N) fracture zones. The objective of this investigation is to better understand the axial processes of a fast spreading ridge (12 cm/yr) and compare those findings with similar efforts already carried out at moderate and slow spreading ridge segments. More specifically, the work between 10° and 15°N seeks to determine the nature of hydrothermal circulation along the axis of the Mid-Ocean Ridge (MOR) and its relationship to the occurrence and distribution of massive sulfide accumulations.

In press: Earth and Planetary
Science Letters.

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WHOI Contribution No. 5431.

MICROTOPOGRAPHY OF A CONTINENTAL RIFT ZONE: THE GULF OF ELAT-AQABA

R.D. Ballard and Z. Ben-Avraham

A bottom photographic study of selected areas within the Gulf of Elat reveals many

details about the microtopography of this continental rift zone. The photographs were taken using a miniature version of the unmanned camera system ANGUS (Mini-ANGUS). During the study, over 3,000 photographs were taken and the water temperature just above the seafloor was continuously measured. The deep water of the Gulf and the excellent visibility in these waters provide a unique situation which allows one to study the continental rifting processes on a very small scale. The bottom photographs indicate that microtopography reflects in a remarkable way the tectonic processes which are currently acting in the Gulf. Active faulting is seen clearly in the bottom photographs. Spreading activity propagates from south to north within the Gulf. The most active region is in the northern part of the central basin where the basin is propagating into the shallow northern basin. This tectonic activity deforms the seafloor of the region into small trenches, fault scarps and other lineaments. The major fault zones not only deform the seafloor but also may affect the biological activity in their vicinity. An observed increase in the biological activity of the faulted areas may be related to hydrothermal activity but the photographs are inconclusive. The area most affected by bioturbation is where two tectonic elements cross each other in the southern part of the Gulf. In this area, temperature anomalies have been discovered near the bottom which also support the existence of hydrothermal activity. Outside the major fault zones bioturbation activity is localized in relatively small areas. Thus, in the basinal areas within the Gulf of Elat, the activity of various tectonic elements deforms and shapes the seafloor by various processes while away from these zones sedimentation maintains flat, smooth and undisturbed seafloor.

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C-0019.

WHOI Contribution No. 5414.

SUBMERSIBLE OBSERVATIONS ON THE EAST PACIFIC RISE: A MODEL FOR GROWTH OF SULFIDE DEPOSITS

R. Hekinian, J. Francheteau
and R.D. Ballard

A submersible study was conducted at the fast-spreading (11 cm yr^{-1}) East Pacific Rise near 12°50'N and 11°50'N, where the seafloor is the shallowest between the Orozco and the 11°49'N transform faults. It revealed the existence of short segments of less than 7 km in length forming

axial depressions (< 50m deep and < 600m wide) running down the summit of the 8 km high 300-400m wide axial topographic ridge. Intense hydrothermal activity occurred in axial depressions (graben) where more than 80 sites containing up to ten sulfide edifices overgrown with chimneys were identified. The growth of an individual chimney monitored over five days through the use of a marker positioned on the seafloor showed fast rates (8 cm per day), implying that the hydrothermal deposits are formed very rapidly (< 100 yr). We propose a qualitative model for the evolution of the sulfide deposits. The early stages are marked by low temperature deposits and by the development of luxuriant animal life communities. The last stage corresponds to the formation of massive ore deposits with the "black smokers" appearing at an intermediate stage. The axial segments where hydrothermal activity takes place show two major structural and morphological domains: the domain of ponded lavas consisting of elongated collapsed structures (< 50m in length) with "pillar" formations similar to those previously described by Francheteau et al. and Ballard et al. This domain is characterized by the occurrence of the freshest flows and the most intense hydrothermalism.

In press: Earth and Planetary
Science Letters.

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WHOI Contribution No. 5631.

INSTRUMENTATION

A CCD CHIRP-Z FFT DOPPLER SIGNAL PROCESSOR FOR LASER VELOCIMETRY

Y.C. Agrawal

A charge-coupled Chirp-Z fast Fourier transform device which has been configured to obtain the frequency of peak spectral amplitude in signals from laser velocimeters is described for use in oceanographic and other low laser power field applications where poor optical signals and frequent drop out are encountered. The resulting signal processor gives 8 bit resolution in the velocity word, with a cycle time of approximately 4 msec while scanning a spectral range of 0-125 kHz; higher frequency ranges are possible at proportionately faster spectral scan rates, up to a maximum of 2 MHz. Error estimates are presented which indicate 2 bit accuracy

at signal-to-noise power ratio of -2 db. The combination of this processor together with a photodiode array detector described by the author (Agrawal and McCullough, 1981) radically simplifies the practice of laser velocimetry.

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Electronics: Scientific
Instruments, 17, 458-461, 1984.

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WHOI Contribution No. 5314.

QUADRATURE DEMODULATION IN LASER DOPPLER VELOCIMETRY

Yogi C. Agrawal

Three optical configurations are described to obtain quadrature signals in laser velocimetry. These are: the polarization method of Bossel, Hiller and Meir (1972), biperiodic detector array imaging method of Agrawal and McCullough (1981) and an electronic dual-mixer method reported here for the first time. This last method makes possible the direct measurement of the phase of a scattered light wave. A complex FFT of these signals obtains the magnitude and direction of the velocity vector. Faster signal processing algorithms such as one due to Rummler (1968) are described.

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1685-1686, 1984.

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C-0019.

WHOI Contribution No. 5499.

DIRECTIONAL LASER VELOCIMETRY WITHOUT FREQUENCY BIASING - PART II

Y.C. Agrawal and J.B. Riley

In an earlier paper, Agrawal and McCullough (1981) demonstrated that a single laser beam focused at the point of measurement can be used to obtain both the magnitude and direction of local fluid velocity without the use of beam splitting optics or frequency biasing devices. Additionally, the photoelectric signal was shown to be a zero-mean sine wave suitable for existing counter-type laser Doppler velocimeter signal processors. The method described in the above paper indicated the use of two offset photo-detector arrays; the resulting photocurrents from the two arrays were

correlated to give direction. In this paper, we describe the implementation of the method using a self scanning diode array. Detector sensitivity in the array is discussed and microchannel plate detectors are suggested for increased sensitivity.

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57-61, 1984.

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WHOI Contribution No. 5314.

OPTICAL PARTICLE SIZING FOR HYDRODYNAMICS BASED ON NEAR FORWARD SCATTERING

Yogi C. Agrawal and James B. Riley

In the study of boundary layer dynamics in the ocean, the stratification induced by suspended matter enters through the parameter $c_n w_n$ where c_n and w_n are, respectively, the concentration and fall velocity of size class n . In this paper, an optical arrangement for instantaneous measurement of the particle size is approximated quite well by the Fraunhofer diffraction through a circular aperture. Thus, when light is scattered by particles illuminated by a collimated laser beam, the observed intensity distribution in the Fourier transform plane of a coaxial lens is the incoherent sum of the Airy patterns from all particles, weighted by area square. An inversion of this observed intensity distribution produces the size distribution. The inversion, based on a Titchmarsh-Bateman formula, is analytic and has been known in the literature to reduce to a Fourier transform of the angular intensity distribution, weighted by the third power of the scattering angle, i.e. $\theta^3 I(\theta)$. The measured intensity distribution is discussed, including the size resolution and minimum and maximum size of particles. The concept of a Hyquist size and aliasing is introduced. By enclosing the scattering volume when the decay of the size distribution is differentiated in time, the fall velocity, hence mass density, at each size can be determined separately.

The above reduction of the observations generates the relevant parameter $c_n w_n$ and also permits the direct observation of the fluctuations in concentrations which are theoretically predicted to follow the $-5/3$ power law but have never before been verified. Theoretical background and analysis of synthetic data will be presented.

In press: Ocean Optics VII.

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WHOI Contribution No. 5734.

CTD LOWERING MECHANICS

H.O. Berteaux and R.G. Walden

The many difficulties encountered in the deployment of CTD instrument packages, including the loss of an appreciable number of them, has prompted a comprehensive study of CTD instrument lowering mechanics. Conditions causing large cyclic cable tensions, shock loads or cable slack had to be investigated, modeled, and, hopefully, measured in situ. The dynamic behavior of the instrument package needed to be assessed. Methods to improve its flight pattern as it travels through the water column and recommendations for safer and more efficient lowering procedures had to be formulated. This paper describes how the study was conducted and presents its salient findings and recommendations. In its conclusion the paper points out the limits of present CTD lowering systems and advocates that servo-controlled motion compensating winches be used in the future.

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181-194, 1984.

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C-0071.

WHOI Contribution No. 5311.

CHARACTERISTICS OF A PHOTOVOLTAIC BATTERY CHARGING SYSTEM FOR THE RELAYS PROGRAM

Clayton W. Collins, Jr.

The NASA-funded RELAYS program is the first project at the Woods Hole Oceanographic Institution to utilize a photovoltaic device to perform useful work. Four panels on each of three drifting buoys convert solar illumination to electric power to maintain a proper state of charge on lead-acid storage batteries inside the buoys. This system constitutes the power supply for sophisticated remote-sensing electronics.

Tests were conducted for a full year on the panels, each of which consists of thirty-six individual cells to produce sufficient voltage and current to charge a twelve volt battery. Series and parallel combinations produce the desired voltage and current.

A solar cell is a large area semiconductor diode so constructed that light can penetrate into the region of the diode junction. The basic material is silicon, with certain impurities deliberately introduced into it to give rise to positive and negative charges which can carry electric current in the silicon.

The cells are mounted under shatter-proof plexiglass and bedded in silicon rubber, to protect them from physical impact and environmental degradation. A full year's exposure has not produced any sign of deterioration.

The battery charging system in the RELAYS design contains provisions for preventing overcharge in the event of excess sunlight and for powering down to conserve energy in periods of low sun.

The systems are presently undergoing operational tests at the Woods Hole Oceanographic Institution; field deployment is scheduled for the latter part of 1984. Every result thus far has been successful. When compared to other power sources, solar energy systems in remote applications such as the RELAYS project appear to be reliable and cost effective.

Supported by: NASA Grant NAG-281.

WHOI Technical Memorandum 1-84.

A MINIATURE URETHANE MOLDED ACOUSTIC TRANSDUCER

Christopher Van Rensselaer Dunn

The development of a reliable miniature molded transducer for the Williams/Koehler acoustic current meter, BASS (Benthic Acoustic Stress Sensor) is documented. The procedures developed and components selected for manufacturing the transducer assemblies are documented as well as some of those rejected.

Engineering tests performed to ensure reliable performance in the field are outlined and discussed as well.

The transducers are now routinely molded with great success (over 1200 operational transducer months to date) and commercial sources are being investigated.

Supported by: ONR Contracts N00014-82-C-0019 and N00014-79-C-0071; NSF Grant OCE80-14938.

WHOI Technical Report 84-30.

USE OF RADIO-CONTROLLED MINIATURE AIRCRAFT FOR DRIFTER AND DYE CURRENT STUDIES IN A TIDAL INLET

F.R. Hess and D.G. Aubrey

A commercially available radio controlled miniature aircraft (wing span 2.4 m) was modified and deployed as a part of a field study of the ebb tidal flow characteristics of a natural, unstructured tidal inlet. To complement Eulerian current measurements within the main inlet channel, surface drifter and rhodamine dye patches were observed from the miniature aircraft and recorded with a 35 mm camera. Position reference was provided with an array of precisely located markers on land and in the water. The miniature aircraft is an inexpensive, accurate alternative for Lagrangian studies in tidal inlets and estuaries, with many advantages over alternate techniques (such as hot-air balloons, fixed platforms, manned aircraft, or chaser boat).

In press: Journal of Limnology and Oceanography.

Supported by: NASA Contract
NA80AA-D-00077.

WHOI Contribution No. 5618.

DIRECT OPTICAL ASSESSMENT OF MACROSCOPIC AGGREGATES IN THE DEEP OCEAN

Susumu Honjo, Kenneth W. Doherty,
Yogesh C. Agrawal and Vernon L. Asper

Large amorphous aggregates (LAA), frequently called "marine snow," may accelerate the flux of fine particles and dissolved matter in the ocean by adsorption. The aggregates are extremely fragile and their sampling with conventional towing and casting is impossible. To assess the size and spatial distribution of such aggregates we have developed a photographic system that can be lowered to full ocean depth. The system, based on light scattering in water, uses a well-collimated beam pointed downward from the vertical at an angle of 45°. The beam is produced by placing high-powered stroboscopic lights at the back focal plane of a Fresnel lens system. Illuminated aggregates in the light are photographed from a direction perpendicular to the beam axis. The photographed volume, 0.66 m³, is 106 x 156 x 40 cm. The resolution of the instrument is about 0.2 mm. Aggregates were distributed throughout the water column at all stations along a 200-km transect off Monterey Bay. The abundance of macroscopic aggregates (less

than 0.5 mm) ranged from several per liter near the surface to 1 or less at depth.

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WHOI Contribution No. 5036.

PREPARATION OF FROZEN-HYDRATED SPECIMENS FOR HIGH RESOLUTION ELECTRON MICROSCOPY

J.S. Jaffe and R.M. Glaeser

A method is presented for preserving the high resolution structure of biological membranes in a frozen-hydrated environment for electron microscopy. The technique consists of sandwiching a specimen between two carbon films and then waiting while some of the solvent evaporates. When the solvent layer is judged to be of an appropriate thickness, the specimen is then frozen in liquid nitrogen. The specimen can then be inserted into the pre-cooled stage of an electron microscope. Electron diffraction studies of the purple membrane of Halobacterium halobium recorded at -120°C have shown that the structure can be preserved to a resolution of 3.5 Å. The main advantage of this method over previous techniques is that the hydrating conditions can be accurately controlled.

Published in: Ultramicroscopy, 13, 373-378, 1984.

Supported by: The Pew Memorial Trust.

WHOI Contribution No. 5834.

POPUP: A PROTOTYPE BOTTOM-MOORED LONG-TERM CURRENT PROFILER

Arthur D. Voorhis and Albert M. Bradley

A self-contained, bottom-mounted instrument for measuring high resolution vertical profiles of horizontal current in the deep ocean over long time periods (up to a year) has been designed, constructed, and successfully tested. It employs an interferometric technique to track small, expendable, buoyant probes containing c.w. acoustic beacons which are released on a preset schedule. A carrying capacity of sixty probes is quite feasible. Tracking data is stored on cassette tape and is recovered with the bottom instrument. The design of the instrument is discussed and errors analyzed. The uncertainty in the horizontal current averaged over 10 m vertical intervals increases near the surface

to approximately 2 cm s^{-1} and is due primarily to acoustic phase noise from reflection off the rough sea surface. Considerable improvement in future design can be expected.

In press: Journal of Atmospheric and Oceanic Technology.

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WHOI Contribution No. 5582.

BOTTOM-MOUNTED PROFILING WINCH

R.G. Walden and C.W. Collins, Jr.

A winch has been developed which can be free-dropped to the ocean bottom in full ocean depths. The winch is powered by self-contained batteries and can be programmed to cycle self-recording instruments from close to the bottom to 100 meters above the bottom continuously or in steps. A typical scenario is envisioned as one complete cycle per day for one year with the instruments pausing each five meters for two minutes while measurements of current, temperature and conductivity are made. The upper section of the tripod contains the winch and instrumentation and is recovered by sending an acoustic command to a release mechanism allowing it to come to the surface.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Technical Report No. 84-12.

HEBBLE SEA DUCT SEMIANNUAL PROJECT REPORT NUMBER 4

Clifford L. Winget

Design, fabrication and assembly of the flume duct work, power pack, microprocessor, x-y-z traverse mechanism, emergency battery packs as well as a back-up recirculating pump design are rapidly nearing completion.

It is anticipated that assembly of the triangular flume support frame will start in the middle of April 1984. Based on present hardware development and availability, the program is considered to be six months behind the original milestone progress chart prepared at the start of the project.

The revised schedule of events assumes a shallow water deployment at diver depth to be accomplished in October 1984. Request for bids to provide a barge, shipboard crane, divers, and a support vessel has been prepared and will be distributed by the WHOI purchasing department in February

1984. It is proposed to deploy and test the sea flume in the Buzzards Bay, Massachusetts, area where bottom sediment consistency closely approximates the material at the HEBBLE site.

Published in: HEBBLE Sea Duct Annual Report No. 4, February, 1984.

Supported by: ONR Contract N00014-82-C-0019.

BASS, AN ACOUSTIC CURRENT METER ARRAY FOR BENTHIC FLOW FIELD MEASUREMENTS

Albert J. Williams, 3rd

A vertical array of acoustic current meters, each measuring the instantaneous flow vector, permits bottom stress to be estimated by three methods: the mean velocity profile applied to a log law-of-the-wall model, the Reynolds stress at each sensor height, and the dissipation of turbulent kinetic energy at each height. Such an array has been built and used in the deep sea in the HEBBLE program to estimate bottom stress over several hours and to monitor the inner boundary layer over a three month period.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5573.

OCEAN ACOUSTICS

A UNIFORMLY VALID SOLUTION FOR ACOUSTIC NORMAL MODE PROPAGATION IN A RANGE-VARYING OCEAN

Yves Desaubies

It is shown that the adiabatic approximation usually presented in the literature for acoustic normal mode propagation in a range dependent ocean has serious limitations and breaks down at rather short ranges. This is because the approximation does not account properly for the phase of the modes. A rigorous, uniformly valid asymptotic expansion is presented which provides a solution with greatly improved range of validity.

In press: Journal of the Acoustical Society of America, 76, 624-626, 1984.

Supported by: ONR Contract N00014-79-C-0071.

WHOI Contribution No. 5578.

RICHARDSON NUMBER APPROACH TO INTERNAL WAVE INSTABILITY IN THE OCEAN AND STRATOSPHERE

Yves Desaubies

Further evidence is presented showing that the internal wave fields in the ocean and atmosphere are such that the Richardson number $Ri = \langle n^2 \rangle / \langle (du/dz)^2 \rangle$, constructed on the variances of buoyancy frequency and velocity shear, is of order one. We argue in favor of shear instability as an instability mechanism. We compare high-resolution temperature and velocity data from the stratosphere (Barat, 1983) with a gravity wave spectral model of VanZandt (1982) and find the agreement to be quite good. This indicates that gravity waves are an important source of fluctuations in the atmosphere, as they are in the ocean.

In press: Proceedings of Hawaiian Winter Workshop, University of Hawaii at Manoa, January 17-20, 1984.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5826.

STATISTICAL ASPECTS OF SOUND PROPAGATION IN THE OCEAN

Yves Desaubies

A tutorial review of sound propagation in a random ocean is presented with emphasis on the oceanography and the statistics of received signals. The list of references should help the reader who wishes to investigate further specific aspects of the problem.

In press: Proceedings of the NATO Advanced Study Institute on Adaptive Methods in Underwater Acoustics.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5676.

GEOACOUSTIC MODELS FOR THE ICELANDIC BASIN

George V. Frisk, James A. Douth
and Earl E. Hays

Geoacoustic models inferred from 220 Hz amplitude versus range data are presented for three locations in the Icelandic Basin. The data were obtained using a deep towed pulsed CW source and two receivers anchored near the bottom. For ranges out to 4800 m, the data are analyzed using an iteration of forward models technique in which the parabolic equation method and a Hankel transform method are used in a sequential fashion to compute acoustic fields for different bottom parameters until best fits to the data are obtained. The inferred geoacoustic models consist of a sediment layer containing a positive sound speed gradient overlying an isovelocity subbottom. The geoacoustic parameters include the layer thickness, linear sound speed gradient, and sound speed discontinuities at the water-bottom and subbottom interfaces. The density and attenuation of the structures are also determined. The geoacoustic models are substantiated by other types of measurements, which include piston coring, 3.5 kHz seismic profiling, and in situ sediment profiling. These additional measurements, combined with the 220 Hz results, yield a consistent picture of the geoacoustic nature of the three areas. Specifically, the highly coherent character of the 220 Hz data, the clearly visible subbottom layering in the 3.5 kHz records, and low values of attenuation are related to the fine grained nature of the sediment at two of the sites. At the third site, the presence of coarse sediment provides an explanation for the major incoherent component in the 220 Hz data, the poorly discernible layering in the 3.5 kHz records, and an anomalously high value of attenuation.

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WHOI Contribution No. 5835.

SHALLOW WATER WAVEGUIDE CHARACTERIZATION USING THE HANKEL TRANSFORM

George V. Frisk and James F. Lynch

A technique for acoustically characterizing shallow water waveguides is presented. For a horizontally stratified ocean and bottom, the method consists of measuring the magnitude and phase versus range of the pressure field due to a cw point source and

numerically Hankel transforming this data to obtain the depth-dependent Green's function versus horizontal wavenumber. It is shown that, in the context of normal mode theory, the Green's function contains information about the nature of the discrete and continuous modal spectra as well as the plane-wave reflection coefficients of the waveguide boundaries. Inversions are performed using pressure field data generated synthetically over reasonable experimental apertures (1-5 km) to obtain Green's functions for the cases of an isovelocity water column overlying both hard and fast isovelocity bottoms (Pekeris waveguide). The Green's function results show excellent agreement with theory, although the subsequently calculated reflection coefficient of the bottom is of substantially lower quality. It is shown that features of the Green's function itself can be used to extract modal properties and characteristics of the bottom. The effects of sediment attenuation and shear in the Pekeris case are discussed, and a comparison of this method with conventional phased array mode resolution techniques is made.

Published in: Journal of the
Acoustical Society of America, 76,
205-216, 1984.

Supported by: ONR Contracts N00014-82-
C-0152 and N00014-83-K-0594.

WHOI Contribution No. 5534.

A CANONICAL OCEAN BOTTOM SOUND VELOCITY PROFILE

Hiroshi Kawahara and George V. Frisk

A new canonical sound velocity profile is presented in which the velocity cubed varies linearly with depth and is characterized by two parameters. The ray acoustic equations have exact analytic solutions for this profile, and the expressions for horizontal range, travel time, and intensity are derived. It is shown that the canonical profile can be derived approximately from Hamilton's profile for bottom sediments obtained from sonobuoy data. The agreement between the two is shown to be excellent for both the velocity and the velocity gradient even for sediment thicknesses of one kilometer.

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Acoustical Society of America, 76,
1254-1257, 1984.

Supported by: ONR Contracts N00014-82-
C-0019 and N00014-83-K-0594.

WHOI Contribution No. 5655.

RAY THEORY MODELING APPLIED TO LOW
FREQUENCY ACOUSTIC INTERACTION WITH
HORIZONTALLY STRATIFIED OCEAN BOTTOMS

Martin W. Lawrence

Ray theory is applied to the interaction of acoustic waves with a horizontally stratified ocean bottom. Local ray calculations are used throughout. At discontinuous interfaces, rays are allowed to split and each resulting ray is then followed. Corrections that are essential for good agreement are caustic boundary corrections and beam displacement corrections. The nature of the $\pi/2$ phase shift associated with caustics is examined, leading to a $+\pi/2$ phase shift for beam displacement caustics in contrast to the $-\pi/2$ phase shift for refraction caustics. Good agreement is observed between pressure fields calculated with this theory in comparison with fields calculated by normal modes, even when many caustic boundary regions overlap in the ray theory model and even for layers of thickness comparable to a wavelength.

In press: Journal of the Acoustical
Society of America.

Supported by: ONR Contract N00014-82-
C-0152.

WHOI Contribution No. 5753.

THEORETICAL ANALYSIS OF ABSS
DATA FOR HEBBLE

James F. Lynch

As part of HEBBLE (High Energy Benthic Boundary Layer Experiment), a 5 MHz Acoustic Backscatter System (ABSS) has been employed to remotely determine the concentration profile of the suspended sediments in the first meter above the benthic boundary. In order to extract this information from the raw data, an ABSS computer simulator has been created. The simulator mimics the ABSS output by solving the sonar equation in a forward modeling approach with the concentration being essentially the only free parameter available for matching simulated and actual output. Both theoretical and experimental results are presented, and directions for future work are discussed.

In press: Marine Geology.

Supported by: ONR Contract N00014-82-
0152.

WHOI Contribution No. 5564.

ON THE USE OF FOCUSED HORIZONTAL ARRAYS
AS MODE SEPARATION AND SOURCE LOCATION
DEVICES IN OCEAN ACOUSTICS

James F. Lynch, Daniel K. Schwartz
and Kondagunta Sivaprasad

It has been shown by Lynch that one can perform acoustic normal mode separation and source location in a shallow water ocean waveguide using focused horizontal phased arrays. This mode separation/source location scheme is discussed for motionless CW sources in both range invariant and range variable environments. Numerical simulations of focused array performance in a typical shallow water waveguide are presented.

In press: NATO Advanced Study
Institute on Adaptive Methods in
Underwater Acoustics.

Supported by: ONR Contract N00014-82-
C-0152.

WHOI Contribution No. 5677.

ON THE USE OF FOCUSED HORIZONTAL ARRAYS AT
MODE SEPARATION AND SOURCE LOCATION
DEVICES IN OCEAN ACOUSTICS
PART II: THEORETICAL AND NUMERICAL

James F. Lynch, Daniel K. Schwartz
and Kondagunta Sivaprasad

This paper extends and completes the description of the properties of focused horizontal arrays in normal mode fields presented in the earlier paper "On the Use of Focused Horizontal Arrays as Mode Separation and Source Location Devices in Ocean Acoustics. Part I: Theory." The topics treated in this paper are: mode resolution criteria, ray-mode picture transitions, the direct measurement of ocean waveguide range variability, and modal "Doppler amplification" by nonlinear curved array refocusing. Both theoretical and numerical results are presented.

Supported by: ONR Contract N00014-82-
C-0152.

WHOI Contribution No. 5718.

A HYBRID NUMERICAL/ANALYTIC TECHNIQUE
FOR THE COMPUTATION OF WAVE FIELDS
IN STRATIFIED MEDIA BASED ON THE
HANKEL TRANSFORM

Douglas R. Mook, George V. Frisk
and Alan V. Oppenheim

A hybrid numerical/analytic technique is presented for computing the field due to a monochromatic point source in a horizontal medium. It is based on the exact Hankel transform relationship between the field in the range domain and the associated depth-dependent Green's function in the horizontal stratified wavenumber domain. The method uses a numerical evaluation of the Hankel transform. It is shown that a major source of error in such an evaluation arises from undersampling of the Green's functions at points where it becomes infinite. This error is described in terms of aliasing, analogous to the aliasing that has been well described for the discrete Fourier transform. It is shown that the error can be substantially reduced by removing the infinities, calculating the Hankel transform of the remaining portion of the Green's function numerically, and adding to it the analytically computed Hankel transform of the infinities. The sum of the analytic terms and the remaining Hankel transform always exactly equals the true field with no errors introduced other than those associated with the numerical evaluation of the Hankel transform, and the method is accurate in both the near and far field regions. The technique is developed in detail for the acoustics problem of a monochromatic point source and receiver in an isovelocity fluid half-space overlying a horizontally stratified fluid medium. It is found that under circumstances of interest in ocean bottom acoustics, where the Green's function has only a few singularities along the real horizontal wavenumber axis, the technique is efficient and extremely accurate.

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WHOI Contribution No. 5453.

TOMOGRAPHIC MAPS OF THE OCEAN
MESOSCALE-1: PURE ACOUSTICS

B. Cornuelle, C. Wunsch, D. Behringer,
T. Birdsall, M. Brown, R. Heinmiller,
R. Knox, K. Metzger, W. Munk,
J. Spiesberger, R. Spindel, D. Webb
and P. Worcester

A field test of ocean acoustic tomography was conducted in 1981 for a two month period in a 300 km square at 26°N, 70°W in the North Atlantic (just south of the MODE region). Nine acoustic deep-sea moorings with sea floor transponders for automated position keeping and with provisions for precise timekeeping were set and recovered. From the measured travel times between moorings, various displays of the three-dimensional field of sound speed (closely related to temperature) have been obtained by inversion procedures. These procedures use historical ocean data as a reference, but all information for the in situ surveys has been withheld; the "pure" tomographic results were then compared to direct in situ observations. The tomographically derived spatial mean profile compares favorably to an equivalent profile from the in situ observations; both differ significantly from the historical average. Maps constructed at three day intervals for a two month period show a pattern of eddy structure in agreement with the direct observations within computed mapping errors, but these mapping errors are too large for many oceanographic purposes. The mapping errors are the result of an unexpectedly large variance in travel time. (A 1983 experiment, using sources with larger bandwidth, reduced this variance to acceptable limits.) The 1981 tomographic results strongly suggest that the ocean sometimes undergoes transitions too rapid to be mapped over such large areas by shipboard observations.

In press: Journal of Physical
Oceanography.

Supported by: ONR Contract N00014-84-C-0199 and NSF Grant OCE82-14895.

WHOI Contribution No. 5833.

GULF STREAM VARIABILITY FOR
ACOUSTIC TOMOGRAPHY

P. Malanotte-Rizzoli, J.L. Spiesberger
and M. Chajes

Fluctuations of sound speed from average conditions in the Slope waters, Gulf Stream and Sargasso Sea are investigated from historical measurements. The

covariance of the sound speed fluctuations is computed as a function of horizontal distance from the north wall of the Gulf Stream in four different vertical layers. Above (below) 500 m the scales are greater (less) in the Slope water than in the Sargasso Sea, indicating a strong anisotropy in the covariance function. The empirical orthogonal functions (EOFs) of the vertical variability are also computed. The EOFs in the Sargasso Sea and Gulf Stream are similar but differ from the EOFs computed for the Slope water. For all three regions the first three EOFs describe about 95 percent of the variance. These statistical descriptions of sound speed variability are useful for mapping Gulf Stream variability using the techniques of ocean acoustic tomography.

In press: Deep Sea Research.

Supported by: ONR Contract N00014-84-0278.

WHOI Contribution No. 5759.

LINEARIZED GEOPHYSICAL INVERSIONS IN LATERALLY INHOMOGENEOUS MEDIA: BIASES

John L. Spiesberger

Geophysical inversions whose data consist of travel time differences between measured and reference acoustic ray paths are inherently nonlinear because the ray paths are functions of the model. Each datum is composed of a linear and a nonlinear constituent. Because the nonlinear constituent is insensitive to the changes of the positions of lateral inhomogeneities (whose scales are small compared with the range of the ray) within the medium being modelled, linearized inversions yield biased results. If a spectrum of the lateral inhomogeneities is known, the nonlinear problem can be inverted. In application to ocean acoustic tomography at gyre scales (>1000 km), lateral inhomogeneities due to the mesoscale eddy field (100 km horizontal scale, 1 part in 300 sound speed variation) can cause significant nonlinearities.

Supported by: NSF Contract OCE82-14895 and ONR Contract N00014-84-C-0199.

WHOI Contribution No. 5754.

NON-RECIPROCITY OF ACOUSTIC RAY TRAVEL TIMES SUBJECT TO MESOSCALE CURRENTS

John Spiesberger

The difference of the travel times of acoustic rays due solely to non-reciprocity of the ray paths in a mesoscale current field between fixed transceivers separated by a long range (~ 1000 km) is predicted to be only a few microseconds.

Supported by: ONR Contract N00014-82-C-0019 and NSF Grant OCE80-17309.

WHOI Contribution No. 5770.

OCEAN ACOUSTIC TOMOGRAPHY: TRAVEL-TIME BIASES

John L. Spiesberger

The travel times of acoustic rays traced through a climatological sound speed profile are compared with travel times computed through the same profile containing an eddy field. The exact travel time difference is compared with its constituent terms, one of which is linearly related to the deviation of sound speed (referenced to the climatological profile) and the others which are nonlinearly related to the deviation. At ranges that are much greater than the eddy scale and for eddy fields whose range-averaged temperature anomaly is small, the numerical results are: 1) the values of the nonlinear terms are insensitive to changes in the positions of the eddies, and 2) the nonlinear terms are approximately proportional to the range between the source and receiver and to the square of the eddy anomaly. At 1084 km range in the east Atlantic at 24°N (36°N), the nonlinear terms can account for 17 percent (90 percent) of the exact travel time change where the temperature anomalies associated with the eddies are typically $\pm 0.5^{\circ}\text{C}$ ($\pm 1^{\circ}\text{C}$).

Linear inversions (based on the linear estimator of the travel time difference) which use the exact travel time difference for data yield biased results since the average values of the nonlinear terms are not zero. If an a priori knowledge of the eddy spectrum is known, the nonlinear terms could be computed for each ray and subtracted from the exact travel time change. It may then be beneficial to use the corrected set of travel time differences in a linear inversion which would require no iteration.

In press: Journal of the
Acoustical Society of America.

Supported by: ONR Contract N00014-82-C-0019 and NSF Grant OCE80-17309.

WHOI Contribution No. 5722.

SIGNAL PROCESSING IN OCEAN TOMOGRAPHY

Robert C. Spindel

This paper addresses acoustic signal processing issues that have arisen in designing systems to measure the sound speed and current fields of the ocean using time-of-flight acoustic tomography. The systems are based on a scheme first proposed by W. Munk and C. Wunsch in 1979, who suggested that dynamic ocean processes could be observed by measuring the change in travel time of acoustic signals transmitted over a number of ocean paths. The travel time is subject to alteration in proportion to the magnitude of the sound speed and current inhomogeneities along each path. An estimate of these quantities can be obtained using inverse techniques.

Published in: Proceedings to the NATO Advanced Study Institute on Adaptive Methods in Underwater Acoustics, 1984.

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WHOI Contribution No. 5661.

SOUND TRANSMISSION IN THE OCEAN

Robert C. Spindel

The ocean is a fluid waveguide, bounded by the air/sea surface above and the topography of the bottom below, through which sound propagates according to the scalar wave equation,

$$D^2 p = c^2 \nabla^2 p, \quad (1)$$

where p is the acoustic pressure perturbation, c is the speed of sound, the operator $D = \partial/\partial t + \mu$, and ∇ represents the material derivative in the presence of a fluid velocity field μ . The sound speed and μ are functions of all spatial coordinates and time, but simplifying assumptions are usually made. Sound speed variations in range are weak compared with vertical variations; to first order they are neglected. The velocity field of the fluid is generally taken to be zero because it is much less than the sound propagation speed. Furthermore, for a large class of problems of practical interest, the temporal scale of oceanic variation is much greater

than the duration of an acoustic transmission so that variations with t can be neglected. Thus the classic problem in sound transmission in the ocean consists of solving the simplified wave equation,

$$\partial_p^2 / \partial t^2 = c^2 \nabla^2 p, \quad (2)$$

for a variety of sound speed versus depth profiles, $c(z)$, and boundary conditions. During the period between 1912, when the Titanic disaster stimulated work on acoustic echo ranging systems for iceberg detection, and the Second World War, the predominant activity in ocean acoustics was the development of hydroacoustic transducers for transmitting and receiving sound, mostly for echo and depth ranging systems (Lasky 1974). Acoustic modelling requirements were not very sophisticated and were satisfied by solutions to this range and time invariant form of the wave equation. Much of the research in modern ocean acoustics has to do with the more complicated propagation picture that emerges when less restrictive, more realistic, conditions are allowed.

Published in: Annual Review of Fluid Mechanics, 17, 217-237, 1984.

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WHOI Contribution No. 5644.

RECIPROCAL ACOUSTIC TRANSMISSIONS: RESULTS FOR MESOSCALE MONITORING OF OCEAN CURRENTS

Peter F. Worcester, Robert C. Spindel
and Bruce M. Howe

By simultaneously transmitting acoustic pulses in opposite directions between two points in mid-ocean, one can separate current effects on acoustic propagation from the effects of sound-speed structure. Reciprocal acoustic transmissions can, therefore, be used to measure ocean currents. Acoustic transceivers have been designed and built to measure the mean currents between two points separated by 300 km. The equipment functioned satisfactorily during a short test conducted during 1983. Preliminary analysis for that experiment has yielded differential travel times that appear reasonable, but more work is required to relate the differential travel times to meaningful ocean current estimates.

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WHOI Contribution No. 5769.

O C E A N D Y N A M I C S

A DESCRIPTION OF THE BOTTOM BOUNDARY LAYER AT THE HEBBLE SITE: LOW FREQUENCY FORCING, BOTTOM STRESS AND TEMPERATURE STRUCTURE

William D. Grant, Albert J. Williams, 3rd
and Thomas F. Gross

A preliminary description of the bottom flow at the HEBBLE site (~ 4800 m) is presented based on bottom tripod measurements in the lower five meters of the bottom mixed layer (extending to within 30 cm of the seabed) and thermistor measurements extending through the mixed layer (up to 110 m). Two different deployment periods are described covering approximately four days in April of 1983 and eighty days from June to September 1983. The near bottom flow during the eighty day period is composed of low frequency motions with fluctuations of 20 days or greater with less energetic fluctuations of tidal and inertial periods riding on the flow. The speed at one meter during the long deployment varies from 0 to 17 cm/sec suggesting that the boundary layer depth should also be modulated at low frequency. Direct Reynolds stress estimates during times of moderate flow indicate the local boundary layer height is reasonably estimated using a simple drag law and classical scaling (u_*^2/f). The mixed layer depths observed at the site are 30-70 meters, corresponding to boundary layer thicknesses estimated for the strongest flows observed and are typically more than five times the estimated boundary layer thickness for moderate flows.

Two flow events observed during the 80 day record correspond to weak and moderate benthic storms during which significant sediment resuspension occurs. One event has eastward flow and the other westward. The potential importance of the role of superposition of fluid motions of several frequencies in determining the magnitude of such storms is demonstrated by comparing these two events.

In press: Journal of Marine Geology.

Supported by: ONR Contract N00014-82-C-0019.

WHOI Contribution No. 5703.

THE VERTICAL STRUCTURE OF TURBULENCE BENEATH GENTLY BREAKING WIND WAVES

E.A. Terray and L.F. Bliven

We present a preliminary analysis of the turbulence energy budget beneath gently breaking laboratory wind-waves. A linear filtration procedure is employed to separate the wave-induced and turbulent motions. The data show a single Kolmogorov inertial subrange and are consistent with observations in the outer layer of a wall-bounded shear flow. However, the turbulent velocity is more intermittent close to the surface than would be expected on the basis of this analogy.

Published in: Proceedings of Symposium on Wave Breaking, Turbulent Mixing and Radio Probing of the Ocean Surface, Tohoku University, Sendai, Japan.

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WHOI Contribution No. 5825.

S U B M E R S I B L E

E N G I N E E R I N G

USER MANUAL FOR THE ALVIN DISCRETE DATA SYSTEM

John J. Akens

The ALVIN Discrete Data System is a subset of the ALVIN Data System which in turn is a subset of the ALVIN/ATLANTIS II Data System. This paper describes both of these major systems briefly and then provides detailed coverage of five general topics related to the Discrete Data System. Details are provided to enable a user to connect instruments to the system. Operating instructions are given for using the system either in ALVIN, or remotely from ATLANTIS II's top lab. A summary of presently available data replay programs is given, along with information required to extend many of these programs. A system for transferring data files to other computers is described. Finally, the file structure for data files is given to enable users to write their own replay programs, if desired.

Supported by: NSF Grant OCE83-20508.

WHOI Technical Memorandum No. 3-84.

WOODS HOLE FORTH

John J. Akens

Woods Hole FORTH, called WORTH, is a real time language for the RCA 1806 micro-processor. It follows the fig-FORTH standard and is used by ALVIN for data acquisition and display tasks, plus play-back and processing tasks at sea and ashore. WORTH is optimized for simple networking with RS-232 uarts. Programs can be installed in Eprom for use in unattended systems and can be configured to run a specific task when power is applied. The error handling can be customized to permit continued operation when errors are encountered. Extensive utilities and development tools are included such as full screen editor, the fig line editor, a single pass assembler, floating point support, disk file access, communication utilities for uploading or downloading files or blocks of memory, and documentation utilities. The complete sources and a glossary for WORTH are included in this publication. Versions are supplied which include compiled development, floating point, and assembler utilities.

Supported by: NSF Grant OCE83-20508.

WHOI Technical Report No. 84-46.

ATLANTIS II: A NEW SUPPORT SHIP FOR ALVIN

Barrie B. Walden and Arnold G. Sharp

R/V LULU, a small, slow, single purpose catamaran vessel, has been operating as mother ship for the research submersible ALVIN since its construction in 1965. It has covered 136,000 miles in support of 1,300 science dives, exceeding its intended life and demonstrating the need for a more capable support vessel. ATLANTIS II, a 210 ft. research ship selected as LULU's replacement, has been refitted for submersible support. Her general oceanographic capability has been retained, so that future voyages may involve more than one mission. The new submersible handling system utilizes a stern-mounted A-frame with a single point lift. The ALVIN structural frame has been modified to permit lifting from above by a single rope.

Published in: 1984 IEEE Oceans.

Supported by: ONR Contract N00014-82-C-0019 and NSF Grant OCE82-14507.

WHOI Contribution No. 5812.

UNDERWATER ROBOTICS

REMOTELY OPERATED VEHICLE DEVELOPMENT AT WOODS HOLE'S DEEP SUBMERGENCE LABORATORY

Robert D. Ballard

The Deep Submergence Laboratory (DSL) of the Woods Hole Oceanographic Institution was established in 1983 to continue the Institution's effort in deep submergence technology. In addition to supporting the manned submersible ALVIN, DSL is developing and operating a variety of unmanned vehicle systems used from both surface ships and submersibles. DSL's emphasis is upon large area search and close-up inspection with its present operational systems including ANGUS, Mini-ANGUS, a Klein side-scan sonar, and the Benthos RPV. In addition to these operational systems, DSL is presently upgrading its 6,000-meter remotely operated vehicle, AMUVS, for use off ALVIN and SEA CLIFF, placing a variety of instrument systems on the NR-1, procuring and testing a Sea MARC I sonar system, and developing a new search and inspection vehicle system called ARGO/JASON. The purpose of this paper is to summarize DSL's overall program. Three separate papers concentrate on more detailed technical discussions of AMUVS, ARGO, and JASON as well as our robotic and control systems programs.

In press: 'Proceedings of the
Remotely Operated Vehicle, San
Diego, May 1984.

Supported by: ONR Contract N00014-82-C-0743.

WHOI Contribution No. 5620.

DEVELOPMENT STATUS: ARGO DEEP OCEAN INSTRUMENT PLATFORM

Stewart E. Harris, William M. Marquet
and Robert D. Ballard

The Deep Submergence Laboratory is developing a deep ocean survey and instrument platform called ARGO. With a design depth of 6,000 meters, ARGO will be towed on a steel-armored co-axial cable which will support several channels of frequency-multiplexed signals. A bank of TV cameras in the imaging pod will provide forward-, side-, and down-looking views of the ocean floor. Strobe lighting and LIBEC geometry will extend the useful range of these cameras to 100 meters. High fidelity acoustic images will be provided by an

integrated side-looking sonar. Our goal is to create a cohesive and overlapping data set of wide swath acoustic images and high resolution optical images. Presented here are early results of ARGO-like vehicle towing characteristics and "snap-shot" video systems. Additionally, we will describe ARGO's modular design approach which affords us the flexibility to incorporate, in the future, additional sensing systems and a smaller, tethered ROV, JASON.

Published in: Proceedings of the
Remotely Operated Vehicle, San
Diego, May 1984.

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C-0743.

WHOI Contribution No. 5619.

AN ADVANCED OBSERVATION AND INSPECTION
REMOTELY OPERATED VEHICLE FOR 6,000
METER OPERATIONS

W.K. Stewart

The Deep Submergence Laboratory of the Woods Hole Oceanographic Institution is developing an enhanced version of the Advanced Maneuverable Underwater Viewing System. The small, highly maneuverable observation and inspection ROV was designed to operate from a manned submersible to a depth of 6,000 meters. The reconfigured system will be controlled from ALVIN or other manned vehicle, from a surface vessel as a towed body subsystem, or from a stand-alone laboratory development console. Analog and discrete subsystems are being eliminated in favor of digital architecture and integrated circuits. Microprocessor-based telemetry and control contribute to a compact, economical design, and a software control scheme offers flexibility and improved performance. Particular attention is given to operator interactions with the system. Keyboard, joystick, and voice recognition and speech synthesis peripherals are being assessed for contributions to control performance.

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WHOI Contribution No. 5621.

MAN MACHINE INTERFACE AND CONTROL
CONCEPTS FOR THE JASON PROGRAM

Dana R. Yoerger

A research program is underway to improve the work capabilities of small, tethered ROVs. An advanced supervisory control system that allows the human operator to control the motions of both the vehicle and manipulator in a coordinated fashion is currently under development. The goal of the system is to allow the human supervisor to think in terms of end effect or motions rather than using separate vehicle and manipulator commands. The resulting supervisory control system will be implemented first in computer simulation, then on an experimental prototype vehicle system consisting of a Benthos-430 and Deep Ocean Engineering manipulator. After sufficient development and experimentation, the supervisory control system will be used on JASON, a deep-ocean tethered ROV that will emerge from the towed ARGO vehicle. JASON will include stereo imaging, dual manipulators, and a fiber-optic telemetry system.

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ROBUST TRAJECTORY CONTROL OF UNDERWATER
VEHICLES USING NONLINEAR
DESIGN TECHNIQUES

Dana R. Yoerger and
Jean-Jacques E. Slotine

A recently developed variation on-sliding control is shown to be very effective for the control of underwater vehicles. Underwater vehicles present difficult control system design problems due to their nonlinear dynamics, uncertain models, and the presence of disturbances that are difficult to measure or estimate. The method presented deals directly with nonlinearities, is highly robust to imprecise models, and is intuitively appealing. Using a nonlinear vehicle simulation, the relationship between model precision and performance is examined. The results show that adequate controllers can be designed using simple nonlinear models, but that performance improves as models are made more precise and that the improvements can be predicted quantitatively.

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WHOI Contribution No. 5802.

DEPARTMENT OF PHYSICAL OCEANOGRAPHY
Nicholas P. Fofonoff, Department Chairman

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COASTAL CIRCULATION

AND DYNAMICS

THE NANTUCKET SHOALS FLUX EXPERIMENT (NSFE79)

PART I: A BASIC DESCRIPTION OF THE CURRENT AND TEMPERATURE VARIABILITY

Robert C. Beardsley, David C. Chapman,
Kenneth H. Brink, Steven R. Ramp,
and Ronald J. Schlitz

The Nantucket Shoals Flux Experiment (NSFE79) was conducted across the continental shelf and upper slope south of Nantucket from March 1979 to April 1980 to study the flow of shelf water from the Georges Bank/Gulf of Maine region into the Middle Atlantic Bight. The experiment included a moored array of current meters and bottom instrumentation deployed at six locations across the shelf and upper slope spanning a depth range from 46 m to 810 m and supporting hydrographic observations. A basic description of the moored current and temperature data is given here with an emphasis on the low-frequency variability.

In the summer period (April-August) when the local vertical stratification reached a maximum due to increased surface heating and reduced wind mixing, the mean flow over the shelf at all instruments was primarily along local isobaths towards the west. The subtidal current fluctuations were coherent both horizontally and vertically over the shelf but not with current fluctuations observed over the upper slope. The wind stress during summer was weak and only moderately correlated with the subtidal current fluctuations.

In the winter period (October-March), when the seasonal thermocline was destroyed and the shelf water locally homogenized by increased surface cooling and wind mixing, the mean currents observed over the shelf were also primarily alongshelf towards the west at speeds comparable to those measured in summer. However, the low-frequency current fluctuations over the shelf were much more energetic in winter. These subtidal current fluctuations were highly coherent horizontally and vertically over the shelf and with surface wind-stress fluctuations (which increased in magnitude by a factor of five over the summer period). The most energetic subtidal current events observed over the shelf also tended to extend into the upper slope region.

The subtidal currents observed over the upper slope in summer were dominated by three bursts of large eastward currents which correspond to the passage of anticyclonic Gulf Stream warm core rings near or

through the moored array. The effect of these rings on the current field does not appear to penetrate shoreward of the shelf break. In winter only two rings passed near the array and their influence on the observed upper slope currents was unclear due, in part, to the increased subtidal current variability caused by the stronger synoptic wind forcing in winter.

Multiple regression analysis was used to identify possible annual variations in the NSFE79 moored current and temperature data. Significant annual variations were found in the temperature field over the shelf and upper slope and in the low-frequency current variability over the shelf. No significant annual variation was observed in the alongshelf current over the shelf, however, suggesting that there is, at least on time scales of one month and more, a continuous flow of shelf water into the Middle Atlantic Bight from the Georges Bank/Gulf of Maine region. The mean westward volume flux between the 40 and 120 m isobaths observed in NSFE79 was $38.3 \pm 6.9 \times 10^4 \text{ m}^3/\text{sec}$.

In press: Journal of Physical
Oceanography.

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WHOI Contribution No. 5654.

DISCHARGE OF THE CHANGJIANG (YANGTZE RIVER) INTO THE EAST CHINA SEA

Robert C. Beardsley, Richard Limeburner,
Honghua Yu and Glenn A. Cannon

Hydrographic and current meter data collected in the East China Sea during June 1980, August 1981, and November 1981 have been used to describe the spatial and temporal structure of the Changjiang (Yangtze River) discharge over the inner and mid-continental shelf off Eastern China. In summer during high runoff, the freshwater discharge near the mouth of the Changjiang exhibited a bimodal distribution, with the freshest water extending in a band to the south along the coast and a relatively shallow, low salinity plume-like structure extending offshore on average towards the northeast. Relatively warm, saline bottom water characteristic of the Taiwan Current Warm Water flowed into the Changjiang estuary along a submerged relic river valley. Direct current measurements suggest that significant transient offshore fluxes of relatively fresh Changjiang water can also occur from the southward flowing coastal current south of the Changjiang estuary. In winter, the reduced Chang-

jiang discharge flowed southward in a narrow band confined to the coast. Some possible physical causes for the observed structure of the Changjiang discharge are presented.

In press: Continental Shelf Research.

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WHOI Contribution No. 5744.

INTRUSIONS OF OUTER SHELF AND SLOPE WATER
WITHIN THE NEARSHORE ZONE
OFF LONG ISLAND, NEW YORK

James H. Churchill

From 1974 through 1978 a series of studies detailed physical properties of the waters within 15 km of the southern Long Island coastline. These studies involved measurement of temperature, salinity, and water velocity by hydrographic surveys and from moored instruments. Data of late summer reveal frequent intrusions of anomalous water which appear to be of slope or outer shelf origin. Three intrusions of notably differing character are described. Two occurred at mid-depth, within the pycnocline. Concurrent hydrographic and current meter data suggest that these water masses were transported shoreward due to circulation forced by wind stress and by longshore density gradients. The third intrusion was initially observed near the surface and was of anomalously high temperature. Its temperature/salinity relation was similar to a warm and salty bolus detected 12 days earlier in the mid-shelf region. Hydrographic data suggest that this bolus may have been a detached slope water parcel. Such intrusions may commonly occur during the summer and fall and may be related to the appearance of tropical fish in the Long Island vicinity during these seasons.

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WHOI Contribution No. 5660.

PROPERTIES OF FLOW WITHIN THE COASTAL
BOUNDARY LAYER OFF LONG ISLAND, NEW YORK

James H. Churchill

Properties of flow within the nearshore waters off the southern coast of Long Island are established by statistical analysis of data from a moored current meter

array and by concurrent hydrographic information. Upwelling-downwelling episodes dominate sub-diurnal frequency fluctuations of the flow within a coastal boundary layer of about 10 km width. The structure of the boundary layer appears to be baroclinic during the presence of a pycnocline and is also influenced by frictional effects because of the increase of bottom depth with distance from shore. Significant mean offshore flow is evidenced by measurements taken in autumn and late summer, despite negligible mean wind stress during the same periods. This flow is most likely related to the large longshore density gradients which are consistently inferred from hydrographic data taken in the vicinity. During events of roughly constant wind heading, the cross-shore flow of a particular direction is often confined within a distinct density band. This has made it possible to detect and estimate cross-shore flow unresolved by the current meter array.

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WHOI Contribution No. 5716.

THE RESPONSE OF STRATIFIED, FRICTIONAL
FLOW OF SHELF AND SLOPE WATERS TO
FLUCTUATING LARGE-SCALE, LOW-FREQUENCY
WIND FORCING

Allan J. Clarke and Kenneth H. Brink

Numerical and analytical models are developed to discuss large-scale, low-frequency, wind-driven fluctuations over the continental shelf and slope in the presence of realistic density stratification and bottom friction. The models employ the "long-wave" assumption that frequencies are small relative to the inertial frequency and that alongshore scales are large relative to cross-shelf scales. An attempt is made to make the effect of bottom friction on the flow as realistic as possible by taking into account the influence of surface gravity waves on bottom stress. The results were obtained for sinusoidal wind forcing having frequency ω and alongshore wave number ℓ and are described below.

(i) A general criterion for barotropic shelf water response for wind forcing frequencies ω in the 'weather' band ($2\pi/\text{few weeks}$ to $2\pi/\text{few days}$) can be derived. For the purpose of rapid calculation, this criterion reduces, approximately, to $N_s^2 \alpha^2 f^{-2} \ll 1$ where N_s^2 is a shelf averaged value of the buoyancy frequency squared, α is an averaged shelf bottom slope, and f is the Coriolis parameter. The criterion implies that shelf waters

respond barotropically on non-narrow non-equatorial shelves. Under the more restrictive condition $N_s \alpha f^{-1} \ll 1$, analysis shows that the shelf edge pressure is zero and essentially all the wind-driven fluctuating flow occurs on the shelf.

(ii) Bottom stress enhancement due to surface gravity waves can significantly affect the low-frequency, large-scale flow.

(iii) As an indication of how the numerical model can be used to determine the stratified frictional shelf and slope water response, calculations were performed for the CODE (Coastal Ocean Dynamics Experiment) region. We found that currents were usually strongest nearshore with a monotonic decrease in amplitude offshore and no zero crossings. Current amplitudes tended to decrease with depth, particularly over the slope. Nearshore fluctuations generally led those farther offshore in time. For 1 dyne cm^{-2} wind stress forcing, typical along-shore current velocity amplitudes decreased from about $15\text{--}25 \text{ cm s}^{-1}$ nearshore to $1\text{--}15 \text{ cm s}^{-1}$ at the shelf edge.

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WHOI Contribution No. 5697.

CIRCULATION INDUCED BY RIVER INFLOW IN WELL-MIXED WATER OVER A SLOPING CONTINENTAL SHELF

Gabriel T. Csanady

The pressure field over a sloping continental shelf subject to freshwater runoff at the coast can be resolved into a nearly two-dimensional dynamic height field and a residual field, the latter arising from the interaction of baroclinity and topography. The residual field is essentially three-dimensional and so constituted as to supply the fluid for the baroclinic alongshore flow off a coastal source of buoyancy associated with the cross-isobath density gradients. The intensity of the induced residual circulation (its total transport in $\text{m}^3 \text{s}^{-1}$) varies directly with the buoyancy input and bottom slope, and inversely with the zero-order alongshore flow velocity and Coriolis parameter. Over the Mid-Atlantic Bight continental shelf the runoff-induced residual circulation makes a generally weak contribution to the observed mean flow field. It could, however, be more important over a low latitude shelf subject to high runoff.

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WHOI Contribution No. 5603.

THE INFLUENCE OF WIND STRESS AND RIVER RUNOFF ON A SHELF-SEA FRONT

Gabriel T. Csanady

Runoff from land gives rise to the formation of a front-jet system separating fresher coastal waters from more saline waters offshore over some continental shelves, notably in the Mid-Atlantic Bight in winter. Three first-order characteristics of such fronts are the anchor depth H , where the front intersects the bottom, the stretch ℓ , i.e., the distance between its surface and bottom intersections, and the buoyancy contrast b across the front. The three characteristics may be determined from the cross-front property transfer rate, the along-front momentum balance, and the turbulence-energy dissipation rate. Key independent variables are the horizontal buoyancy transport B_x , the friction velocity u_* and direction θ of the wind, and the Coriolis parameter f . Simple approximate formulae connecting dependent to independent variables are

$$fH/u_* = m(u_*^3/B_x)\cos\theta,$$

$$f\ell/u_* = (m/\lambda)\cos\theta,$$

$$b/fu_* = \mu^{-1}[B_x/(u_*^3 \cos\theta)],$$

where m , λ , and μ are constants of order 300, 1, and 0.1 respectively. The entrainment rate across the front is $\mu u_*^2 f^{-1} \cos\theta$, which is small compared to Ekman transport on some continental shelves, but possibly not on all.

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WHOI Contribution No. 5633.

"PYCNOGRAPHIC" CURRENTS OVER THE UPPER CONTINENTAL SLOPE

Gabriel T. Csanady

The dynamic interaction of a sloping seafloor with along-isobath density variation is calculated for cases involving a sharp pycnocline and a surface to bottom front. The pycnocline is supposed to consist of horizontal generators, running perpendicularly into a steep continental slope; the bottom trace of the surface to bottom front is supposed to cut across

isobaths. The calculations are diagnostic and make use of linearized equations with a linear bottom friction term.

The results illustrate the manner in which the cross-isobath baroclinic flow is converted at the slope into a barotropic flow field, with velocities nearly parallel to the isobaths. The "forward" portion of the slope (that which lies in the direction of Kelvin wave propagation) is affected if there is only one inflow or outflow region. However, for equal and opposite inflow and outflow, a closed circulation pattern arises connecting these two regions, accompanied by a secondary closed circulation forward of both the inflow and outflow legs. The pressure distribution at the coast is a strongly filtered and phase-shifted version of the offshore steric height variation.

In the example of a surface to bottom front, the divergence of the intensifying baroclinic flow over increasing depth is again drawn from the forward sector, or discharged into that sector, when the baroclinic flow is convergent, i.e. passes from deep into shallow water.

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WHOI Contribution No. 5821.

A ZERO POTENTIAL VORTICITY MODEL OF THE NORTH BRAZILIAN COASTAL CURRENT

Gabriel T. Csanady

The North Brazilian Coastal Current (NBCC) is idealized as an inertial, surface layer jet of equatorial origin, intruding along the coast into a northern water mass of constant, positive potential vorticity. Dissipation is accounted for by supposing that some equatorial water leaks out in the northwest corner of the intrusion. The problem is closed by adopting the free streamline boundary condition (between the northern and equatorial water masses) of continuous layer depth and velocity.

Calculations are made for flow (intruding and return) supposed parallel to the coast; this approximation is verified *a posteriori*. The results show a narrow intrusion region along the coast, equatorial fluid flowing northwestward next to the coast, peeling off and returning along the boundary streamline. When no leakage is postulated, the northern limit of the intrusion becomes a stagnation point where the coast and the boundary streamline meet. With substantial leakage postulated, the flow chokes at some limiting latitude, where the inviscid inertial model breaks down. However, a realistic intrusion-

return flow pattern is calculated south of the choking latitude for a number of different illustrative cases. The key control parameter is the potential vorticity of the northern water mass or, in a nondimensional form, the ratio of the rest-depths at a given latitude of the equatorial and northern water masses.

The model accounts for a number of observed facets of NBCC behavior, notably its seasonal cycle, magnitude of the transports, intrusive and return flow.

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WHOI Contribution No. 5702.

HYDROGRAPHIC AND CURRENT OBSERVATIONS ON THE CONTINENTAL SLOPE AND SHELF OF THE WESTERN EQUATORIAL ATLANTIC

Charles N. Flagg and Scott E. McDowell

Hydrographic and current profile data from the slope and shelf region of the western equatorial Atlantic between 2 and 7°N are used to describe the character of the North Brazil Coastal Current (NBCC). The most significant feature of the data is the clear distinction between the upper and lower layers of this current system. The upper NBCC has a width which decreases from 250 to 150 km between 2 and 5°N with observed maximum currents at the time of the cruise of between 100 and 130 cm/sec. The lower layer NBCC, which extends from the top quarter of the thermocline to at least a depth of 500 meters, is approximately 200 km wide with typical current magnitudes of 40 cm/sec. The lower layer NBCC water properties are characterized by relatively low temperatures and salinities and high dissolved oxygens. At the base of the upper layer, the core of the NBCC is initially distinguished by relatively high temperatures, salinities, and dissolved oxygen values. In the region of the turnoff of the lower layer these values are all reduced somewhat by the advection offshore of near-shore NBCC water by the lower layer. The current profile data are used to calculate the total potential vorticity field which shows the NBCC with negative potential vorticity in both layers as it crosses the equator. In both layers the negative vorticity is confined southeast of the lower layer point of separation from the coast. The turnoff of the lower layer is well resolved by the data showing virtually all the deep NBCC turning to the east. In the upper layer, the NBCC flows through the survey region without turning off; however, a return flow from the northwest of water with NBCC water characteristics is

observed. The transport of the NBCC in the upper layer is between 15 and 20 Sv with approximately 20 to 25 Sv in the lower layer. The transport of the return flow from the northwest in the upper layer is about 75 percent of the NBCC itself.

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WHOI Contribution No. 5670.

I N S T R U M E N T A T I O N

A NEW ALGORITHM FOR CTD OXYGEN CALIBRATION

W. Brechner Owens
and Robert C. Millard, Jr.

An algorithm for converting the Beckman dissolved oxygen probe variables with other data from a WHOI/Brown CTD/O₂ system to oxygen concentration is presented. Improvements over earlier oxygen algorithms are inclusion of an oxygen current bias and time-lag correction estimated using a non-linear, least-squares calibration to the titrated oxygen bottle samples. The calibration technique uses a quasi-Newtonian minimization scheme available in scientific subroutine libraries such as the "IMSL" library.

Oxygen probe parameters are found to be stable over several (as many as 25) stations and give typical rms errors in the deep water of 0.05 ml/l which is roughly the expected error for the bottle samples. Oxygen current biases can be equivalent to concentrations as large as .8 ml/l. Typical oxygen lag correction values, associated with diffusion times through the probe membrane, are in the range of 4 to 10 seconds. Examples from the North Pacific where the shallow oxygen minimum severely tests the algorithm and from the North Atlantic are shown, demonstrating the effectiveness of the algorithm for a wide range of oxygen profile shapes.

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WHOI Contribution No. 5679.

L A B O R A T O R Y M O D E L S

THE DEFLECTION OF A BAROCLINIC JET BY A WALL IN A ROTATING FLUID

John A. Whitehead, Jr.

The momentum integral of a baroclinic jet of fluid in a rotating frame determines the relative size of two jets which are produced when the jet is split by a wall. Due to lateral variation of velocity and depth of the jet, the percentage of fluid which goes to the right or left differs from that of the non-rotating jet which is generally assumed to have no shear. For a northern hemisphere jet of zero or constant potential vorticity, much more fluid flows to the right than to the left; for a jet normal to the wall, more than 65 percent goes to the right and less than 35 percent goes to the left.

In press: Journal of Fluid Mechanics.

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WHOI Contribution No. 5651.

LABORATORY OBSERVATIONS OF A FRESH WATER GRAVITY CURRENT ON A SHELF: THE GENERATION AND EFFECTS OF SHELF WAVES

John A. Whitehead, Jr.

A source of light water was started along the outside vertical wall of a cylindrical tank in uniform rotation. Like wall gravity currents studied previously, it had a nose which detrained eddies as it propagated. The gravity current then impinged upon a sloping wall after which the propagation speed of the nose and the width, and characters of the flow over the topography, were observed to change as follows: (1) the current became wider; (2) the current became more laminar; the detraining of eddies at the nose and off the side of the current decreased; (3) if the current was slower than fL , where f is the Coriolis parameter and L is width of the current, a shelf wave radiated ahead of the current and initiated a barotropic current in front of the nose; and (4) the current propagated more slowly and constantly decelerated. Evidence is presented that the slowdown was due to radiation of coastal waves rather than drag due to friction. Based on these observations, theoretical estimates of a maximum penetration length of the current along the shelf are developed. When the barotropic current ahead of

the nose hit a far vertical wall, a dramatic westward intensified current moved the current offshore. Implications for coastal currents on real shelves are discussed.

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WHOI Contribution No. 5851.

A POSSIBLE COHERENT STRUCTURE IN THE OCEAN: EDDY GENERATION BY A DENSITY CURRENT

John A. Whitehead, Jr.

In a rotating fluid dynamical laboratory experiment, a turbulent current of dense water next to a vertical wall generates a cyclonic vortex above it because of entrainment of the upper fluid into the lower density current. The cyclonic vortex moves along the wall possibly driven by its eddy "image." It moves away from its formation region, thus opening the possibility of the formation of a second gyre. Ultimately more gyres may be formed and lead to a regular street of vortices moving along the wall above the density current. It is not known whether this process happens in the ocean, but there is at least one observation of gyre activity above the density current of high salinity "Mediterranean" water which sinks into the Atlantic Ocean west of Gibraltar.

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WHOI Contribution No. 5832.

A MECHANISM FOR MAGMATIC ACCRETION UNDER SPREADING CENTRES

John A. Whitehead, Jr.,
Henry J. B. Dick and Hans Schouten

The most active volcanic zone on Earth occurs along the global mid-ocean ridge system where the lithosphere is pulled apart and new oceanic crust is created at rates between 10 and 200 km Myr⁻¹. This volcanism is segmented, and is concentrated along the axial valleys and highs of slow- and fast-spreading ridges respectively, with transform fault zones separating, and generally offsetting, each active ridge segment. Volcanic activity may be nearly absent at the ridge transform intersection where a slow-spreading ridge is offset and greatly reduced where a fast-spreading ridge is offset, implying thinner crust in these regions. The source of magmas erupted along ocean ridges is the underlying mantle, which undergoes decompression

melting when rising to fill the gap between the spreading plates. The resulting magma aggregates in the upper mantle and ascends to the crust due to its low density compared with the parent mantle rock. The melt is believed to pool in crustal magma chambers--whence it periodically erupts to the surface. Typically, the formation, ascent, and aggregation of magmas along the mid-ocean ridges is regarded two-dimensionally and modelled in a section through the crust and mantle across the strike of the ridges. Here, however, we consider the problem with a three-dimensional model for which we provide supporting geological evidence, in which the magmas rise as a result of a gravitational instability (modified Rayleigh-Taylor) in the underlying partial melt zone.

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WHOI Contribution No. 5668.

LARGE SCALE OCEANIC HEAT AND WATER PROPERTIES

STRONG-CURRENT EVENTS RELATED TO A SUBTROPICAL FRONT IN THE NORTHEAST ATLANTIC

Gerold Siedler, Walter Zenk
and William J. Emery

Long-term current and temperature meter records from moorings in the northern Canary Basin display strong-current events with time scales between one and three months and larger vertical scales. The data are compared to hydrographic surveys in the area that show a meandering subtropical front. The strong-current events are found to be related to the passage of the front through the mooring positions. An analysis of composite time series, for selected depths, indicates a westward propagation of frontal meanders. The frontal pattern is also found in geopotential anomalies inferred from historical XBT data sets, suggesting that the front is a persistent feature of the density field. In two cases strong-current events appear to be related to a Mediterranean Water lens.

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WHOI Contribution No. 5758.

HEAT AND FRESH WATER BUDGETS OF THE INDIAN OCEAN REVISITED

John M. Toole and Mary E. Raymer

Hydrographic data along 32°S are combined with temperature, salinity, and absolute horizontal velocity observations in the Agulhas Current off Durban to obtain new estimates of the heat and fresh water budgets of the Indian Ocean. The method used is that employed by Hall and Bryden (Deep-Sea Res., 29A, 339-359, 1982) in the North Atlantic. Assuming no net volume transport across 32°S, we obtain a value of $0.6 \times 10^{15} \text{W}$ for the net heat gain by the ocean north of 32°S and $-0.2 \times 10^6 \text{m}^3/\text{s}$ for the net precipitation minus evaporation plus run-off. The major sources of error are poor spatial resolution in the section along 32°S and the unknown strength of the flow from the Pacific to the Indian through Indonesia. The present result, when combined with recent findings for the South Atlantic and Pacific, suggests that the oceans contribute little to the net heat flux across 30°S effected by the ocean-atmosphere system.

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WHOI Contribution No. 5773.

OCEAN CIRCULATION

DIAGNOSTIC MODEL OF CIRCULATION IN THE EQUATORIAL PACIFIC OCEAN

Harry L. Bryden and Esther C. Brady

To investigate the processes which maintain the large-scale, annual-average thermal structure of the equatorial Pacific, the three-dimensional ocean circulation for a large area is determined from a diagnostic model applied to repeated, meridional hydrographic sections along 150°W and 110°W from 5°N to 5°S. Geostrophic balances are used to determine velocity profiles from 0 to 500 dbar across the boundaries of the region: zonal velocities across 150°W and 110°W at approximately 1°-latitude intervals from 5°N to 5°S and meridional velocities across 5°N and 5°S averaged over the zonal distance

between 150°W and 110°W. Poleward wind-driven flows across 5°N and 5°S based on climatological zonal wind stresses are added to the geostrophic velocities in the mixed layers. To achieve overall mass conservation, the reference dynamic height field at 500 dbar is adjusted at 4 of the 21 stations by about 1 dyn cm. Horizontal nondivergence is used to determine meridional velocities between 0.75° and 5° latitudes. Three-dimensional nondivergence is used between 0.75°N and 0.75°S to determine a vertical profile of vertical velocity at the equator. The resulting model circulation, which is generally consistent with previous interpretations, is then analyzed to estimate the heat budget for the region and the zonal momentum balance at the equator.

The model circulation requires an annual-average heat gain from the atmosphere of 57 W m^{-2} , which is consistent with existing estimates of air-sea heat exchange from bulk formula. The heat gain converts about $35 \times 10^{12} \text{cm}^3 \text{s}^{-1}$ of water flowing into the region with temperatures between 19° and 26°C into an equal amount of 27° to 28°C water flowing out of the region. Little of the heat gain warms the locally upwelled waters at the equator, however; rather, about half acts to increase the temperature of the westward flowing South Equatorial Current as it traverses the region and about half warms the poleward flow of water away from the equator. There is large upwelling at the equator extending down to 180 dbar with a maximum upward velocity of $2.9 \times 10^{-3} \text{cm s}^{-1}$ and upward transport of $21 \times 10^{12} \text{cm}^3 \text{s}^{-1}$ across the 62.5 dbar surface. Because this upwelling occurs in conjunction with the eastward flow of the Equatorial Undercurrent which shallows to the east, the flow is nearly along isotherms and the maximum cross-isotherm transport is only $7 \times 10^{12} \text{cm}^3 \text{s}^{-1}$ across the 23°-isotherm. Thus, the eastward and upward flows act to decrease the surface water temperature to the east. In combination with the atmospheric warming of the poleward surface flow away from the equator, this eastward and upward flow along isotherms creates the Cold Tongue in the equatorial Pacific, which is characterized by minimum surface temperature at the equator in any meridional section and colder surface waters to the east.

For the zonal momentum balance at the equator, the vertically integrated zonal pressure gradient balances about 80 percent of the climatological westward wind stress. Eastward and vertical advection of zonal momentum each acts to balance about 20 percent of the wind stress. The derived eastward stress profile suggests that eddy mixing extends deeper than 200 dbar at the equator and that there must be a substan-

tial divergence of the eastward eddy momentum flux to maintain the zonal momentum balance in this region.

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WHOI Contribution No. 5788.

PROFILING THE GULF STREAM WITH A CURRENT METER MOORING

Mindy M. Hall and Harry L. Bryden

A current meter mooring was deployed for one year at the mean position of the Gulf Stream at 68°W. With instruments from 400 m to 4000 m, it provides the first unambiguous evidence that the Gulf Stream extends from top to bottom of the water column. Using the strong cross-stream temperature structure to derive a horizontal coordinate related to temperature, we can estimate the width and transport of the Gulf Stream for four individual events and we can determine an average profile of the vertical and cross-stream structure of the Gulf Stream. A conservative estimate of transport for this average profile indicates that the Gulf Stream has a transport of $103 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ at 68°W.

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WHOI Contribution No. 5757.

ON THE RELATIONSHIP BETWEEN THE DEEP CIRCULATION AND THE GULF STREAM

Nelson G. Hogg and Henry M. Stommel

A kinematic argument is used to estimate the direction and amplitude of the recirculating gyre in the deep water associated with the Gulf Stream. The model consists of two layers separated by the thermocline. In the region between Cape Hatteras and the Grand Banks of Newfoundland, the depth of the bottom increases offshore, so the thickness of the lower layer generally increases offshore too. The exception is in the region of the Gulf Stream near the foot of the Continental Rise where the thermocline deepens so abruptly that the thickness of the lower layer actually decreases offshore locally. The amplitude and shape of a freely circulating gyre of uniform potential vorticity in the lower layer is determined by the horizontal distribution of its thickness (pattern of isopachs) and is compared to that inferred by other authors from

observations. A similar argument is used to explore the manner in which the Deep Western Boundary Current crosses under the Gulf Stream at Cape Hatteras.

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WHOI Contribution No. 5629.

ESTIMATES OF THE GEOSTROPHIC STREAM FUNCTION IN THE WESTERN NORTH PACIFIC FROM XBT SURVEYS

Chester J. Koblinsky, Robert L. Bernstein,
William J. Schmitz, Jr. and
Pearn P. Niiler

The upper ocean temperature and dynamic height fields are correlated in the western North Pacific Ocean. This relationship can be used to map a relative geostrophic stream function of the Kuroshio Extension using temperature data from expendable bathythermograph (XBT) surveys. We have examined the ability of the North Pacific ship of opportunity XBT program, known as TRANSPAC, to carry out this procedure. Estimates of 600/1200 dbar geostrophic shear were generated from the XBT data utilizing objective mapping techniques. These estimates were compared with measured currents at 600 m relative to 1200 m along 152°E from 27°N to 42°N. The estimated and measured relative currents are positively correlated, with an rms error of $\pm 6 \text{ cm/s}$ over a measured dynamic range of 30 cm/s. However, the XBT estimated shears consistently underestimate the measured currents by a factor of 2 to 3. The underestimate of the amplitude is the result of both undersampling and mapping procedures that eliminate high wavenumber contributions of the dynamic height variability. These factors appear to be responsible for previous differences in amplitude between directly measured and TRANSPAC XBT estimated values of relative eddy kinetic energy and Reynolds stress. The TRANSPAC XBT survey can only monitor qualitatively the dynamic topography of the Kuroshio Extension meanders and rings. The variability outside of the extension with a temperature range of 3°C cannot be resolved because of inaccuracies in the temperature-dynamic height relationship. To monitor the Kuroshio Extension variability in the future, it is recommended that TRANSPAC XBT resources in the western North Pacific concentrate on obtaining a denser sample of the field during the fall and winter seasons because of incomplete ship track coverage in spring and summer.

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THE 26-DAY OSCILLATION IN THE EQUATORIAL INDIAN OCEAN

James R. Luyten and Dean H. Roemmich

Observations of meridional velocities from an array of moored current meters in the equatorial western Indian Ocean reveal a strong oscillation with a period of approximately 26 days. The observations at nominal depths of 200, 500 and 750 meters are coherent over the array extending from 50°E to 62°E and show persistent westward and upward propagation of phase. The zonal wavelength of these oscillations is approximately 1400 km. A WKB model is used to interpret the upward phase propagation in terms of vertically propagating waves although the energetics are not found to be consistent with the WKB approximation.

These observations are consistent with the kinematics of a linear mixed Rossby-gravity wave, propagating energy downwards into the ocean. Comparisons between east and north components both on and off the equator and a direct but crude estimate of the zonal group velocity are also consistent with this interpretation.

The meridional oscillation is embedded in a slowly varying zonal oscillation of 180 days period so that we expect and observe a Doppler shift of the frequency of the meridional oscillation between different phases of the zonal motion.

The WKB approximation is shown to be a poor one for the observed vertical scale of the wave field. An alternative method is applied using a numerical integration of the vertical structure equation. This allows us to fit the vertical structure of both the phase, kinetic and available potential energy density. The vertical flux of total energy is estimated.

Such meridional oscillations are ubiquitous in the equatorial oceans, although they occur with various periods, vertical and zonal scales, and apparently different sources. Whatever the source, the equatorial oceans appear to respond strongly in this range of periods, where no other linear equatorial waves are available than the mixed Rossby-gravity wave. No conclusive source for the meridional oscillations in the Indian Ocean is identified, although crude kinematics suggest a source in the

vicinity of the thermocline in the Somali current during its onset.

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WHOI Contribution No. 5790.

EASTWARD FLOW THROUGH THE MID-ATLANTIC RIDGE FRACTURE AT 11°N AND ITS INFLUENCE ON THE ABYSSAL WATER MASS OF THE EASTERN BASIN

Michael S. McCartney, Sara L. Bennett,
Mary E. Raymer and Mary L. Bremer

The abyss of the Atlantic Ocean is longitudinally divided by the Mid-Atlantic Ridge. In the trough east of the Ridge the coldest and densest bottom waters are found in the tropical zone. West to east flow through fractures in the Ridge supplies these waters from the western trough, which is in turn supplied with diluted Antarctic Bottom Water from high southern latitudes by western intensified northward flow. Influence of eastward flow through the equatorial Romanche Fracture Zone on the western trough near the equator has been previously noted in property distributions. Data in the Vema Fracture Zone at 11°N have been mainly restricted to the region west of the sills (near 41°W). In 1983 CTD stations in and near the Vema Fracture Zone were collected well east of the sills. Substantial isopycnal slopes were detected within the Fracture Zone, indicative of geostrophic transports of perhaps 1 or 2 x 10⁶ m³/sec to the east. Additional CTD stations to the north in the interior of the eastern basin in 1981 and 1983 reveal a tongue of cold water emanating from the neighborhood of the Vema and flowing northwards in the eastern trough, with western intensification. At these temperatures, the Kane Gap Sill of the Sierra Leone Rise effectively blocks the Romanche Fracture Zone influence in the equatorial zone from the remainder of the eastern trough north of the Rise. Thus the eastward flow through the Vema Fracture Zone is inferred to be the source of the coldest, densest water in the eastern trough of the Atlantic Ocean north of the Sierra Leone Rise.

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WHOI Contribution No. 5858.

AVERAGE VELOCITY AND TRANSPORT OF THE
GULF STREAM NEAR 55°W

Philip L. Richardson

Long-term current measurements made with surface drifters, SOFAR floats at 700 m and 2000 m, and current meters at 4000 m have been combined to produce for the first time a vertical section of directly measured average zonal currents in and adjacent to the Gulf Stream. The results from the different data sets are remarkably consistent in showing three vertically coherent zonal jets--the Gulf Stream and two flanking countercurrents. The consistency in location, velocity and transport (per unit width) of these currents supports the conclusion that these are real features of the long-term average velocity field. The current jets coincide with a region of high eddy kinetic energy and its gradient, implying a dynamical connection.

The Gulf Stream is defined to be the eastward current bounded by the Countercurrents. The surface Gulf Stream is ~ 900 km wide and has a maximum eastward velocity of 28 cm s^{-1} at 39.5°N , averaged over a one degree latitude band. The Stream extends to the sea floor about 200 km south of its surface axis. The deep Stream is only ~ 200 km wide and has a maximum mean velocity of 7 cm s^{-1} . The total mean volume transport of the Stream is estimated to be $93 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ by fitting a smooth transport profile to the four directly measured values. About a third of this is depth-independent. Including estimates of local wind-driven surface velocity diminishes the total transport by $8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, to $85 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. The mean transport is significantly less than the estimated synoptic transport of the Stream in this region, approximately $150 \times 10^6 \text{ m}^3 \text{ s}^{-1}$.

The subsurface Stream is flanked by relatively narrow, westward flowing countercurrents. The combined westward transport of the countercurrents is more than enough to locally recirculate the increase of Gulf Stream transport over the $30 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ wind-driven component of the subtropical gyre, returned in a gyre scale flow. The northern countercurrent, located between the Stream and continental shelf and rise, transports $41 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. Part of this westward transport is the mean southwestward flow of the Western Boundary Undercurrent, which transports 10 to $15 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. The southern countercurrent is located between $35\text{--}37^\circ\text{N}$ and transports about $29 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. Part of this transport ($\sim 12 \times 10^6 \text{ m}^3 \text{ s}^{-1}$) is probably recirculated as eastward flow south of 35°N . The net transport across 55°W north of 35°N

is eastward and equal to $11\text{--}23 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (the low value includes the wind correction).

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WHOI Contribution No. 5623.

DRIFTING BUOY TRAJECTORIES IN THE
ATLANTIC NORTH EQUATORIAL COUNTERCURRENT
DURING 1983

Philip L. Richardson

During 1983, 21 freely drifting buoys measured trajectories in the vicinity of the Atlantic North Equatorial Countercurrent. These provide a visualization of the flow field and the first direct measure of the seasonal variation of the velocity during a single year. From February to May the buoys moved gradually westward. From June to December the buoys moved swiftly eastward with maximum speeds of 90 cm sec^{-1} located in the western Atlantic. The seasonal variation in current was similar to that measured by historical ship drifts except that the onset of the Countercurrent in 1983 was about a month earlier than usual. Of the buoys that drifted eastward in the Countercurrent, three went into the North Equatorial Current, two into the South Equatorial Current and seven into the Guinea Current.

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MOORED CURRENT METER MEASUREMENTS IN
THE ATLANTIC NORTH EQUATORIAL
COUNTERCURRENT DURING 1983

Philip L. Richardson

Current meters were moored at depths of 20, 50, 75 and 150 m near 6°N , 28°W from February 25 to September 13, 1983. From February to May the low frequency zonal velocity was slow and westward. From May to September the zonal velocity was eastward with peak (low passed) speeds up to 60 cm sec^{-1} . During July the eastward flow was approximately 40 cm sec^{-1} at all four depths. The surface and subsurface North Equatorial Countercurrent disappeared on a seasonal basis during 1983. Strong

fluctuations were observed with periods in the bands 1-2 months and 4-5 days. The amplitude of these fluctuations appeared to be maximum during the period of swift eastward Countercurrent flow.

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SOFAR FLOAT TRAJECTORIES ASSOCIATED WITH THE NEWFOUNDLAND BASIN

William J. Schmitz, Jr.

The connection between the current systems and water masses in the Newfoundland Basin and the North Atlantic Subtropical Gyre has been controversial for some time. SOFAR floats have now been launched in the Newfoundland Basin, and others observed to move there. Floats were typically deployed in pairs at nominal depths of 700 m (thermocline level) and 2000 m (deep). A thermocline level float set in the North Atlantic Current near 45°N drifted to about 50°N before recirculating, whereas the deep float deployed concurrently eventually moved south and west around the Grand Banks. A float pair deployed in the interior of the Newfoundland Basin moved in the mean consistent with a recirculation that transports roughly 15 to $20 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ above 2000 m depth (nominal). Three thermocline level floats have drifted from west of the Grand Banks into the Newfoundland Basin, whereas deep floats have not yet been observed to do so. A crude estimate of the implied transport above 2000 m depth (nominal) branching from the Gulf Stream System into the North Atlantic Current is 15 to $20 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. The evidence points to branching above but not below 2000 m, whereas the recirculation in the Newfoundland Basin penetrates below 2000 m in the float data.

The float pair deployed in the interior of the Newfoundland Basin exhibited significantly less energetic eddy motion than the float pair deployed in the vicinity of the North Atlantic Current. The estimated eddy kinetic energy in the thermocline in the North Atlantic Current is comparable to that observed for the Gulf Stream, whereas the deep eddy kinetic energy is notably less. The general structure of the eddy field (and mean flow) points to the type of horizontal or geographical inhomogeneity from strong current to interior regimes similar to that observed for the subtropical gyre.

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WHOI Contribution No. 5819.

NEAR EQUATORIAL CTD OBSERVATIONS AT 85°W IN OCTOBER 1982

John M. Toole

CTD data collected about the equator along 85°W between October 8 and 12, 1982, are used to investigate stratification changes in the upper 1 km associated with the 1982/83 El Niño. With respect to the thermal field observed in November 1981, virtually the entire section exhibited downward displacements in the upper kilometer of the water column. Observed displacements at the depth of the mean thermocline were large (~ 150 m) and relatively symmetric about the equator. Displacements around 1 km depth were near zero. This stratification change appears to have been produced by a zonal convergence of mass at temperatures above 15°C, with divergence below. Least square modal decompositions of the vertical displaced profiles revealed significant contributions from modes 1 and 2 with meridional structure consistent with Kelvin waves. The observations thus support current theories that relate El Niño onset in the eastern Pacific to anomalous wind forcing in the west.

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WHOI Contribution No. 5714.

RINGS, EDDIES

EDDY POTENTIAL VORTICITY FLUXES IN THE GULF STREAM RECIRCULATION

Ellen D. Brown, W. Brechner Owens and Harry L. Bryden

The local effect of the mesoscale eddy field on the mean potential vorticity distribution of the Gulf Stream recirculation region is determined from the quasigeostrophic eddy potential vorticity flux. This flux is calculated by finite difference of current and temperature time series from the Local Dynamics Experiment. This long-term array of moorings is the only

experimental data from which the complete eddy flux can be calculated. The total eddy flux is dominated by the term due to the time variation in the thickness of isopycnal layers. This thickness flux is an order of magnitude larger than the relative vorticity flux. The total flux is statistically significant and directed 217°T to the southwest with a magnitude of $1.57 \times 10^{-5} \text{ cm/s}^2$.

The direction of the eddy flux with respect to the mean large scale potential vorticity gradient from hydrographic data indicates that eddies in this region tend to reduce the mean potential vorticity gradient. The results are qualitatively consistent with numerical model results and with other data from the Gulf Stream recirculation region. The strength of the eddy transfer in the enstrophy cascade is comparable to the source terms in the mean enstrophy balance. The Austausch coefficient for potential vorticity mixing is estimated to be $O(10^7 \text{ cm}^2/\text{sec})$. An order of magnitude estimate of the enstrophy dissipation due only to the internal wave field shows that other processes must be important in enstrophy dissipation.

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WHOI Contribution No. 5805.

AN OBJECTIVE ANALYSIS OF THE POLYMODE LOCAL DYNAMICS EXPERIMENT

II. STREAMFUNCTION AND POTENTIAL VORTICITY FIELDS DURING THE INTENSIVE PERIOD

Bach Lien Hua, James C. McWilliams and W. Brechner Owens

An analysis is made of the geostrophic streamfunction, potential vorticity, and dynamical balances for the mesoscale flow during the Intensive Period of the POLYMODE Local Dynamics Experiment. The methodology is objective analysis based upon three-dimensional, anisotropic covariance functions and an expansion in the vertical modes of linear theory. The flow field during the Intensive Period is highly anisotropic in both vertical modes. The barotropic mode behaves as a propagating wave with significant rotation in the latter part of the period; its dynamical balances are substantially linear except at the time of the rotation, when there is also a transfer of energy from the first baroclinic mode. The baroclinic flow exhibits a frontogenetic intensification into a strong jet due to straining of an initially large-scale baroclinic flow by the barotropic wave, together with some aspects of phase propagation as well. The

baroclinic modal dynamical balance has identifiable linear contributions, but they are relatively weak compared to the nonlinear terms, in contrast with the barotropic modal balance. Comparisons are made with MODE analysis calculations of homogeneous, geostrophic turbulence.

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WHOI Contribution No. 5806.

UPPER OCEAN VELOCITY STRUCTURE OF GULF STREAM WARM CORE RING 82B

Terrence M. Joyce and Maureen A. Kennelly

Acoustic doppler current profiling of Warm Core Ring (WCR) 82B revealed changes in the velocity structure over much of the ring's seven month lifespan. As ring diameter decreased, peak speeds in the high velocity region decreased from 0.8 m s^{-1} in April 1982, to $.5 \text{ m s}^{-1}$ in August 1982. Azimuthally averaged velocities revealed the core of WCR 82B to be in near solid body rotation, with no measurable horizontal divergence at 100 m. In addition, potential vorticity was conserved in the ring core despite interactions with the Gulf Stream and large changes in ring size. Deviations from symmetry in WCR 82B were caused by superposition with the shelf-slope front, small cyclonic eddies, and upper layer mean flow.

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WHOI Contribution No. 5512.

WINTERTIME CONVECTION IN A GULF STREAM WARM-CORE RING

Terrence M. Joyce and Marvel C. Stalcup

Wintertime convection creates deep mixed layers which determine the water mass characteristics and potential vorticity for waters in the main pycnocline of the world ocean. Diabatic cooling is most intense in the northern hemisphere near the northwestern boundary of subtropical gyres where outbreaks of cold, dry continental air over warm surface waters produce large sensible and latent heat losses from the ocean. Gulf Stream warm-core rings containing warm salty Sargasso Sea Water are cast off to the north of the Gulf Stream in close proximity to the northeastern coast of North America. We have

observed the convective cooling of one of these rings, 82I, during January, 1982 from the USNS Bartlett. During one cold air outbreak, we calculate a net heat surface loss from the ring to the atmosphere of 800 W m^{-2} and a deepening of the surface mixed layer from 50 to 190 m. The heat budget for the ring required a lateral heat transfer with the surrounding Slope Water, approximately 40 percent of that to the atmosphere, in order to achieve a balanced heat budget. This lateral transfer, most likely limited to the upper 50 m of the ring, can be expressed as a sub-ring scale diffusivity of $2 \times 10^2 \text{ m}^2 \text{ s}^{-1}$. In addition, the permanent thermocline in the ring center was observed to deepen at a rate of 1 m day^{-1} , thus increasing the deep horizontal temperature contrast between the anticyclonic ring and its surroundings.

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WHOI Contribution No. 5701.

SMALL-SCALE CYCLONES ON THE PERIPHERY OF A GULF STREAM WARM-CORE RING

Maureen A. Kennelly, Robert H. Evans and Terrence M. Joyce

Small scale cyclones found around Gulf Stream warm core ring 82B are investigated using infrared satellite imagery and current information obtained with an acoustic-Doppler velocimeter. Currents in these cyclones reveal speeds ranging from 20 to 80 cm/sec. One small cyclone or "ringlet" found in June 1982 was studied extensively by removing the basic rotational velocities of 82B. The azimuthal velocity field for this ringlet was used with the gradient current equation to calculate the absolute dynamic topography at 100 dbars. It was found that the ringlet was 13 dynamic-cm lower than its surroundings. In addition, neglect of the centrifugal term would have changed the dynamic topography of the ringlet by 30 percent. From a comparison with CTD data the absolute reference level was determined and a vertical profile of horizontal currents was calculated for the ringlet. Other cyclones were found throughout the Slope Water region around warm core ring 82B with observable lifetimes of one to two weeks. The northeast quadrant of 82B was a favored generation site for ringlets. Two cyclones were observed to form in this region and were advected anticyclonically around 82B. Typically, at any one time, six cyclones with diameters of approximately 40 to 50 km can be detected north of the Gulf Stream using satellite imagery.

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WHOI Contribution No. 5780.

ON THE STRUCTURE AND ORIGIN OF A SMALL CYCLONIC EDDY OBSERVED DURING THE POLYMODE

LOCAL DYNAMICS EXPERIMENT

Eric J. Lindstrom, Curtis C. Ebbesmeyer and W. Brechner Owens

In the POLYMODE Local Dynamics Experiment (31°N ; 69.5°W) a small cyclonic eddy was discovered and mapped. The eddy was characterized by an upward doming of isotherms in the upper part of the main thermocline. The dynamical signal extended from the surface downward to a pressure of 800 dbar and outwards to a radius of 25-30 km. There was no deep water property signal associated with the eddy, but a layer ($\sim 10 \text{ m}$ thick) of very low salinity water was observed at the sea surface immediately above the feature. The salinities in the surface layer were lower than any reported in the historical hydrographic data for the region. Rainfall is discounted as a possible source of this signal because of the layer's thickness and horizontal scale. Alternatively, the closest source for the low salinity water is in the Slope Water, some 500 km away. The eddy may have originated by the splitting of a Gulf Stream ring, a hypothesis which is supported by observations of eddies of similar size and structure near several Gulf Stream rings. This mechanism could also account for the unusually low surface salinities since rings may trap Slope Water and transport it into the Sargasso Sea.

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WHOI Contribution No. 5588.

DISTRIBUTION AND COMPOSITION OF BIOGENIC PARTICULATE MATTER IN A GULF STREAM WARM CORE RING

David M. Nelson, Hugh W. Ducklow, Gary L. Hitchcock, Mark A. Brzezinski, Timothy J. Cowles, Christopher Garside, Richard W. Gould, Jr., Terrence M. Joyce, Christopher Langdon, James J. McCarthy and Charles S. Yentsch

We collected data along two transects of Gulf Stream warm-core ring 82-B in June

of 1982 to quantify and characterize the biogenic particle field in the upper 700 m, with greatest emphasis given to the upper 110 m. Parameters measured included chlorophyll, adenosine triphosphate (ATP), particulate organic carbon, biogenic silica, total particle volume, particle size distribution, bacterial abundance and biomass and the abundances of diatoms, dinoflagellates and coccolithophorids. There was a distinct maximum in phytoplankton biomass at the ring's center of rotation, embedded within the seasonal thermocline (20-40 m). This maximum exhibited a high degree of axial symmetry about the center of the ring, with biomass decreasing outward from ring center. There was a second biomass maximum associated with shelf surface water that was being entrained into the anticyclonic flow field of the ring 60-70 km from its center. Maximum chlorophyll and ATP concentrations observed in the two biomass maxima were similar, but the ring-center maximum was 2-10 times richer in particulate carbon, biogenic silica, particles $> 5 \mu\text{m}$ in diameter, dinoflagellates, diatoms and estimated organic detritus. The shelf streamer had 2-5 times greater abundances of bacteria and small, unicellular monads.

There are two possible mechanisms for the development of an axially symmetrical maximum in biogenic particulate matter in the center of a warm-core ring: concentration by the flow field and in situ growth. Our data on the distribution and composition of biogenic material in ring 82-B indicate a greater likelihood that this particular ring-center maximum developed in situ.

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(among others).

WHOI Contribution No. 5865.

ON THE GEOSTROPHIC VOLUME TRANSPORT IN HIGH EDDY ENERGY AREAS OF KUROSHIO EXTENSION AND GULF STREAM

Pearn P. Niiler, William J. Schmitz
and Dong-Kyu Lee

Three new deep hydrographic sections taken in July 1980, May 1981, and May 1982, between 29°N - 41°N along 152°E across the high eddy energy area of the Kuroshio Extension are used to compute the relative geostrophic transport as a function of depth. The mean eastward geostrophic transport relative to the bottom through this section is $56 \times 10^6 \text{ m}^3/\text{s}$. These sections were occupied across an array of ten moorings deployed from mid-1980 to mid-1982. Using the twenty-two month aver-

age directly-measured currents at 1200 m and 4000 m depth for reference levels in the least square sense, the absolute transport is estimated to be $31 \pm 18 \times 10^6 \text{ m}^3/\text{s}$ to the west. The uncertainty of the net transport estimate is based on the uncertainty of the measured mean currents. At 55°W , we use July 1976 and July 1977 deep hydrographic sections to compute the bottom relative geostrophic transport across the high eddy energy area of the Gulf Stream. Between 42°N and 32°N , it is $31 \times 10^6 \text{ m}^3/\text{s}$ to the east. Using twenty-four month average directly-measured currents at 4000 m for a reference level, the absolute transport is estimated to be $47 \pm 36 \times 10^6 \text{ m}^3/\text{s}$ to the west. Sverdrup mass divergence requires a net eastward transport of $17 \times 10^6 \text{ m}^3/\text{s}$ in the Pacific and $10 \times 10^6 \text{ m}^3/\text{s}$ in the Atlantic. Thus, the net westward circulations must be maintained by eddy or bottom or thermohaline interaction processes.

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A TWO-LAYER DIAGNOSTIC MODEL OF THE LONG TERM PHYSICAL EVOLUTION OF WARM CORE RING 82B

Donald B. Olson, Raymond W. Schmitt,
Maureen A. Kennelly and Terrence M. Joyce

Shipboard data from cruises in the 1982 time series on a single Gulf Stream warm core ring are composited in a cylindrical coordinate system following the motion of the ring. Measurements of 10°C isotherm depth are used with a two-layer model of the ring's structure to compute gradient current, kinetic energy, available potential energy (APE), and potential vorticity in the ring. The momentum related quantities are compared with surface derived velocity measurements using an acoustic doppler log (APOC). The volume of waters carried with the ring are also computed based on thermal data. The changes in these quantities as the ring evolves are discussed. The evolution of the ring can be divided into two periods. The first from April to late June, while the ring is isolated from strong interactions with the Gulf Stream, is associated with slow changes in ring properties. During this period the ring loses APE at a rate of $94 \times 10^6 \text{ W}$ (94 MW). Kinetic energy is constant within the measurement errors. Ring volume

for waters warmer than 10°C decreases at $0.04 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (0.04 Sv). A shift in ring volume out to larger radius is observed. After this interval the ring is involved in several interactions with the Gulf Stream and topography. Ring energy is lost at rates exceeding 900 MW. The ring volume is diminished at 1.4 Sv during the July period. Within the measurement errors, however, the potential vorticity at the center of the ring is nearly conserved from April through August implying nearly inviscid dynamics.

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WHOI Contribution No. 5796.

A STATISTICAL DESCRIPTION OF THE VERTICAL AND HORIZONTAL STRUCTURE OF EDDY VARIABILITY ON THE EDGE OF THE GULF STREAM RECIRCULATION

W. Brechner Owens

The vertical structure of eddy variability on the southern edge of the Gulf Stream recirculation is presented as a number of different forms of empirical orthogonal modes. The velocity dot-product modes show more barotropic eddy variability than the MODE experiment which was 300 km to the south. Temperature modes are consistent with the velocity modes and indicate a rapid decrease in energy with increasing modal index.

The empirical modes describing the variability within the lowest frequency bands that the measurements resolved (covering periods from 580 to 32 days) are consistent with simple wave dynamics. The dominant velocity component and temperature for the lowest frequency band are nearly in quadrature. The band which includes periods from 64 to 32 days has a barotropic velocity structure consistent with the topographic Rossby wave description deduced from SOFAR floats, but with a significant velocity-temperature coherence in the thermocline.

Time-averaged horizontal correlation functions of velocity are isotropic when normalized by the covariances at zero separation. At the same time the covariances have significant anisotropy, suggesting that the dominant scales are the same for each direction while the energy content and energy fluxes vary significantly with direction. Within the lowest two frequency bands, the horizontal structure again has strong signatures of wave dynamics.

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WHOI Contribution No. 5768.

WINTERTIME CONVECTION IN WARM-CORE RINGS: THERMOCLINE VENTILATION AND THE FORMATION OF MESOSCALE LENSES

Raymond W. Schmitt and Donald B. Olson

Large heat losses from Warm-Core Ring 82B during February, March, and April formed a 400 m thick thermostat in the center of the ring. Two different models were constructed to simulate the formation of the thermostat water mass properties: a one dimensional vertical model forced with a meteorological time series and a volumetric mixing model with climatological input. Both models indicate that a flux of Slope Water into the ring is necessary to yield the observed thermostat salinities. The subsequent slow decay of the ring core in the Slope Water suggests that such winter-convected rings can easily maintain the "warm band" water identified by Wright and Parker (Limnol. Oceanogr., 21, 563-571, 1976). The large loss of core water during interactions with the Gulf Stream suggests that the reabsorption of such winter-cooled warm rings is an important source of high salinity, high oxygen anomalies in the main thermocline of the Sargasso Sea. The volume of water in each ring reabsorption is sufficient to generate many (> 20) intrathermocline eddies with T-S properties nearly identical to those of recently reported lenses. This suggests that many of these small eddies are much more local in origin and may be more highly dissipative than has previously been suggested. The flux of high salinity, high oxygen water into the main thermocline by this mechanism leads to ventilation at a rate which is a significant fraction of the Ekman pumping at these density levels. Thus, the reabsorption of winter-cooled warm-core rings by the Gulf Stream is an important eddy ventilation mechanism for the Sargasso Sea.

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WHOI Contribution No. 5476.

THEORETICAL MODELS

ON THE NUMERICAL TREATMENT OF CROSS-SHELF OPEN BOUNDARIES IN A BAROTROPIC COASTAL OCEAN MODEL

David C. Chapman

Using a barotropic coastal ocean model with a straight coastline and uniform cross-shelf bottom slope, seven different cross-shelf open boundary conditions (four of which are applied in either implicit or explicit form) are compared in three numerical experiments. (1) A mound of water is allowed to collapse and radiate waves toward the open boundaries. (2) A uniform along-shelf wind stress is applied at time = 0 over the entire shelf and held constant for the duration of the experiment. (3) A uniform cross-shelf wind stress is applied at time = 0 over the entire shelf and held constant for the duration of the experiment.

The boundary condition which is most transparent to waves consists of a sponge at the outer edge of the model domain with an Orlanski radiation condition at the outer edge of the sponge. Several open boundary conditions perform adequately in the wind stress experiments, but the Orlanski radiation condition alone (without a sponge) appears to give the best total performance through all of the experiments. It is adequate at transmitting wave energy, and its response is entirely acceptable in the wind stress experiments.

The results suggest that a clamped open boundary is probably the worst choice of cross-shelf open boundary condition for almost any barotropic coastal model. In fact, any open boundary condition which significantly restricts the cross-shelf open boundary should be avoided.

Supported by: NSF Grant OCE80-14941.

WHOI Contribution No. 5828.

MULTILAYER HYDRAULIC CONTROL WITH APPLICATION TO THE ALBORAN SEA CIRCULATION

Nelson G. Hogg

The flow of a single layer of fluid along a channel of variable dimensions is hydraulically controlled when long gravity waves can no longer propagate upstream at the cross-section of minimum area. For a multilayer fluid, it is shown that a controlled situation exists when there is a separate geometrical extremum for each of the gravity wave modes. The structure of

each control section must be different, reflecting the different vertical structures of the internal modes.

A channel with three layers of different density is studied in some detail as an analogue to the principal water masses in the Alboran Sea and Strait of Gibraltar. With the lowest layer at rest and the surface rigid, the control for the slowest, second internal mode is primarily a width contraction while that for the first mode must also involve a reduction in bottom depth. The problem separates into control problems for each mode. That for the first mode is a classic lock exchange problem with just two layers (controlled at the Strait of Gibraltar) while that for the second mode reduces to that for a single layer (suggested to be controlled at Alboran Strait).

For the Alboran Sea rotational effects are important, particularly at the second mode control point. With these included the principal qualitative features of the circulation are reproduced. Anticyclonic vorticity is produced in both the Atlantic Water and the Levantine Intermediate Water as both are vertically compressed upon entering the western Alboran Sea through the two control points. The Deep Mediterranean Water is uplifted at the second mode control point (Alboran Strait) and is banked against the southern wall thereafter as the intermediate water separates from wall. A secondary circulation is forced in the upper layer which causes southward, cross-channel flow to the west of Alboran Island.

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WHOI Contribution No. 5728

THE HETON, AN ELEMENTARY INTERACTION BETWEEN DISCRETE BAROCLINIC GEOSTROPHIC VORTICES, AND ITS IMPLICATIONS CONCERNING EDDY HEAT-FLOW

Nelson G. Hogg and Henry M. Stommel

Amongst the interactions of two discrete baroclinic geostrophic vortices in a two-layer system there is one class of interaction that is non-trivial: when the two vortices are of opposite sign and in different layers, and close enough together, they transport heat. Because this particular interaction can transport heat, we propose to call it the heton. It is a tilted baroclinic pair. In the Northern Hemisphere it transports heat to the left of the direction toward which its top tilts. Two warm or two cold hetons repel each other when outside the radius of deformation. A warm and a cold heton

attract one another.

A simple two-heton engine that exhibits vortex splitting, loss of available potential energy, and meridional heat transport is presented.

In press: Proceedings of the Royal Society of London, A.

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WHOI Contribution No. 5617.

HETONIC EXPLOSIONS: THE BREAKUP AND SPREAD OF WARM POOLS AS EXPLAINED BY BAROCLINIC POINT VORTICES

Nelson G. Hogg and Henry M. Stommel

As an alternative to small amplitude continuous theories, we study the disintegration of warm pools of fluid on a rotating earth using clouds of baroclinic point vortices or hetons. The equations describing the motion of the hetons are relatively simple ordinary differential equations whose numerical integration makes it possible to physically interpret the temporal evolution of finite amplitude disturbances. Using experience with small numbers of hetons as a guide, a heuristic model is proposed. This predicts that the number of baroclinic vortices forming at the rim of a circular warm pool is given by the radius of the pool divided by 1.27 times the Rossby radius while these vortices should expand outward at a rate given by 1.65 times the Rossby radius times the vorticity density of the pool. The first prediction is in agreement with previous laboratory experiments while the second has not previously been reported upon.

Supported by: ONR Contract N00014-76-C-0197, NR 083-400 and NSF Grant OCE80-15789.

WHOI Contribution No. 5789.

BAROCLINIC INSTABILITY IN A MERIDIONALLY VARYING TWO-LAYER MODEL: LINEAR THEORY

Stephen P. Meacham

We have examined weak baroclinic instability in a two-layer model distinguished by the inclusion of a meridionally varying potential vorticity gradient in the lower layer of the basic flow. This gradient is chosen so that it exhibits a minimum at the median latitude of a zonal channel model.

Such a feature could correspond to a meridionally confined jet or be a result of topographic beta effects.

While meridionally varying models of baroclinic instability are not new, the novelty of this study lies in its focus on the slightly supercritical regime. Both linear and weakly finite-amplitude solutions are considered in this regime.

The eigenfunction structure of the unstable linear normal mode differs considerably from that of a meridionally uniform, two-layer shear flow. In particular, the solution varies rapidly on a short meridional length scale in the neighborhood of the center-line of the channel. The presence of this critical layer has significant consequences for the weakly non-linear evolution of the unstable mode. At sufficiently small supercriticality, the growth of the linearly unstable mode from weak initial conditions is modified by interaction with neutral linear modes via a triad resonance mechanism before the unstable mode has grown sufficiently to significantly modify the mean flow. One can obtain amplitude equations governing the evolution of the unstable mode and a pair of neutral modes that together form a nearly resonant triad. These are difficult to solve since both the amplitude of the unstable mode and its spatial structure evolve on the same slow time scale. Theoretical analysis shows that in this regime the amplitude scales of the neutral sidebands become larger than those of the unstable wave and that all three amplitudes are too small to modify the mean flow sufficiently to alter the evolution on the same time scale as that of the three-wave interaction. Numerical studies of this three-mode system show that the triad interaction can halt the growth of the instability within the amplitude regime in question.

It seems that the consequences of the results of this study may be that a slightly supercritical instability of the sort of flow described leads not to a state equilibrated by wave-mean flow interaction with energy limited to a smaller number of wavenumbers, but to a state in which a large number of wavenumbers are indirectly forced by the instability and receive energies comparable to or exceeding that of the unstable wavenumber.

Properties of the slightly supercritical linear modes are discussed below. The details of their weakly finite-amplitude evolution are dealt within a companion paper (Meacham, Baroclinic instability in a meridionally varying two-layer model: Weakly non-linear theory).

Supported by: NSF Grant ATM79-21431.

WHOI Contribution No. 5822.

BAROCLINIC INSTABILITY IN A
MERIDIONALLY VARYING TWO-LAYER MODEL:
WEAKLY NON-LINEAR THEORY

Stephen P. Meacham

We have examined weak baroclinic instability in a two-layer model distinguished by the inclusion of a meridionally varying potential vorticity gradient in the lower layer of the basic flow. This gradient is chosen so that it exhibits a minimum at the median latitude of a zonal channel model. Such a feature could correspond to a meridionally confined jet or be a result of topographic beta effects.

While meridionally varying models of baroclinic instability are not new, the novelty of this study lies in its focus on the slightly supercritical regime. Both linear and weakly finite-amplitude solutions are considered in this regime.

The eigenfunction structure of the unstable linear normal mode differs considerably from that of a meridionally uniform, two-layer shear flow. In particular, the solution varies rapidly on a short meridional length scale in the neighborhood of the center-line of the channel. The presence of the critical layer has significant consequences for the weakly non-linear evolution of the unstable mode. At sufficiently small supercriticality, the growth of the linearly unstable mode from weak initial conditions is modified by interaction with neutral linear modes via a triad resonance mechanism before the unstable mode has grown sufficiently to significantly modify the mean flow. One can obtain amplitude equations governing the evolution of the unstable mode and a pair of neutral modes that together form a nearly resonant triad. These are difficult to solve since both the amplitude of the unstable mode and its spatial structure evolve on the same slow time scale. Theoretical analysis shows that in this regime the amplitude scales of the neutral sidebands become larger than those of the unstable wave and that all three amplitudes are too small to modify the mean flow sufficiently to alter the evolution on the same time scale as that of the three-wave interaction. Numerical studies of this three-mode system show that the triad interaction can halt the growth of the instability within the amplitude regime in question.

It seems that the consequences of the results of this study may be that a slightly supercritical instability of the sort of flow described leads not to a state equilibrated by wave-mean flow interaction and with energy limited to a smaller number of wavenumbers, but to a state in which a large number of wavenumbers are indirectly forced by the instability and receive ener-

gies comparable to or exceeding that of the unstable wavenumber.

Properties of the non-linear evolution of slightly supercritical, unstable disturbances are discussed below. The details of the linear problem are dealt with in a companion paper (Meacham, Baroclinic instability in a meridionally varying two-layer model: Linear theory).

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WHOI Contribution No. 5831.

A NUMERICAL STUDY OF THE ROLES OF
SUB-GYRE SCALE MIXING AND THE
WESTERN BOUNDARY CURRENT ON
HOMOGENIZATION OF A PASSIVE TRACER

David L. Musgrave

A numerical model integrated the steady advection-diffusion equation using a kinematic circulation with characteristics of a sub-tropical gyre: i.e. closed streamlines and western intensification. Homogenization of the interior concentration increased and the gradients were forced to the boundaries as mixing, parameterized as eddy diffusion, decreased. As the western boundary current intensified, the value of the homogenized interior became closer to the southern boundary value. This indicated that cross-stream mixing was enhanced within the western boundary current. Tongues of high and low tracer concentration spiraled across streamlines toward the center of the gyre. These simulations will be helpful in the interpretation of lateral distributions of geochemical tracers which are being generated by programs such as Transient Tracers in the Ocean.

In press: Journal of Geophysical
Research.

Supported by: WHOI Postdoctoral Scholarship and Center for Analysis of Marine Systems.

WHOI Contribution No. 5760.

ON THE CIRCULATION OF THE WARM WATER
OF THE SUBTROPICAL GYRES

Joseph Pedlosky

The ventilated thermocline model of Luyten, Pedlosky and Stommel (J. Phys. Oceanogr., 13, 292-309, 1983) is used to discuss the circulation of the warm water of the subtropical gyre. It is suggested on theoretical grounds that the warm water layers which outcrop well south of the zero

wind stress curl line are completely replenished by the mass flux pumped down from the upper Ekman layer while recirculation of mass through the western boundary current plays a relatively insignificant role for these layers. The recirculation seems, instead, to be confined to the deeper layers of the thermocline.

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WHOI Contribution No. 5723.

CROSS-GYRE VENTILATION OF THE SUBTROPICAL GYRE: AN INTERNAL MODE IN THE VENTILATED THERMOCLINE

Joseph Pedlosky

A model of cross-gyre geostrophic flow is presented. The model is a two-layer model of the subtropical thermocline above a resting lower ocean. The northern boundary of the gyre is taken to be a latitude circle on which the Ekman pumping vanishes.

In distinction to previous theories, the meridional, geostrophic velocity at the line of vanishing Ekman pumping is not zero. Instead, an internal mode is found which consists of southward, potential vorticity conserving flow in the lower layer and northward flow in the upper layer. There is no net transport, in agreement with the Sverdrup relation, across the gyre boundary.

The theory describes the longitudinal extent of the internal mode. Sufficient distortion of the isolines of potential vorticity by the wind stress curl south of the gyre boundary are required to allow the flux of fluid in the internal mode to penetrate into the subtropical gyre. The model is presented as an additional example of gyre ventilation, in this case due to interaction with a neighboring gyre rather than the sea surface. Attention is drawn to the similarity of the calculated flow with the circulation pattern for the eastern North Atlantic proposed by Saunders (J. Mar. Res., 40 (Suppl.), 641-651, 1982).

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WHOI Contribution No. 5630.

THE INSTABILITY OF CONTINUOUS HETON CLOUDS

Joseph Pedlosky

The linear and weakly non-linear instability of a continuous model of the Heton

cloud of Hogg and Stommel is studied. Particular attention is paid to the manner in which the continuous model presented here overlaps in behavior the point vortex dynamics described by Hogg and Stommel.

The Heton cloud, which consists of a region of cyclonic vorticity overlying anticyclonic vorticity in the layer below (or vice-versa), develops wavelike perturbations on the cloud boundary if the perturbation wavelength is long enough compared to the deformation radius. This is shown to be the case for both cloud bands and cylindrical Heton clouds.

An analysis of the weakly non-linear behavior of the Heton cloud band shows that the interaction of the fundamental wave with its next harmonic leads to non-linear instability at long wavelengths. The resulting explosive behavior is suggestive of the cloud fragmentation found in the point vortex model. Similarly, the non-linear stability at shorter wavelengths is reminiscent of the finite amplitude pulsations observed in some numerical calculations of the cloud dynamics.

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WHOI Contribution No. 5752.

ON THE DYNAMICS OF THE COUPLED MIXED LAYER-THERMOCLINE SYSTEM AND THE DETERMINATION OF THE OCEANIC SURFACE DENSITY

Joseph Pedlosky, Wendy M. Smith and
James R. Luyten

A simple model of the oceanic mixed layer is coupled to a model of the ventilated thermocline. The model allows a combination of advection and surface heating to determine the position of the outcrop lines of the isopycnals. The resulting isopycnal outcrops determine the circulation in the ventilated thermocline as in the 1983 study by Luyten, Pedlosky and Stommel (LPS; J. Phys. Ocean., 13, 292-309). The isopycnal outcrop line is affected by both Ekman wind drift and the surface geostrophic flow. Hence, the outcrop position and the thermocline circulation are coupled.

The mixed layer and the thermocline models are extremely simple. Each is modeled by layers of constant density. The mixed layer, in which the isopycnals are vertical, is distinguished by the ability of fluid to cross the interfaces between adjacent layers under the influence of atmospheric heating. The heating is parameterized in terms of the departure of the isopycnal line from the position it would have if the ocean were heated, but at rest.

Although in most major respects the thermocline circulation is qualitatively similar to the model of LPS, the effect of the variation of the outcrop latitude with longitude introduces the possibility of potential-vorticity minima along latitude circles.

The model also predicts cooling of the most southern portion of the subtropical gyre under the influence of northward Ekman wind drift.

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WHOI Contribution No. 5642.

U P P E R O C E A N , S U R F A C E
L A Y E R P R O C E S S E S ,
A N D M E T E O R O L O G Y

AIR-SEA MOMENTUM TRANSFER BY MEANS OF
SHORT WIND-WAVES

Gabriel T. Csanady

Short and steep, three-dimensional ("crescentic") wavelets, of a phase velocity of order 0.5 m s^{-1} , are supposed responsible for air-sea momentum transfer in moderate to strong winds. From laboratory evidence it is inferred that the air flow separates from such wavelets in a typically 3-dimensional manner, the low speed fluid in the lee escaping sideways. In the re-attachment region, over the next crest, a large shear-stress spike develops in consequence. Wavelets of a waveheight to wavelength ratio around 0.08 are thus sustained in quasi-equilibrium by the shear stress spikes. The drag force of the air on the water is exerted primarily by the shear stress spikes, and appears on the water side, in a wave-following frame of reference, as the momentum deficit of many wakes, each generated by a shear stress spike. The resulting velocity gradient of the free surface turbulent shear layer at small depths is proportional to the wavelet frequency. The energy supply is dissipated primarily by turbulence in the low speed fluid accumulations at each wave crest. A quasiequilibrium state between energy supply and dissipation is possible at a specific phase velocity, proportional to the friction velocity. The $c \sim u_*$ relationship

implies a Charnock-type roughness length, and energy supply to capillary wavelets in front of the crests increasing as u_*^3 , and a surface velocity gradient varying as u_*^{-1} .

Supported by: DoE Contract DE-AC02-79EV10005.

WHOI Contribution No. 5721.

THE INFLUENCE OF WINDS AND TOPOGRAPHY
ON THE SEA SURFACE TEMPERATURE PATTERNS
OVER THE NORTHERN CALIFORNIA SLOPE

Kathryn A. Kelly

As part of the Coastal Ocean Dynamics Experiment (CODE), 57 infrared images from the satellite NOAA-6 were analyzed and compared with in situ data to investigate the relationship between SST patterns and winds, topography and sea level height. After extensive processing to eliminate clouds and to obtain better temperature accuracy, the decimated images were decomposed into a mean SST and empirical orthogonal functions. The SST patterns were closely related to the coast shape and to shallow bathymetry. The first mode described a seasonal warming trend which was probably modified by large-scale advection. Comparison of the time-varying amplitudes with those of wind stress show that the second SST mode was closely connected with longshore variations in the intensity of upwelling-favorable winds. Additional information from the sea-level height analysis verified that the SST patterns, which extend about 60 km offshore, describe locally-driven coastal upwelling which is modified by shelf topography.

Supported by: ONR Contracts N00014-75-C-300 and N00014-80-C-0440; NSF Grant OCE78-19888; and WHOI Postdoctoral Scholarship.

WHOI Contribution No. 5767.

SURFACE WIND MEASUREMENTS IN SEQUAL I

Richard E. Payne

Data from meteorological recorders at 29.37°W , 24.00°W and 14.93°W , all within one degree latitude of the equator, show that a relaxation event in the wind speed occurred nearly simultaneously at all three during late March 1983 during SEQUAL I. Wind stress subsequently increased by approximately a factor of two. The event was not recognizable in the data from a fourth recorder at 6.10°N , 27.88°W .

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WHOI Contribution No. 5689.

NEAR SURFACE VELOCITY VARIABILITY AT
INERTIAL AND SUBINERTIAL FREQUENCIES IN
THE VICINITY OF THE CALIFORNIA CURRENT

Robert A. Weller

Observations of the horizontal velocity field in the upper 150 m, made from the Research Platform FLIP as it drifted off the coast of Baja California, were used to examine the variability of the velocity field and its relation to local wind forcing. At subinertial frequencies a spatially varying flow field associated with the California Current system was encountered. In addition, there was low frequency near-surface flow to the right of the wind stress that decayed with depth. At near-inertial frequencies oscillatory motion with an amplitude of up to 40 cm s^{-1} was observed. Most of the energy in the near-inertial frequency band was associated with modes with vertical wavelengths large compared to the thickness of the mixed layer. The local wind alone had neither the strength nor the variability needed to directly produce the observed inertial period variability. It is suggested that FLIP encountered regions in which the shear of the quasi-geostrophic flow resulted in localized intensifications of near-inertial motion.

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Oceanography.

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C-0152 (UCSD) and N00014-76-C-0197,
NR 083-400.

WHOI Contribution No. 5632.

T E C H N I C A L R E P O R T S

ANALYSIS OF FLOW WITHIN THE COASTAL
BOUNDARY LAYER OFF LONG ISLAND, NEW YORK

James H. Churchill

From 1974 through 1978 a series of intensive measurements were made in the coastal waters within 12 km of Long Island. The data were derived from two sources: a mooring array from which time series of

temperature, salinity and water velocity were measured at four depths at each of four offshore distances; and high resolution, daily hydrographic surveys. Analysis of subtidal cross-shore velocity fluctuations has indicated a two-layer response to wind forcing, with near-surface flow to the right of the longshore wind and opposing flow below. The magnitude of these fluctuations increased in the seaward direction on a scale nearly equal to the internal deformation radius. The phase between longshore velocity fluctuations and longshore wind stress approached zero with decreasing bottom depth, probably the result of bottom stress. The vertical structure of longshore fluctuations during stratified conditions markedly differed from that during unstratified conditions, and resembled the structure derived from a simple two-layer coastal flow model. Significant mean offshore flow was measured during experiments in August and September, despite negligible mean wind stress during the same periods. This flow was most likely due to persistent longshore density gradients, as are consistently inferred from hydrographic data taken in the vicinity.

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DE-AC02-79EV10005.

WHOI Technical Report 84-14.

SLOPE WATER INTRUSIONS WITHIN THE
NEARSHORE WATERS OFF LONG ISLAND, NEW YORK

James H. Churchill

From 1974 through 1978 intensive measurements were made of the salinity, temperature and current structure of the waters within 12 km of the southern Long Island coastline. The data were derived from two sources: a mooring array from which time series of temperature, salinity and water velocity were measured at four depths at each of four offshore distances; and high resolution, daily STD and current meter surveys. During August and September intrusions of slope or outer shelf water were often observed by the STD surveys. Three intrusions have been studied in detail. Two were observed at mid-depth following periods of upwelling-favorable winds. Concurrent hydrographic and current meter data suggest that these water masses were transported shoreward by a combination of wind forcing and longshore density gradients. The third intrusion, initially observed near the surface, had coinciding salinity and temperature maxima. This water mass appears to have entered the shelf as a result of a shelf/slope water exchange, possibly induced by a warm-core

ring near the shelf break. Such intrusions may commonly occur during the summer and fall and may be related to the appearance of tropical fish in the Long Island vicinity during these seasons.

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DE-AC02-79EV10005.

WHOI Technical Report 84-15.

MODELS AND SIMULATIONS OF TRACER DISPERSAL BY MID-OCEAN MESOSCALE EDDIES

Dale B. Haidvogel and Thomas Keffer

Haidvogel and Keffer (Dyn. Atmos. Oceans, 8, 1-40, 1984) have examined the stirring and mixing of a passive tracer in a turbulent mesoscale eddy field for environmental parameters characteristic of a homogeneous mid-ocean region. This study utilized two numerical models, based respectively on the barotropic vorticity and advective-diffusive equations, to simulate the evolving mid-ocean eddy field and the associated dispersion of an embedded tracer spot. Here, these models are described in detail and the full suite of tracer release simulations are shown in the form of contour plots.

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WHOI Technical Report 84-24.

THE VELOCITY STRUCTURE OF WARM CORE RING 82B AND ASSOCIATED CYCLONIC FEATURES

Maureen A. Kennelly

Warm Core Ring (WCR) 82B was studied by three cruises of the Warm Core Rings Program. Continuous profiling of ocean currents was done using an acoustic Doppler velocimeter. Ring center determinations were made using a center of momentum method which is based on the intersection of normal lines to the velocity vectors and compared to centers obtained from a center of mass algorithm. The maximum current sampled in 82B was on the order of 1 m/sec in April, in the high velocity region and decreased to approximately 0.5 m/sec in August, after which 82B was absorbed by the Gulf Stream. The velocity vectors at 100 m were decomposed into their radial and azimuthal components. Polynomials were fit to the azimuthal velocity fields and various averaging techniques were applied to the radial fields. It was found that the core of 82B was in near solid body rotation

with ω increasing from $1.6 \times 10^{-5} \text{sec}^{-1}$ to $2.4 \times 10^{-5} \text{sec}^{-1}$ over 82B's lifetime. A time series of physical parameters for the core of 82B is presented including relative vorticity, Rossby number, radius to maximum velocity and potential vorticity. The relative vorticity distribution for an entire radial section was calculated for the first star shaped pattern in June. The potential vorticity distribution was also determined using a fit to the depth of the 10°C isotherm as H.

Satellite imagery revealed small cyclonic features around the larger anticyclonically rotating 82B. The vectors for these cyclones revealed speeds ranging from 20 to 60 cm/sec. One cyclone or "ringlet" found in June, 1982, was studied extensively by removing the basic state of the ring. The azimuthal velocity data for this ringlet was used with the gradient current equation to calculate the absolute dynamic topography at 100 dbars. It was found that the ringlet was 13 dynamic-cm lower than its surroundings. In addition it was determined that neglect of the centrifugal term would change the dynamic topography of the ringlet by 30 percent. From a comparison with CTD data the absolute reference level was determined and a vertical profile of horizontal currents was calculated for the ringlet. It is suggested that the cyclones that were observed may be evidence of the theoretically described modon.

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WHOI Technical Report 84-10.

GULF STREAM RECIRCULATION EXPERIMENT (GUSREX) AND LINE EXPERIMENT SOFAR FLOAT DATA 1980 - 1982

Maureen A. Kennelly and Theresa K. McKee

Thirty-nine neutrally buoyant SOFAR floats were tracked in the western North Atlantic at depths of 700 m and 2000 m. These floats were launched in an effort to measure the deep current structure of the Gulf Stream and its recirculation near 55°W . Three separate deployments were made in April and October 1980 and July 1981. The floats were tracked by means of moored autonomous listening stations. The basic data consist of float trajectories, and temperature, pressure, and velocity measurements along the trajectories. This report describes the GUSREX experiment and instrument performance. It presents plots illustrating the horizontal structure and scales of the general circulation in the

Gulf Stream and its recirculation for the period October 1980 to May 1982.

Prepared for: NSF under Grant OCE81-09145.

WHOI Technical Report 84-45.

MOORED CURRENT METER DATA FROM THE
ATLANTIC NORTH EQUATORIAL COUNTERCURRENT
NEAR 6°N, 28°W (FEBRUARY - SEPTEMBER,
1983), VOLUME XXXIV

Ellen Levy and Philip L. Richardson

This report presents current and wind data from the first of three surface mooring deployments in the Atlantic North Equatorial Countercurrent near 6°N and 28°W. A Vector Averaging Wind Recorder (VAWR) measured wind velocity, sea surface temperature and air temperature, barometric pressure and solar insolation. Four Vector Measuring Current Meters (VMCM) measured current velocity and temperature at depths of 20, 50, 75 and 150 m. The mooring was deployed on February 25 and recovered (and replaced) on September 13, 1983.

Prepared for: NSF under grants OCE82-17112 and OCE82-11108.

WHOI Technical Report 84-16.

MOORED CURRENT METER DATA FROM THE
ATLANTIC NORTH EQUATORIAL COUNTERCURRENT
NEAR 6°N, 28°W (SEPTEMBER, 1983 -
MARCH, 1984), VOLUME XXXVI

Ellen Levy and Philip L. Richardson

This report presents current and wind data from the second of three surface mooring deployments in the Atlantic North Equatorial Countercurrent near 6°N and 28°W. A Vector Averaging Wind Recorder (VAWR) measured wind velocity, sea surface temperature, air temperature, barometric pressure and solar insolation. Four Vector Measuring Current Meters (VMCM) measured current velocity and temperature at depths of 20, 50, 75 and 150 m. The mooring was deployed on September 12, 1983, and recovered (and replaced) on March 24, 1984.

Prepared for: NSF under Grants
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WHOI Technical Report 84-37.

A COMPILATION AND DESCRIPTION OF
HYDROGRAPHIC TRANSECTS OF THE
MID-ATLANTIC BIGHT SHELF-BREAK FRONT

Vincent D. Lyne and Gabriel T. Csanady

Historical hydrographic transects of the Mid-Atlantic Bight shelf-break front are compiled by month and described in this report. Interannual variability of the meteorological forcing and slope water mass properties are presented as an aid in interpreting the variability of the frontal structure. Descriptions of the significant features of the front, shelf and slope water masses precede the compiled transects. The sections are limited to the upper 350 m of the water column, and a cross-shore extent of 280 m.

This report provides the observational perspective for interpreting measurements to be made during the Shelf Edge Exchange Processes (SEEP) field experiments funded by the Department of Energy.

Prepared for: DoE under Contract
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WHOI Technical Report 84-19.

THE LONG TERM UPPER OCEAN STUDY (LOTUS)
CRUISE SUMMARY AND HYDROGRAPHIC DATA
REPORT, OCEANUS 141, OCTOBER 1983
AND OCEANUS 145, JANUARY 1984

Ellyn T. Montgomery, Nancy J.
Pennington and Melbourne G. Briscoe

OCEANUS cruises 141 (28 October to 4 November 1983) and 145 (22 to 29 January 1984) were the tenth and eleventh cruises to the Long Term Upper Ocean Study (LOTUS) area centered at 34°N, 70°W. During OCEANUS 141, a C. S. Draper Laboratory profiling current meter (PCM) was set, the fifth LOTUS surface mooring was recovered, and the deployment of the sixth LOTUS surface mooring was unsuccessfully attempted. The sixth surface mooring was finally deployed in January, on OCEANUS 145. This report provides details of the work accomplished on both cruises, as well as presenting the hydrographic data collected.

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N00014-76-C-0197, NR 083-400 and
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 84-26.

THE LONG TERM UPPER OCEAN STUDY (LOTUS)
CRUISE SUMMARY AND HYDROGRAPHIC DATA REPORT
OCEANUS 154, MAY 1984

Ellyn T. Montgomery, Nancy J. Pennington
and Melbourne G. Briscoe

OCEANUS cruise 154 (16-23 May 1984) was the final cruise in the two-year field program of the Long Term Upper Ocean Study (LOTUS). The work occurred primarily in the LOTUS area (34°N, 70°W), where the entire moored array was recovered. The moorings were the following: the LOTUS-6 surface mooring (No. 792), a subsurface mooring (No. 788), two intermediate moorings (Nos. 789, 790), and a C. S. Draper Laboratory profiling current meter (PCM) mooring.

Also on OCEANUS 154, a mooring was deployed for the U.S. Geological Survey at approximately 40°10'N, 69°58'W. On the return trip, an engineering test mooring was recovered at approximately 39°11'N, 70°01'W, some elements removed for testing, and then redeployed in the same location.

This report presents the hydrographic data collected on OCEANUS 154, as well as providing details of the work that was accomplished.

Prepared for: ONR under Contract
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 84-39.

HYDROGRAPHIC STUDY OF BUZZARDS BAY,
1982-1983, DATA REPORT

Leslie K. Rosenfeld, Richard P. Signell
and Glenn G. Gawarkiewicz

A series of four hydrographic cruises at three-month intervals was undertaken in Buzzards Bay in 1982-83. Buzzards Bay is located on the southern coast of Massachusetts, west of Cape Cod. Listings and vertical profiles of one-meter-averaged values of temperatures, salinity, sigma-t and light transmission are presented. Selected vertical cross-sections of temperature, salinity and sigma-t are also included, as are horizontal maps of the same variables at depths of 1 m and 8 m.

Prepared for: NOAA, National Sea Grant College Program, under Grants NA80-AA-D-00077 (R/P-16; R/P-15) and NA83-AA-D-00049 (R/P-13) and the WHOI Coastal Research Center under a grant from the Andrew W. Mellon Foundation.

WHOI Technical Report 84-5.

A COMPILATION OF MOORED CURRENT METER DATA
FROM THE REGION OF THE NORTH PACIFIC
BOUNDARY CURRENT, VOLUME XXXIII

Ann Spencer, Dolores H. Chausse, and
W. Brechner Owens

An array of 15 current meters was set in the Northern Pacific from June 1981 to July 1982. It was located along 175°W from 51°N to 46°N, and instruments were set at 2000 m and deeper. The objective was to explore the northern boundary current system of the North Pacific.

Current and temperature measurements were made. The data are presented graphically as time series, histograms, scatter plots, progressive vector diagrams and spectral plots. Tables of statistics of temperature and velocity are also shown.

Prepared for: ONR under Contracts
N00014-79-C-0071, NR 083-004 and
N00014-82-C-0019, NR 083-004.

WHOI Technical Report 84-6.

A COMPILATION OF MOORED CURRENT METER AND
WIND RECORDER DATA, Volume XXXV, LONG-TERM
UPPER OCEAN STUDY (LOTUS), (MOORINGS 764,
765, 766, 767, 770) MAY 1982-APRIL 1983

Susan A. Tarbell, Nancy J. Pennington
and Melbourne G. Briscoe

LOTUS was a two-year experiment near 34°N, 70°W, designed to acquire and analyze a continuous set of measurements of currents and temperatures in the upper, open ocean together with local hydrography, meteorology, and mesoscale oceanographic features. The first scientific moorings were deployed in May 1982. The first year of mooring data, from May 1982-April 1983, is presented here.

Prepared for: ONR under Contracts
N00014-76-C-0197, NR 083-400 and
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 84-36.

DRIFTER STUDIES IN WARM CORE RINGS

Cynthia T. Tynan and Stanford B. Hooker

The results of multiple deployments of surface drifters in warm core rings of the Gulf Stream are presented. Four satellite drifters (tracked by the Argos system) were deployed on nine separate occasions and two LORAN-C drifters (operated by the University of Miami) were deployed three times. Drifter studies were conducted

during four cruises aboard the R/V
ENDAEVOR in 1982 in conjunction with the
Warm Core Rings Experiment and one cruise
of the USNS BARTLETT in January 1983 which
was sponsored by the Office of Naval Re-
search. Translational velocities and
periods of rotation are provided for two
rings: 82B and 82H.

Prepared for: NSF under Grant
OCE80-16983.

WHOI Technical Report 84-27.

During four cruises aboard the EAV
SANDPAPER in 1963 in cooperation with the
Naval Ordnance Laboratory and one cruise
of the EAV SANDPAPER in January 1963 which
was sponsored by the Office of Naval Re-
search. Transmittal facilities and
periods of rotation are provided for the
target, EAV and EAV.

Approved for: EAV under Grant
ONR-66-00001

Naval Technical Report 66-17

MARINE POLICY
AND OCEAN MANAGEMENT PROGRAM
David A. Ross, Director

THEORY AND PRACTICE
OF MANAGEMENT
David A. Aaker, Director

REVIEW OF INDONESIAN MARINE FISHERIES

Conner Bailey, A. Dwiponggo
and Firial Marahundin

This book provides a review and synthesis of a large but scattered body of literature, much of it unpublished or otherwise underutilized, on Indonesian marine fisheries. The broad goal of this study is to assess fisheries management and development programs in light of existing knowledge and to suggest a set of priorities for future biological and socio-economic research appropriate to the needs of policy makers.

Results of this study indicate that maximum sustainable yields from marine fisheries resources are approximately 4.5 million mt, compared with 1982 harvests of 1.5 million mt. However, fisheries resources are unevenly exploited, and many of the most productive and accessible resources already are heavily exploited.

The structure of the fishing industry is examined. Small scale fisheries continue to dominate this sector in landings and employment. The medium scale sub-sector developed rapidly since the late 1960s, led by otter trawlers and purse seiners. Large scale commercial fisheries, including joint ventures and state enterprises, play a small role in total production but a more important role in fisheries exports. Programs which have shaped the direction of fisheries development and policies established to manage resource utilization are examined.

Costs and earnings data, and data on income of fishermen, are reviewed. Relative to investment costs, the level of profitability of small scale fishing units generally is higher than that of the other sub-sectors, but in absolute terms profits among small scale fishermen are far smaller. Parallel to this, per capita and household incomes of small scale fishermen are far below those of the other two sub-sectors, and in many cases are below a poverty threshold pegged to the retail price of rice.

Fish marketing and distribution patterns were examined. Relatively abundant fisheries resources, low population densities, and high levels of per capita fish consumption characterize most areas of Indonesia outside of Java. Available fish landings from waters off Java are insufficient to meet demand by the 95 million consumers on that island, while the absence of demand for increased supply acts as the primary constraint to increased harvests. Matching supply and demand is a central problem of fisheries development in Indonesia. There is evidence that both fresh and processed fish markets are

controlled by oligopolistic wholesalers, but the effect of this on inter-island trade is unclear.

A wide range of socio-economic literature is reviewed and synthesized to highlight the salient characteristics of small scale fishermen and communities. Assumptions regarding resistance to change and the role of middlemen which appear to guide development policy are assessed and found inconsistent with available facts.

In press: ICLARM Studies and Reviews Series. Manila and Jakarta:
International Center for Living Aquatic Resources Management; Directorate General of Fisheries (Indonesia); and the Marine Fisheries Research Institute (Indonesia). To be published in both English and Indonesian.

Supported in part by: Pew Memorial Trust and Marine Policy and Ocean Management Center.

SEJARAH KERAJAAN MELAYU PATANI

Conner Bailey and John N. Miksic,
Translators

This translation of Ibrahim Syukri's (pseudonym) *Sejarah Kerajaan Melayu Patani* ("History of the Malay Kingdom of Patani") or SKMP makes available a little known but important manuscript published privately ca. 1950 and printed in "jawi," Malay written in a modified Arabic script. The book subsequently was banned in both Thailand and Malaysia; few copies appear to have survived.

The SKMP is divided into four chapters, the first three of which are clearly within the Malay "hikayat" tradition. After tracing the origins of the area's first inhabitants (Chapter 1), the author describes the founding of Patani, the coming of Islam, and the growth of Patani as a major port of call for Asian and European traders during the 16th and 17th centuries (Chapter 2). In this second chapter, Patani is shown at the pinnacle of her prestige and power, repelling four invasions from the powerful Kingdom of Siam.

Patani's fortunes gradually declined during the 18th century as Dutch and English trading companies established entrepôts elsewhere in Southeast Asia, causing a shift in trade patterns away from Patani (Chapter 3). Internal disputes regarding succession to the throne also affected Patani's ability to withstand external pressures. The author describes Patani's defeat by Siam in 1784 and the series of unsuccessful revolts against Siamese rule

which followed over the next 50 years.

In Chapter 4 the author moves from "hikayat" to polemic, issuing a strongly worded attack on national policies during the first half of the 20th century, which he characterizes as culturally and politically repressive and economically exploitative.

The SKMP represents a valuable contribution to the limited literature available on the Malay population of present-day southern Thailand. The author's rendering of Patani's history is based on a distinctly Malay interpretation of the historical record. The SKMP, however, is less important as objective history than as a political statement by the author, who describes the proud history and the strong sense of ethnic identity shared by Patani's Malay population. The SKMP will be of particular interest to those who seek to understand the persistence of conflict in southern Thailand.

Published in: History of the Malay Kingdom of Patani. Southeast Asia Monograph Series No. 68. Ohio University Center for International Affairs, Athens Ohio. 1985.

Supported in part by: Pew Memorial Trust and Marine Policy and Ocean Management Center.

ECONOMICS OF NON-FUEL MINERALS

James M. Broadus

Non-fuel marine minerals actually are produced and do make a contribution to the world's economy. They are not entirely a speculative resource. The economic contribution of offshore non-fuel minerals production is not very important compared to the more conventional onshore sources of the same commodities. Further, compared to the annual value of offshore oil and gas production, production of offshore non-fuel minerals represents about one third of one percent. The policy issues associated with development of offshore non-fuel mineral sources are discussed, using marine polymetallic sulfides as an example. National investment decisions for marine polymetallic sulfides would be better made according to scientific selection criteria than according to commercial ones. However, further research into the question of external benefits derived from offshore mineral development efforts is needed.

Published in: Resource Use and Conflicts in the Exclusive Economic Zone, Chapter 20. L.C. Hanson and L. Alexander, eds. Times Press, Wakefield, R.I. 1984.

Supported by: Pew Memorial Trust; NOAA Grant NA83AA-D-00049; and Marine Policy and Ocean Management Center.

POLYMETALLIC SULFIDES AND POLICY SPHERES

James M. Broadus and Robert E. Bowen

The recently discovered marine polymetallic sulfides are of great interest scientifically. Much remains to be learned about their economic significance, their implications for strategic materials supply, and their potential effects on international legal and political systems, but a number of issues now face policymakers and the public in the absence of such information. These issues involve the deposits' economic potential and appropriate levels of public investment, research strategies, agency assignments and their relationship to commercial development, international jurisdiction, and environmental concerns. The deposits almost certainly will not be exploited for a very long time, if at all. Meanwhile, if too much emphasis is placed on their resource potential, time, money and effort may be wasted in planning for their development. Attention to the needs of basic scientific research on the phenomenon may also be diverted.

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RIVALRY AND COORDINATION IN MARINE HARD MINERALS REGULATION

James M. Broadus and Porter Hoagland III

Marine hard minerals are being promoted for potential contribution to national supply. The timely and efficient development of these potential public resources could be distorted by rivalrous federal agency behavior in the multiple agency framework that includes both the Commerce and Interior Departments. The importance of marine hard minerals development may be exaggerated as agencies bid for constituency and seek to expand jurisdictional domain. Alternatively, impediments may be created by duplication of effort, confusing signals, false starts, and diversion of resources to rivalrous activities. Under some conditions, however, competition between agencies can serve as a check on regulatory excesses and can provide valuable diversity of information to policymakers.

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Conference, IEEE/MTS, September,
1984.

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Policy and Ocean Management Center.

ECONOMIC SIGNIFICANCE OF POLYMETALLIC SULFIDES

James M. Broadus

Policies of national governments -- with respect to marine resources jurisdiction, international marine science, and long-run minerals supplies -- are being influenced by suggestions that marine polymetallic sulfides (MPS) around hydrothermal vents are important economic resources. Yet no systematic analysis of their economic significance has heretofore been reported. Too little is known about the nature of these deposits to permit confident estimates of their economic promise. First-order approximation of their current economic significance is nonetheless possible on the basis of: a) current economic understanding of the dynamics of natural resources creation and use; b) projection of aggregate consumption of the contained metals; c) projection of long-run alternative supplies; d) informed speculation about the sources and relative magnitudes of costs and the relative pace of technological development; e) scientific modeling results on geographic, size and grade distribution; and f) expressions of commercial interest by profit-oriented organizations. It is determined that MPS are still largely a scientific phenomenon with little current economic significance. They may eventually provide metallogenesis data valuable for onshore exploration. That remains to be seen. They may someday even become a valuable economic resource in their own right. But they are not now. Evaluations of expenditures on MPS are most appropriately made through scientific selection criteria rather than through commercial ones.

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Internatinal Seminar on Offshore
Mineral Resources. GERMINAL.
Centre Oceanologique de Bretagne.
Brest, France.

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Marine Policy and Ocean Management
Center.

COASTAL AND MARINE RESOURCES MANAGEMENT FOR THE GALAPAGOS ISLANDS

James M. Broadus, Ivon Pires,
Arthur Gaines, Conner Bailey, Robert Knecht
and Biliana Cicin-Sain

The report briefly describes coastal and marine resource uses and problems in Ecuador's Galapagos Islands, discusses general principles of coastal zone management (CZM) and marine resources management (MRM), examines the current status of CZM and MRM in the Galapagos Islands, and offers observations on possible avenues for improvement. The archipelago has long been the object of worldwide scientific interest. Increased demands on its coastal and marine resources, to serve a growing resident population and to accommodate potentially lucrative tourism, signal a need for greater attention to the management of these resources. Coastal and marine affairs and problems in the Galapagos which can be addressed by a CZM/MRM process include: conservation of the Islands' unique biota and habitats; tourism; port development; waste disposal; resource extraction; and fisheries. The basic elements of a CZM and MRM system are already in place in the Galapagos, but they are uncoordinated and largely ad hoc in nature. Existing and potential jurisdictional ambiguities or conflicts between the Navy/Port Captaincies, the municipalities, the National Park, the development agency for the Galapagos (INGALA) and other organizations are described. A two-zone management scheme for coastal and marine resources is outlined. It avoids the establishment of complicated new systems of boundaries and institutions, instead adapting itself to the existing situation. Four possible mechanisms for improved coordination are identified: cooperative management; a coastal zone and marine resources council; a series of agreements ("convenios") between relevant agencies; and application of incentives. The possible creation of a marine protected area is discussed, including rationale for the area's establishment, its designation and organization, jurisdictions, boundaries and zoning, and the protection of traditional uses.

Supported by: William H. Donner Foundation; Tinker Foundation; Pew Memorial Trust; and Johnson Endowment Fund.

WHOI Technical Report 84-43.

ADJACENT STATE ISSUES FOR THE UNITED STATES
IN ESTABLISHING AN EXCLUSIVE ECONOMIC ZONE:
THE CASES OF CANADA AND MEXICO

Robert E. Bowen and Timothy M. Hennessey

One of the more pressing sets of issues that the United States will face in formalizing its EEZ claim will be that relating to the delimitation and definition of jurisdiction between itself and adjacent states. Near term differences in views over the legal status of the United Nations Convention on the Law of the Sea, in interpretation of customary international law, and in resource management approaches will likely be sources of confusion and conflict between the United States and its neighbors. This paper will examine the range of those issues, specifically as they relate to U.S./Canadian and U.S./Mexican relations, and will discuss the range of appropriate policy options and concerns. The discussion will be divided into two general sets of issues: those dealing primarily with boundary delimitation and those dealing primarily with the jurisdiction over and the management of coastal resources and activities.

In press: Ocean Development and
International Law.

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Foundation; Johnson Endowment Fund;
and Pew Memorial Trust.

U.S. EEZ RELATIONS WITH CANADA
AND MEXICO

Robert E. Bowen and Timothy M. Hennessey

One of the more immediate concerns facing the United States in the aftermath of the Exclusive Economic Zone (EEZ) Proclamation is the establishment of mutually agreed upon boundaries with Canada and Mexico. In setting these boundaries, differences in views over the legal status of the United Nations Convention on the Law of the Sea, in interpretation of customary international law, and in resource management approaches, are likely to cause confusion and conflict between the United States and its neighbors.

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1984.

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U.S.-MEXICAN PARLEY DEBATES RELATIONS
ON MARINE RESOURCES

Biliana Cicin-Sain, Michael K. Orbach
and Jorge A. Vargas

A conference on U.S.-Mexican Relations on Marine Resources, held at the University of California at San Diego in September 1983 brought together distinguished marine analysts and policy makers from both Mexico and the United States, including former Mexican President Luis Echeverria, to discuss issues that both unite and separate the two nations.

Significant differences of opinion were expressed by government, interest-group and academic representatives from each nation. The major topics discussed were: 1) the implications of the changing international context for bilateral U.S.-Mexico relations (most prominently, the recent adoption of the Law of the Sea Convention); 2) the domestic forces (political, administrative, social, and economic) that shape bilateral relations on marine issues between the United States and Mexico; 3) conflicts over the management of tuna; and 4) conflicts over the conduct of marine scientific research.

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1983-84.

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Management Center.

A MODEL FOR ASSESSING MEAN
AGE-SPECIFIC FECUNDITY
IN SEA TURTLE POPULATIONS

Nat B. Frazer

A model is developed to estimate mean age-specific fecundity for sea turtle populations. Information on the numbers of eggs laid by female turtles of known relative ages is used to estimate the mean number of eggs that will be laid by females that are reproducing at a given age. Information on the frequencies of interseasonal nesting intervals is then used to adjust mean age-specific fecundities to reflect the substantial proportion of females in each age class that do not reproduce in a particular season (i.e., at a particular age). The model is developed with data collected on adult female loggerhead turtles, Caretta caretta, nesting on Little Cumberland Island, Georgia, USA, from 1969 through 1981. The model is applicable to species of both marine and freshwater turtles in which individual females may not reproduce each year (i.e., at each consecutive age).

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281-291, 1984.

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PROTECTING CARIBBEAN WATERS:
THE CARTAGENA CONVENTION

Nat B. Frazer and M. J. Peterson

The Wider Caribbean is one of eleven designated "Regional Seas" under the United Nations Environment Program. Recent development in the Caribbean has led to increases in domestic sewage, upland erosion and wastes from both industry and agriculture. In addition, the Caribbean is criss-crossed by major shipping lanes used to transport petroleum and there are major refineries and storage facilities in the region. Thus, the beaches, reefs, mangroves and sea grasses all face the potential of environmental pollutants which could damage fisheries and destroy much of the aesthetic value that makes the region attractive to tourists.

Representatives of 16 states drafted the "Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region" (Cartagena Convention) at Cartagena de Indias, Colombia, on 24 March 1983. The Cartagena Convention addresses the control of marine pollution from ships, ocean dumping of wastes, land-based activities and airborne emissions, as well as exploration and exploitation of nonliving resources of the seabed. The Cartagena Convention enables Caribbean states to adopt measures to protect their own resources, thus supplementing the general rules on marine pollution negotiated at the Third United Nations Conference on the Law of the Sea.

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Fall 1984.

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Center

GROWTH CURVES FOR CAPTIVE LOGGERHEAD
TURTLES, Caretta caretta,
IN NORTH CAROLINA, USA

Nat B. Frazer and Frank J. Schwartz

Growth curves are not available for individuals from natural populations of loggerhead turtles, Caretta caretta. In this study, we fit logistic and von Bertalanffy growth equations for length to

data from two loggerheads raised in captivity for 14 years. Growth of both was best described by logistic equations. Our results suggest that female loggerheads mature in 19 to 20 years. Thus, conservation programs aimed at protecting eggs or maintaining hatcheries may not increase the observed numbers of nesting females for up to two decades.

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Science, 34, 485-489, 1984.

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Management Center.

GROWTH IN WEIGHT FOR LOGGERHEAD TURTLES,
Caretta caretta, REARED IN CAPTIVITY
FOR 14 YEARS IN NORTH CAROLINA

Frank J. Schwartz and Nat B. Frazer

Growth curves are not available for individuals from natural populations of loggerhead turtles, Caretta caretta. Data on growth in weight for a male and a female loggerhead, born and reared for 14 years under conditions approximating those found in the wild, were fit to logistic and von Bertalanffy equations. Turtles were hatched from eggs collected at Emerald Isle, North Carolina, in 1968 and incubated in styrofoam coolers at 28°C. Weights were taken semiannually when the turtles were moved between large outdoor concrete and smaller indoor tanks. Unfiltered saltwater was pumped through the tanks continuously. Indoor transfer was necessary to prevent stress or death from winter waters cooler than 10°C. Diet of the captive turtles consisted primarily of fishes and other local marine organisms. Feeding was to satiation during June to mid-August; during fall and spring feeding was every two or three days and every third day as their activity decreased during the winter. The non-linear logistic equations, male $w = 93.1 / (1 + 1796.8e^{-0.735t})$ and female $w = 77.5 / (1 + 18684.4e^{-0.960t})$ provided the best fit of the weight data (w = weight, e = base of the natural logarithms, t = age in years). The von Bertalanffy equations projected unrealistic higher asymptotic weight estimates. Our data support Uchida's (1967) assertions that growth of captive loggrheads fits a logistic equation, but sizes he reported for his 4.5 year old turtles were influenced by a constant 25°C rearing temperature and daily feeding to satiation.

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1984.

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Management Center.

PRELIMINARY GROWTH MODELS FOR GREEN,
Chelonia mydas, AND LOGGERHEAD,
Caretta caretta, SEA TURTLES
IN THE WILD

Nat B. Frazer and Llewellyn M. Ehrhart

Capture-recapture measurements of 11 wild green turtles, Chelonia mydas, and of 28 wild loggerhead turtles, Caretta caretta, in Florida indicate that growth in straight-line carapace length fits von Bertalanffy growth models better than logistic models. The von Bertalanffy model for green turtle growth yields estimates for age at maturity of between 18 and 27 years, based on the carapace length of the smallest nesting female (88cm) and the mean carapace length of all nesting females (99cm). The model for loggerheads yields estimates of between 12 and 30 years, also based on the carapace measurement of the smallest nesting female (74cm) and the mean carapace length of all nesting females (92cm). It is suggested that the upper estimates provide more realistic indications of mean age at first maturity.

In press: Copeia, 73-79, 1985.

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Trust and Marine Policy and Ocean
Management Center.

THE RELATIONSHIP OF CLUTCH SIZE AND
FREQUENCY TO BODY SIZE
IN LOGGERHEAD TURTLES, Caretta caretta

Nat B. Frazer and James I. Richardson

This paper examines the relationship of clutch size (the number of eggs in a nest) and clutch frequency (the number of nests laid) to body size in loggerhead sea turtles, Caretta caretta, nesting at Little Cumberland Island, Georgia. There is a significant positive correlation between body size and clutch size, and model II analysis of variance indicates that there is a highly significant added variance component in clutch size due to differences among females. However, no significant correlation is apparent between the size of a female and the number of clutches she lays.

In press: Journal of Herpetology, 19.

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Center.

SEASONAL VARIATION IN CLUTCH SIZE FOR
LOGGERHEAD SEA TURTLES, Caretta caretta,
NESTING ON LITTLE CUMBERLAND ISLAND,
GEORGIA USA

Nat B. Frazer and James I. Richardson

In an attempt to assess seasonal trends in clutch size for loggerhead sea turtles, Caretta caretta, we divided the nesting season into six periods and recorded the sizes of clutches laid during each period for the combined 1978-1983 nesting seasons. We also followed individual turtles over the course of a nesting season as they laid successive clutches during the 1965 to 1983 nesting seasons.

Analysis of variance revealed significant differences in mean clutch size over the course of the nesting season for the population as a whole, although means did not differ significantly during the first four periods. Mean clutch size for nests laid during the last two periods (after July 15) was significantly smaller than for nests laid earlier, but this did not reflect a continual decrease throughout the season.

For the two groups of turtles that laid only three or four known nests, there was a decrease in mean clutch size for each subsequent nest, although the trend was not significant. Mean clutch size did not differ significantly in successive clutches of turtles that laid five known nests, nor was there any apparent trend in mean clutch size for these turtles. The mean size of the last clutch was significantly smaller than for earlier clutches for turtles that laid six known nests, but mean clutch size first increased and then decreased as successive clutches were laid.

In press: Copeia.

Supported by: Pew Memorial Trust and
Marine Policy and Ocean Management
Center.

A GUIDE TO THE USE AND EVOLUTION OF
THE 1982 CONVENTION ON THE
LAW OF THE SEA

John King Gamble

The U.N. Convention on the Law of the Sea (herein after the M.B.C. or the Convention), signed December 10, 1982 by 117 states, stands as one of the most important treaties of this century. While the fate of the Convention is uncertain, i.e. it may take a long time to enter into force, it will command an unprecedentedly high amount of interest from academics, practitioners, and, more generally, anyone professionally involved with oceans affairs. The only

recent treaty of comparable interest -- the U.N. Charter -- is much less complex and far shorter.

Concomitant with the emergence of the new treaty has been a huge array of books and monographs including some excellent multi-volume series analyzing all aspects of the text and context of the Convention. No doubt attention will increase further in the next several years. The book is intended to be a single-volume reference work usable by people with a wide range of interests in the law of the sea. The contents of the volume were selected to provide users with an efficient method to find the information needed most frequently.

In press: University of Washington Press, Seattle.

Supported by: Pew Memorial Trust; Johnson Endowment Fund; and Marine Policy and Ocean Management Center.

THE LIMITS OF "MUDDLING THROUGH" IN NATURAL RESOURCE MANAGEMENT

Timothy M. Hennessey

In the last twenty-five years political scientists have come to recognize the importance of complexity and uncertainty for the quality of public policy decisions. Indeed, there is a large and growing body of literature which suggests that complex problems force decision makers to behave in ways which are sharply at odds with conventional models of rational decision-making.

Yet despite this body of literature, there has been relatively little research identifying the critical characteristics of the task environment which call for different decision strategies. This paper examines the relationship between a particular task environment and the utility of Charles Lindblom's "muddling through" as a decision strategy.

The task environment we examine is that of the New England Fishery Management Council as they make regulatory decisions for the highly complex groundfishery. The decision making environment of the council is characterized by uncertainty associated with multiple decision-makers, multiple levels of government, and incomplete information regarding the dynamics and behavior of the groundfishery.

We test a hypothesis which states that the utility of muddling through as a decision strategy for managing the complex fishery must be discounted to the extent that there are significant biological, economic and social interdependences in the task environment.

In press: Proceedings of the Annual Meeting of the Western Political Science Association, April 12-14, 1984.

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THE MANAGEMENT OF OCEAN AND COASTAL RESOURCES IN COLOMBIA: AN ASSESSMENT

Robert W. Knecht, Biliانا Cicin-Sain,
James M. Broadus, Maynard E. Silva,
Robert E. Bowen, Henry S. Marcus
and Susan B. Peterson

This report summarizes the results of an 18-month study of coastal and marine resources development in Colombia. The study was a result of a request by the Direccion General Maritima y Portuaria (DIMAR) of the Colombian Navy to the Marine Policy and Ocean Management Center of WHOI and was carried out jointly with that group. Observations of the present situation and potential for four sectors are presented: fisheries and aquaculture, marine minerals and energy, marine transportation and ports, and tourism and coastal development. The coastal tourism and fisheries sectors appear to be the most promising in terms of near-term potential. Suggestions for achieving increased economic and social benefits from these sectors are provided. In addition, institutional arrangements among the ocean-related agencies in Colombia are reviewed and recommendations aimed at achieving a higher degree of policy integration are offered.

Supported by: William H. Donner Foundation; Direccion General Maritima y Portuaria of the Armada Nacional in Colombia; The Pew Memorial Trust; and NOAA Grants NA80-AA-D-0007 (E/L-1) and NA83-AA-D-00049 (E/L-1).

WHOI Technical Report 84-21.

EVALUATING THE RISKS OF OFFSHORE OIL DEVELOPMENT

William Lahey and Thomas Leschine

The increasing world appetite for oil and the recognition of oil as an important strategic weapon and diplomatic tool has spurred intensive efforts to develop offshore oil resources. Drilling offshore for oil is not new. What is new, however, is the rapid expansion of offshore leasing activity in all types of marine environ-

ments. Currently about one thousand wells are drilled in the outer continental shelf (OCS) per year. In many areas, especially in frontier areas such as the North Atlantic and the Alaskan continental shelf, this increased activity has given rise to concern about a variety of impacts -- to the environment, to the social and economic stability of coastal communities and to public health and safety. How the potential impacts should be considered, however, is a very difficult question to answer. Identification of the potential impacts is clearly an important first step. Estimating the probability and magnitude of a particular impact, a basic risk assessment computation, is another ingredient of an informed impact assessment.

In the article, the potential impacts associated with oil and gas activities on the OCS are identified and described. The discussion then focuses on risk assessment to evaluate whether this methodology might improve OCS impact assessment.

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ECONOMIC EVALUATION OF ETHANOL FUEL PRODUCTION FROM AGRICULTURAL CROPS AND RESIDUES IN CALIFORNIA

Mark Meo

The economic feasibility of producing ethanol fuel from a variety of starch and sugar rich crops and crop residues at an off-farm cooperative scale plant (3,408,000 liters per year) is evaluated within an agriculturally diverse and productive region of the Sacramento Valley, California (U.S.A.). A linear programming model of a county (Yolo) representative of the region is used to compare conventional starch and sugar crop fermentation and distillation technology with innovative cellulosic hydrolysis. Parametric programming is used to estimate breakeven prices for ethanol fuel production for several different planning scenarios.

Land use data in the model are based upon 1981 crop acreage inventory maps, a soil quality map, and a map of different trip distances to a centrally located plant. Vegetable and field crop hectares of barley, corn, grain sorghum, rice, sugar beet, tomato, and wheat are digitized and upper and lower hectareage flexibility restraints are estimated by regression based upon

hectareage changes in the past. High and medium productivity soil groups, Storie Index Rating (SIR) I and II, and III and IV, respectively, are also digitized. SIR is used to classify soils on the basis of pedologic characteristics and their usefulness to agriculture. Trip distance costs for trucking are calculated for 13, 26, and 39 kilometer routes.

Candidate starch and sugar feedstocks include barley, corn, corn silage, grain sorghum, wheat, fodder beet, Jerusalem artichoke, sugar beet, and sweet sorghum. Lignocellulosic feedstocks include the residues of barley, corn, grain sorghum, rice, and wheat.

Planning options comparing the effect of including or excluding currently available subsidies in the form of tax credits on ethanol fuel breakeven prices are modeled for a base year, 1981, and a forecast year, 1992, when these subsidies are scheduled to expire. Technological innovation is assumed to reduce capital costs by 20% by 1992. Prices of gasoline and diesel fuel are projected to rise from \$0.34 and \$0.30 per liter respectively, to \$0.75 and \$0.71 per liter (1981 \$), respectively.

It was found that in 1981 the least-cost feedstock using conventional fermentation technology was fodder beet. Estimated breakeven prices sufficient to equal fixed, variable, and opportunity costs of production were \$0.29 and \$0.46 per liter, with and without subsidy, respectively. In 1992, the least-cost feedstock will also be fodder beet. Its estimated breakeven price is \$0.40 per liter. For lignocellulosic feedstocks, breakeven costs using acid hydrolysis technology ranged from \$0.27 to \$0.35 per liter depending upon conversion efficiency and subsidization. By 1992, the estimated breakeven cost could range from \$0.42 to \$0.47 per liter without subsidization.

Fodder beet appears more favorable than other fuel crops because of its cheaper storage costs, a factor not shared by sweet sorghum or Jerusalem artichoke when the distillery is operated year-round rather than seasonally.

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Conservation, 11, 1-25, 1984.

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SELECTION OF FEEDSTOCKS FOR SMALL
AND INTERMEDIATE SCALE FUEL
ETHANOL DISTILLERIES

Mark Meo

A variety of commercial and experimental starch and sugar-rich crops were evaluated for their suitability as feedstocks in both small scale on-farm and intermediate scale off-farm production in the Sacramento Valley of California. Solutions of linear programming models indicate that for representative farms, sweet sorghum is the least-cost feedstock for ethanol production at fifty thousand gallons per year, and fodder beet is the least-cost feedstock for an annual off-farm production of one million gallons. Model results are sensitive to assumed crop yields, market prices, processing efficiencies, discount rates, and tax credits.

In press: Journal of Soil and Water
Conservation, May-June 1985.

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CONFIDENCE BUILDING MEASURES IN
LATIN AMERICA

Michael A. Morris

In contrast to the situation on the European continent, the perception of the variable "confidence" differs considerably in other latitudes. Nor are the causes of distrust the same for all regions. In order to apply confidence building measures (CBMs) effectively in Latin America, much wider concerns than enhancing confidence in strictly military matters must be considered, even though this is the focus of CBMs in Europe.

In spite of differences in perspective regarding CBMs in the military field, these have been included in proposals to resolve the Central American crisis. Related CBMs have been included in the Declarations of Ayacucho and Washington, as well as in diverse subregional agreements, including the Andean Pact and SELA (Latin American Economic System). There is an urgent need in Latin America to promote such CBMs in the military area and to extend them to political, economic, and social problems as well.

Distinctive regional trends, including differences between the more than two dozen states in and around the Caribbean Basin and South America, characterize conflict and conflict resolution and set the context for CBMs in Latin America. Such a distinc-

tive context requires tailor-made CBMs at the regional level, subregionally for the Caribbean Basin and South America, and for specific conflicts and national situations. The general context for CBMs is set forth in an introductory section followed by examples of CBMs tailored to the two Latin American subregions (the Caribbean Basin and South America) and to some prominent conflicts, and a final section presents some conclusions about confidence building measures in Latin America.

In press: Confidence Building
Measures in the 80s. Institute for
East-West Security Studies, New
York, 1985.

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Marine Policy and Ocean Management
Center.

SOUTHERN CONE EEZ PRACTICE

Michael A. Morris

This article focuses on the contemporary Exclusive Economic Zone (EEZ) practice of the two key Southern Cone states, Argentina and Chile. EEZ practice by local states is necessarily decentralized in nature, and yet law-of-the-sea norms establish global guidelines for this practice. Moreover, the maritime powers will judge individually whether local EEZ practice conforms sufficiently with the global EEZ consensus contained in the 1982 Third United Nations Conference on the Law of the Sea Treaty (UNCLOS III). They may be expected to contest local EEZ practice that diverges markedly from global norms and/or challenges their interests. Local EEZ-related conflicts may further complicate this panorama.

Indeed, disputes both between local states and with the maritime powers characterize Southern Cone EEZs. The strategic location and resource-rich nature of these EEZs have contributed to such disputes. However, important cooperative developments characterize Southern Cone EEZ practice as well. An assessment of both the conflictual and cooperative aspects of Southern Cone EEZ practice will help place local events in comparative perspective.

In press: Ocean Yearbook 6. Elizabeth
Mann Borgese and Norton Ginsburg,
eds. University of Chicago Press,
Chicago, 1985.

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Center.

COMPARATIVE MARITIME LIENS: ANGLO-BASED
AND LATIN-BASED LAW IN THE AMERICAS

Ivon Pires

Principles of international comity have established that the application of the law by the court in one country should be upheld by the courts of all other countries. The sale of a vessel by decree of a U.S. or a foreign court in a maritime action "in rem" is therefore valid against the world. This procedure does not require prior notice to the vessel's owner, frees the vessel of all previous bonds and vests unchallengeable title in the new purchaser. Admiralty, however, like any other branch of the law, is not exempt from the immense variation of rules among legal families and within different systems of the same family, where national interests have traditionally avoided international uniformity. The importance of a comparative study of maritime law to understand these differences is directly related to the protection of property and stability of expectations needed in maritime commerce.

The purpose of this paper is to examine and compare the unique institution of maritime liens in various national legal systems on the American continent and in applicable international conventions. An analysis of every national legal system is not necessary to show the peculiarities of the two supra-national systems. The Anglo-American system will be represented by its two major countries, Canada and the United States. The Latin-American system will consist of Argentina, Brazil, Mexico, Panama and Venezuela, which represent the five largest merchant marine fleets and, as a group, account for over 90 percent of the regional tonnage.

In press: The Maritime Lawyer
(Admiralty Journal of the Tulane
University School of Law), Vol. 9,
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W.H.O.I. Contribution No. 5635.

PRIORITY OF MARITIME LIENS IN THE WESTERN
HEMISPHERE: HOW SECURE IS YOUR CLAIM?

Ivon Pires

The primary function of a maritime lien is to ensure that credit be given to a vessel so that she can be adequately furnished to proceed on her voyage, while concurrently providing security to the suppliers of services and materials. The unsettled issue

is the security of these liens when the vessel leaves port and enters the jurisdiction of other countries. Will these claims have the same status whether or not they are recognized as liens abroad? If so, what priority will they receive?

The Western Hemisphere offers a microcosm of the complex legal web that affects international navigation. Beyond the diversity of national laws, national legal systems deriving from different legal families also vary structurally and procedurally. This paper will explore how these two variables lead to results that defeat the uniformity of rules desired in maritime commerce. Maritime liens and their priority are thus viewed from this comparative perspective.

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University of Miami, Vol 16-2,
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W.H.O.I. Contribution No. 5784.

A CHANGING OCEAN POLICY HORIZON
FOR MARINE SCIENCE

David A. Ross

A requisite for rational EEZ resource management is the continued integration of marine science and policy. Policymakers will increasingly need reliable scientific information as national borders expand seaward and as technology affords greater access to more marine resources. Developments in marine science should open new concepts of ocean and resources use, and these in turn will pose new sets of policy issues. Some of the science-policy possibilities include: 1) expanding our knowledge of global ocean circulation, thus improving fish stock assessment, weather prediction and innovative energy use; 2) continuing pollution research with a focus on the limits of acceptable degradation of an environment (including the problems of carbon dioxide in the atmosphere); 3) integrating the discovery and eventual exploitation of marine minerals with the environmental, legal and political constraints; and 4) insuring access to all areas of the ocean for marine science research in light of the stringent conditions imposed by some nations on research in their territorial seas and exclusive economic zones.

In press: Ocean Development and
International Law.

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W.H.O.I. Contribution No. 5778.

EEZ OFFERS A CHANCE FOR FOREIGN COLLABORATION

David A. Ross

The United States should establish an office in conjunction with our new Exclusive Economic Zone (EEZ) to promote and develop international cooperation in marine science. The Law of the Sea Treaty, regardless of whether or not it is ultimately ratified, will bring marine science in approximately 42 percent of the oceans under control of various nations through its EEZ and continental shelf provisions, or their own. American marine scientists will be (and already are) experiencing difficulties in working in such foreign waters; examples presently include India and Trinidad and Tobago. If such difficulties do not cease, there will be problems in implementing many important international oceanographic and marine programs.

The Law of the Sea Treaty and the declaration of a U.S. EEZ mark the beginning of an exciting new era in oceanography. To capitalize fully on this opportunity will require the collective efforts of government, industry, and academia. The benefits of such a collaboration would far exceed the modest funds needed to initiate an "Office for International Cooperation in Marine Science."

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THE ANTARCTIC TREATY: HISTORY, SUBSTANCE AND SPECULATION

Kurt M. Shusterich

Over the past two years Antarctica has received close attention from a larger number of national governments and the general media than ever before. Pressures for change in the present regime have been exerted with increasing regularity by various interest groups, including governments from a handful of Third World nations. The first part of this paper sketches out the genesis of the Antarctic Treaty. The second analyzes the circumstances that have

surrounded its successful implementation to this date. Pressures for change and proposed alternatives to the Antarctic regime are explored in the third and fourth parts of the paper. The final section of the paper reflects upon the strength of these pressures for change and the likely future of the Antarctic regime.

In press: *International Journal*.

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WHOI Contribution No. 5686.

ARCTIC ISSUES COMING TO FORE

Kurt M. Shusterich

Although geographically remote and often an extremely difficult place in which to work and live, the Arctic will be of growing importance to the United States during the next two decades. Issues of national security, resource development, science, and environmental protection have brought new players into Arctic affairs and have increased the activities and concerns of those traditionally involved. A prerequisite for improved relations among Arctic-rim countries is knowledge and understanding of each nation's resource development and strategic objectives in the Arctic. Cooperation in any region is more likely to take place when nations and other constituencies are convinced that benefits can be derived from working with, or at least not against, one another.

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MARINE RESOURCE DEVELOPMENT IN BELIZE

Kurt Shusterich

Marine resource development has increased its importance for most of the world's coastal nations. This is especially true for developing coastal states that are now looking to the sea to help provide new sources of food and income. Belize is an example of such a developing state with certain features that make it particularly interesting for study.

Belize has a unique physical setting -- on the western Caribbean Sea with one of the world's largest barrier reefs running almost

the entire 175-mile length of the nation. This setting lays the foundation for the focus of this report on the successful development of a Belize fishing cooperative network, hopes for offshore hydrocarbon exploitation, and a philosophy that encourages a cautious development of the nation's (significantly marine-related) tourist industry.

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LAND GRANT AND SEA GRANT: IMPLICATIONS AND LIMITATIONS OF THE MODEL

Maynard E. Silva

The Sea Grant system was created to assist in the development of ocean science and technology. This mission is accomplished through education, research and advisory services. The system's structure resulted from the explicit effort of early Sea Grant supporters to forge the system as an oceans' equivalent of Land Grant. There are, however, structural differences that create inherent limitations in this analogy. Criticisms of the Land Grant system have been raised. Sea Grant may wish to blunt similar criticisms by examining and evaluating the analogy along with its limitations and implications. The present may be propitious for such an evaluation.

The article will: 1) provide a short history of the creation of Sea Grant based on the Land Grant analogy; 2) compare the two systems, including criticisms that have been made of Land Grant; and 3) suggest ways in which Sea Grant might avoid some of the alleged shortcomings of Land Grant.

In press: Ocean Development and International Law.

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THE LAW OF THE SEA AND THE U.S. EXCLUSIVE ECONOMIC ZONE: PERSPECTIVES ON MARINE TRANSPORTATION AND FISHERIES

Maynard Silva and William Westermeyer

Reacting to the United States decision not to sign the U.N. Law of the Sea Treaty and the issuance of a proclamation by President Reagan for a U.S. 200-nautical mile Exclusive Economic Zone (EEZ), various

interest groups have argued that difficulties would arise for U.S. management of ocean resources. The authors examine two of the more important ocean activities regulated by the United States -- marine transportation and fisheries. They posit that though some small modifications of U.S. policy may be required because of the treaty and the EEZ proclamation, generally these activities will not be affected.

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WHOI Contribution No. 5785.

UNITED STATES ARCTIC INTERESTS

William Westermeyer and
Kurt Shusterich, eds.

Remote, sparsely populated, often an extremely difficult place in which to live, yet rich in resources, the Arctic remains one of our last great frontiers. However, the need to recover the energy wealth of the Arctic and the development of technologies to accomplish this have been the catalyst for many changes, and made us aware of a broad range of interests in this region. As Elliot Richardson states in the foreward, "The United States is finally awakening to the fact that it has a stake in the future of the Arctic." The book identifies the nature of that stake as well as articulates the manner in which these multiple, sometimes conflicting interests are related to one another.

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GRADUATE STUDENTS

Abstracts of papers or theses submitted in 1984 by graduate students of the Woods Hole Oceanographic Institution Doctoral Degree Program and the Woods Hole Oceanographic Institution/Massachusetts Institute of Technology Joint Program in Oceanography/Oceanographic Engineering. Other papers authored or coauthored by graduate students are included in the departmental sections. Students are indicated by an asterisk in the Author Index.

GRADUATE STUDENTS

Abstracts of papers or theses submitted in 1954 by graduate students of the State University of New York at Stony Brook, New York, and the State University of New York at Binghamton, New York, are listed in this section. The papers are listed in the order in which they were received by the Graduate Council. The names of the authors are listed in the order in which they were received by the Graduate Council.

EDDY FORCING OF THE MEAN CIRCULATION IN THE WESTERN NORTH ATLANTIC

Ellen D. Brown

This thesis addresses several aspects of the problem of determining the effect of the low-frequency eddy variability on the mean circulation of the Western North Atlantic. A framework for this study is first established by scale analysis of the eddy and mean terms in the mean momentum, vorticity, and heat balances in three regions of the Western North Atlantic -- the northern recirculation, the southern recirculation, and the mid-ocean. The data from the last decade of field experiments suggest somewhat different conclusions from the earlier analysis of Harrison (1980). In the momentum balance we confirm that the eddy terms are negligible compared to the lowest order mean geostrophic balance. The eddy term may be an $O(1)$ term in the vorticity balance only in the northern recirculation region where the mean flow is anisotropic. In the mean heat balance, if the mean temperature advection is scaled using the thermal wind relation, then the eddy heat flux is negligible in the mid-ocean, but it may be important in the recirculation areas. For all the balances the eddy terms are comparable to or an order of magnitude larger than the mean advective terms. We conclude from the scale analysis that the eddy field is most likely to be important in the Gulf Stream recirculation region.

These balances are subsequently examined in more detail using data from the Local Dynamics Experiment (LDE). Several inconsistencies are first shown in McWilliams' (1983) model for the mean dynamical balances in the LDE. The sampling uncertainties do not allow us to draw conclusions about the long-term dynamical balances. However, it is shown that if we assume that the linear vorticity balance holds between the surface and the thermocline for a finite record, then the vertical velocity induced by the eddy heat flux divergence is non-zero.

The local effect of the mesoscale eddy field on the mean potential vorticity distribution of the Gulf Stream recirculation region is determined from the quasigeostrophic eddy potential vorticity flux. This flux is calculated by finite difference of current and temperature time series from the Local Dynamics Experiment. This long-term array of moorings is the only experimental data from which the complete eddy flux can be calculated. The total eddy flux is dominated by the term due to the time variation in the thickness of isopycnal layers. This thickness flux is an order of magnitude larger than the relative

vorticity flux. The total flux is statistically significant and directed 217°T to the southwest with a magnitude of $1.57 \times 10^{-5} \text{ cm/s}^2$.

The direction of the eddy flux with respect to the mean large scale potential vorticity gradient from hydrographic data indicates that eddies in this region tend to reduce the mean potential vorticity gradient. The results are qualitatively consistent with numerical model results and with other data from the Gulf Stream recirculation region. We find that the strength of the eddy transfer in the enstrophy cascade is comparable to the source terms in the mean enstrophy balance. The Austausch coefficient for potential vorticity mixing is estimated to be $O(10^7 \text{ cm}^2/\text{sec})$. An order of magnitude estimate of the enstrophy dissipation due only to the internal wave field shows that other processes must be important in enstrophy dissipation.

The measured eddy potential vorticity fluxes are compared to the linear stability model of Gill, Green, and Simmons (1974). An earlier study (Hogg, 1984) has shown agreement between the empirical orthogonal modes of the data and the predicted wavenumbers, growth rates, and phase speeds of the most unstable waves. However, we show substantial disagreement in a comparison of the higher moments -- the eddy heat and potential vorticity fluxes. Because the critical layer of the model is located near the surface, the model predicts that most of the eddy potential vorticity and eddy heat flux should occur within about 300 meters of the surface. The data show much greater deep eddy heat flux than predicted by the model. It is suggested that the unstable modes in the ocean have a longer vertical scale because of the reduction in the buoyancy frequency near the surface.

The evidence for in situ instability is also examined in the decay region of the Gulf Stream from an array of current and temperature recorders. Although there is vertical phase propagation in the empirical orthogonal modes for some of the variables at some of the moorings, there is not much evidence for a strong ongoing process of wave generation.

Supported by: NSF Contracts OCE77-19403, ATM79-21431 and OCE82-00154.

THE ROLE OF HETEROTROPHIC MICROFLAGELLATES IN PLANKTON COMMUNITIES

David A. Caron

The distribution and feeding behavior of bacterivorous microflagellates (2-20 μm protozoa) and their ingestion by cope-

Pods were examined in an attempt to assess the importance of these protozoa as a trophic link between planktonic bacteria and zooplankton. The abundance of microflagellates relative to other picoplankton (0.2-2.0 μm) and nanoplankton (2-20 μm) populations in water samples in the North Atlantic and in Lake Ontario and on macroaggregates in the North Atlantic was determined using direct microscopical and culture estimation techniques. Seasonal, vertical and geographical changes in the density of microflagellates were generally not greater than one order of magnitude. Microscopical counts of heterotrophic nanoplankton (presumably microflagellates) typically ranged from a few hundred to a few thousand ml^{-1} for a variety of planktonic environments. They constituted approximately 1/3 to 1/2 of the nanoplankton in the euphotic zone and dominated the nanoplankton in the aphotic zone. Most Probable Number (MPN) estimation of the density of bacterivorous protozoa indicated that microflagellates were, on average, an order of magnitude more abundant than bacterivorous ciliates and amoebae. MPN and direct microscopical counts of microflagellates differed by as much as 10^4 . This discrepancy was smaller in eutrophic environments (e.g. Continental Shelf and Lake Ontario) and on macroscopic detrital aggregates.

All microbial populations enumerated were highly concentrated on macroscopic detrital aggregates relative to their abundance in the water surrounding the aggregates. Enrichment factors (the ratio of abundance of a population on a macroaggregate to its abundance in the surrounding water) increased along a eutrophic-to-oligotrophic gradient because of the combined effects of an increased abundance of microorganisms on macroaggregates in oligotrophic environments and a decreased abundance in the surrounding water in these same environments. Average enrichment factors for direct microscopical counts of heterotrophic nanoplankton (range = 17-114) were not as large as enrichment factors observed for MPN estimates of the number of bacterivorous microflagellates (range = 273-18400). Microflagellates numerically dominated the bacterivorous protozoa cultured from macroaggregates by one to two orders of magnitude, but ciliates and amoebae were also highly enriched on macroaggregates. Microenvironments are therefore a potentially important aspect for the ecology of planktonic microorganisms. Observations on the microbial colonization of mucus sloughed by ctenophores and discarded appendicularian houses suggest that these materials may be important sources of macroaggregates.

Batch and continuous culture experiments were conducted with clonal cultures

of microflagellates to test their ability to grow on various types and densities of bacteria. The doubling time of *Monas* sp. 1 ranged from 43 hr (when fed the cyanobacterium *Synechococcus* Strain WH 8101) to 6.9 hr (when fed the heterotrophic bacterium *Serratia marino*rubra). Cell yields (i.e. the conversion of bacterial biomass into protozoan biomass) of *Monas* sp. 1 fed two species of heterotrophic bacteria were greater than yields for the microflagellate fed two species chroococcoid cyanobacteria (range = 7-68 percent). Cell yields of two other species of microflagellates (*Monas* sp. 2 and *Cryptobia maris*) were 48 percent and 61 percent, respectively, on the bacterium *Pseudomonas halodurans*. Microflagellates grew in continuous culture at concentrations of bacteria which were lower than bacterial densities required for the growth of ciliates as shown by other investigations. Therefore, microflagellates appear to be well-adapted for grazing bacterioplankton.

Microflagellates were also investigated for their ability to graze bacteria attached to particles. *Bodo nanorensis* and *Rhynchomonas nasuta* both showed a marked ability to graze attached bacteria and a limited ability to graze unattached cells. These results suggest that microflagellates may also be important consumers of bacteria attached to particles in the plankton and may explain the highly elevated densities of microflagellates on macroaggregates.

Grazing experiments performed with the copepod *Acartia tonsa* indicated that heterotrophic microflagellates were ingested by the copepods at rates comparable to the ingestion of phytoplankton of similar size. The presence of heterotrophic microflagellates did not depress filtration rates of the copepods, and one species (*Cryptobia maris*) appeared to be selectively grazed. Survival of *A. tonsa* on a diet of heterotrophic microflagellates was similar to survival on a diet of phytoplankton and was significantly longer than survival of starved controls or copepods fed only bacteria.

Due to their ability to grow at in situ densities of planktonic bacteria, their relatively high cell yields, and their acceptability as food for zooplankton, it is concluded that bacterivorous microflagellates may constitute an important trophic link between bacteria and zooplankton. This link may provide a mechanism whereby organic material and energy from the detrital food chain can be returned to the classical phytoplankton-copepod-fish food chain.

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SODIUM AND GLUCOSE TRANSPORT ACROSS
THE IN VITRO PERFUSED MIDGUT OF THE
BLUE CRAB, Callinectes sapidus Rathbun

Ka Hou Chu

The principal objectives of the present study are: (1) To investigate sodium transport across the midgut as well as the hindgut of Callinectes sapidus and the functioning of these two regions of the gut in osmotic and ionic regulation of the animal, and (2) to elucidate the mechanism of glucose absorption across the midgut of C. sapidus and to assess its role in nutrient absorption. The transport processes across the gut tissues were studied with an in vitro perfusion technique.

I demonstrated a net mucosal to serosal sodium transport across the midgut of C. sapidus. This net flux was within the same order of magnitude as the fluxes of isolated gut tissues of many other animal species. The flux displayed saturation kinetics and was ouabain-sensitive. The flux did not vary with environmental salinity, thus providing no evidence for an active regulatory role of the midgut in sodium balance. A reduction of passive permeability with salinity, however, was suggested. There was no measurable net sodium transport across the hindgut of the animal.

The midgut of C. sapidus was also capable of net transmural glucose absorption. The net flux was considerably less than the fluxes reported in mammalian intestine. The unidirectional mucosal to serosal glucose flux was depressed by metabolic inhibitors, the absence of mucosal Na^+ , and the presence of mucosal phlorizin or serosal ouabain. The flux was also decreased by the presence of mucosal D-galactose, but not D-fructose or L-glucose. The net glucose flux followed Michaelis-Menten kinetics.

The mucosal glucose uptake by the midgut was composed of two processes: a sodium-dependent, saturable component and a sodium-independent, non-saturable counterpart. The kinetic characteristics of the uptake suggest that the midgut does not play a major role in total nutrient absorption. Nutrients taken up by the midgut may be largely utilized to provide energy for other physiological functions served by this tissue.

Thin layer chromatographic analyses showed that whereas most glucose appeared as phosphorylated forms upon entering the midgut, free glucose was translocated a-

cross the tissue. These results suggest that the mucosal and serosal membrane transport processes are coupled to phosphorylation-dephosphorylation mechanisms, respectively. An alternative hypothesis is the presence of a high-affinity glucose carrier in the serosal border of the midgut.

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THE MARINE GEOCHEMISTRY
OF THE RARE EARTH ELEMENTS

Hein J. W. de Baar

Novel methods were developed for the determination of 12 of the 14 Rare Earth Elements (REE) in seawater. Initial extractions of the REE by chelating ion exchange chromatography is followed by cation exchange for removal of co-extracted U and remaining traces of major ions. Finally traces of U are removed by anion exchange before irradiation for 8 hours at a flux of 5×10^{13} neutrons. $\text{cm}^{-2} \cdot \text{sec}^{-1}$. After post-irradiation separation of ^{24}Na , the gamma spectra are recorded over four different time intervals with a Ge(Li) detector. An internal standard (^{144}Ce) is carried all along the procedure for improved precision by avoidance of counting geometry errors.

Vertical profiles are reported for three stations in respectively the Northwest Atlantic Ocean, the Eastern Equatorial Pacific Ocean and the Cariaco Trench, an anoxic basin. This data set represents the first detailed profiles of Pr, Tb, Ho, Tm and Lu in seawater, together with profiles of La, Ce, Nd, Sm, Eu, Gd and Yb. The first observations of positive Ce anomalies in seawater are ascribed to regeneration of Ce under reducing conditions. The first reported positive Gd anomalies are ascribed to the unique chemical properties of the Gd(III)-cation, which has an exactly half-filled 4f electron shell.

Concentrations of the REE range from 0.3 $\text{pmol} \cdot \text{kg}^{-1}$ (Lu) to 86 $\text{pmol} \cdot \text{kg}^{-1}$ (Ce) and are among the lowest reported so far for trace elements in seawater. The REE as a group typically exhibit a quasi-linear increase with depth. In the deep water there appears to be some degree of correlation with silicate. Concentration levels in the deep Pacific Ocean are 2-4 times those in deep Atlantic waters. Ce has an opposite behavior, with very strong depletions in deep Pacific waters. In the Cariaco Trench all REE, but especially Ce, are

strongly affected by the chemical changes across the oxic/anoxic interface.

The REE distributions normalized versus shales (crustal abundance) exhibit four major features: i) a gradual enrichment of the heavy REE, most strongly developed in the deep Pacific Ocean. This is compatible with the stabilization of heavy REE by stronger inorganic complexation in seawater as predicted by the TURNER-WHITFIELD-DICKSON speciation model; ii) the first description of positive Gd anomalies, in agreement with the anomalously strong complexation of the Gd(III)-cation predicted by the same speciation model; iii) most commonly negative, but sometimes positive, Ce anomalies; and iv) a linear Eu/Sm relation for all samples.

Distributions of the dissolved REE in ocean waters seem to be dominated by their internal cycling within the ocean basins. With a few notable exceptions, the ultimate external sources (riverine, aeolian, hydrothermal) and sinks (authigenic minerals) appear to have little impact on the spatial distribution of the REE in oceanic water masses. Analogies with distributions of other properties within the oceans suggest that the REE as a group are controlled by two simultaneous processes: A) cycling like or identical to opal and calcium-carbonate, with circumstantial evidence in support of the latter as a possible carrier, and B) adsorptive scavenging, possibly by manganese-oxide phases on settling particles. The latter mechanism is strongly supported by the parallel between REE(III) speciation in seawater and the "typical" seawater REE pattern. This general correspondence is highlighted by the very distinct excursions of Gd in both Gd(III) speciation and the observed seawater REE patterns.

Combination of both apparent mechanisms, for instance scavenging of REE by adsorptive coatings (Mn oxides) on settling skeletal material, is very well conceivable. Upon dissolution of the shells at or near the seafloor the adsorbed REE fraction would be released into the bottom waters.

The observations of 1) positive Ce anomalies in Northwest Atlantic surface waters, 2) enhanced Ce anomalies and Mn levels in the O₂-minimum zone of the Eastern Equatorial Pacific Ocean, and 3) enhanced Ce concentrations in anoxic waters all support the contention that a vigorous cycling driven by oxidation and reduction reactions dominates both Ce and Mn in the ocean basins.

Under conditions of thermodynamic equilibrium, Ce tends to become depleted in well-oxygenated open ocean waters, and normal or enriched in waters below a pO₂ threshold of about 0.001-0.010 atm partial

pressure. The latter threshold level generally lies below the sediment/water interface.

However, the kinetics of oxidation (and reduction) of Ce appears to be slow relative to various transport processes. This leads to disequilibria, i.e. a major uncoupling of the pO₂ threshold level and the Ce anomaly distribution.

The REE are definitely non-conservative in seawater and in general the REE pattern or ¹⁴³Nd/¹⁴⁴Nd isotopic ratio cannot be treated as ideal water mass tracers. The continuous redistribution of Ce within the modern ocean, combined with the likelihood of active diagenesis, precludes the use of Ce anomalies as indicators of oxic versus anoxic conditions in ancient oceans. On the other hand, the Eu/Sm ratio, possibly combined with ¹⁴³Nd/¹⁴⁴Nd, would have potential as a tracer for understanding modern and ancient processes of hydrothermal circulation.

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INITIAL SETTLEMENT OF MARINE INVERTEBRATE LARVAE: THE ROLE OF PASSIVE SINKING IN A NEAR-BOTTOM TURBULENT FLOW ENVIRONMENT

Cheryl Ann Hannan

The hypothesis that planktonic larvae of benthic invertebrates sink through the water like passive particles in turbulent flows near the seabed was tested in the field using several groups of geometrically different sediment trap designs. A priori predictions regarding the rank order that the various traps would collect larvae in the field were dictated from laboratory flume experiments to determine the relative particle collection efficiencies of traps. The flume flow was seeded with particles having fall velocities similar to those measured, in the laboratory, for nonswimming polychaete larvae. The flume flow speed (of ~ 10 cm/sec) was within the range of near-bottom current velocities measured during trap collecting intervals at the study site.

In seven field experiments, each lasting from one to eleven days, trap collections of Mediomastus ambiseta (a polychaete worm) postlarvae, total bivalve larvae and postlarvae, sabellariid polychaete larvae, and enteropneust postlarvae generally fit the patterns predicted for passive particle collections between or among the trap designs. While the results were statistically more significant during some intervals than during others, the rank order of larval collections within each group of trap

designs tested nearly always corresponded precisely to the rank order of passive particle collections by the traps in the flume experiments. Thus, the hypothesis that larvae sinking toward the seabed in the field and passive particles (with fall velocities similar to larvae) sinking in a flume are collected in the same rank order of abundance by near-bottom traps could not be falsified for collections of organisms from three invertebrate phyla.

Collections of the polychaete, *Pectinaria gouldii*, and of metamorphosing seastar larvae between or among trap designs significantly differed from the patterns predicted for passive particle collections. A testable hypothesis to explain the *Pectinaria* collections involves unique hydrodynamic properties of these post-larvae, relative to the other organisms collected, and is consistent with the passive sinking hypothesis. Trap collections of the seastars may have resulted, at least in part, from larvae adhering to solid trap surfaces during metamorphosis.

The passive sinking hypothesis could not be falsified in most of the field experiments conducted in this study. Thus, hydrodynamical processes must be included in any future studies of processes that determine patterns of larval settlement. However, passive sinking by larvae is not the explicit result of this experimental study. Other processes that could have produced the observed patterns of larval collections among the trap designs now must be tested against the passive sinking alternative hypothesis. However, much more information on the biology and ecology of the larvae collected in this study is required before future process-oriented experiments can be designed.

If larvae sink like passive particles to heights of ~ 50-cm above the seabed, as the results of this study suggest, then it is possible that larvae initially reach the seafloor at sites where particulates, with fall velocities similar to larvae, initially settle. This hypothesis requires experimental testing. Larvae may not remain at these initial settlement sites; however, after larvae initially reach the seafloor via passive physical processes, the larvae may redistribute by actively choosing a preferred microenvironment within that location, by actively swimming above the bottom or remaining on the sediment surface to be resuspended and transported away, by resuspension only during storm events, and/or by passively accumulating around microtopographic structures.

As a precursor to the flume tests of traps, a theoretical analysis of the physical nature of trap biases was conducted. A dimensional analysis of the independent variables involved in the process of trap-

ping particulates suggested that trap collection efficiencies should be a function primarily of trap Reynolds number, trap aspect ratio, the ratio of the fluid velocity to the particle fall velocity, and trap geometry. A review of data from previous studies that flume-tested various trap designs further suggested that particle collection efficiencies of cylindrical traps should decrease over some range of increasing trap Reynolds number, decrease over some range of decreasing particle fall velocity and increase over some range of increasing trap aspect ratio. Theoretical models were then provided to account for these effects. Flume tests, in the present study, of cylinders varying by one order of magnitude in trap Reynolds number supported one of the predictions: particle collection efficiencies of the cylinders decreased by a factor of two over this range of increasing trap Reynolds number. Results of this theoretical and experimental study of trap collection characteristics suggest that more flume experiments to quantitatively determine the nature of trap biases are required before flux estimates, using traps in the field, can be adequately interpreted.

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THE THERMOCLINE AND CURRENT STRUCTURE IN SUBTROPICAL/SUBPOLAR BASINS

Rui Xin Huang

Part One of this thesis discusses the structure of the thermocline and the current pattern within a two-layer model. The corresponding flow field is explored as the amount of water in the upper layer is gradually reduced (or as the wind stress is gradually increased).

In the model, when the amount of water in the upper layer is less than a first critical value, the lower layer outcrops near the middle of the western boundary. A dynamically consistent picture includes a whole loop of boundary currents, which surround the outcropping zone completely and have quite different structures. In addition to the boundary currents found in previous models, there is an isolated western boundary current (i.e. bounded on one side

by the wall and on the other by a stream-line along which the upper layer thickness vanishes), an internal boundary current and possibly isolated northern/southern boundary currents. Within the limitations of the two-layer model, the isolated western boundary current appears to represent the Labrador Current while the internal boundary current may represent the North Atlantic Current. A first baroclinic mode of water mass exchange occurs across the ZWCL (zero-wind-curl-line).

When the amount of water in the upper layer is less than a second critical value, the upper layer separates from the eastern wall and becomes a warm water pool in the southwest corner of the basin. Under this warm water pool is the ventilated lower layer.

The sea surface density distribution is not specified; it is determined from a consistent dynamical and mass balance. Implicit in this model is the assumption that advection dominates in the mixed layer.

The subtropical gyre and the subpolar gyre combine asymmetrically with respect to the ZWCL.

Chapter I discusses the case when the lower layer depth is infinite. Chapter II discusses the case when the lower layer depth is finite. In the Addendum the climatological meaning of this two-layer model is discussed.

Part Two of this thesis concerns the use of a continuously stratified model to represent the thermocline and current structures in subtropical/subpolar basins. The ideal fluid thermocline equation system is a nonlinear, non-strict hyperbolic system. In an Addendum to Chapter III the mathematical properties of this equation system are studied and a proper way of formulating boundary value problems is discussed. Although the equations are not of standard type, so that no firm conclusions about the existence and uniqueness of solutions have been drawn, some possible approaches to properly posed boundary value problem are suggested. Chapter III presents some simple numerical solutions of the ideal fluid thermocline equation for a subtropical gyre and a subtropical/subpolar basin using one of these approaches. Our model predicts the continuous three dimensional thermocline and current structures in a continuously stratified wind-driven ocean. The upper surface density and Ekman pumping velocity are specified as input data; in addition, the functional form of the potential vorticity is specified.

The present model emphasizes the idea that the ideal fluid thermocline model is incomplete. The potential vorticity distribution can not be determined within this idealized model. This suggests that the diffusion and upwelling/downwelling within

the western boundary current and the outcropping zone in the northwest corner are important parts of the entire circulation system.

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ASYMPTOTIC ANALYSIS OF OCEAN BOTTOM REFLECTED ACOUSTIC FIELDS

Hiroshi Kawahara

Pronounced spatial acoustic interference patterns versus horizontal range were observed near the deep ocean bottom from a 220-Hz CW point source also located near the bottom. This is a result of the direct water wave field interacting with a strongly reflected field from the ocean sediments. If the bottom structures are horizontally stratified media, the reflected field can be expressed by a Sommerfeld integral whose integrand is weighted by a total plane wave reflection coefficient.

In this thesis the reflected fields are analytically evaluated in order to understand the physical mechanism of the propagating waves through the bottom layer structure. Based on a canonical geoacoustic model, the Langer uniform asymptotic approximation is applied to evaluate the total plane wave reflection coefficient accurately. Then the Sommerfeld integral is evaluated by the method of steepest descents. The expression for the reflected field is fully analytic and provides physical insight into the understanding of energy partitioning in the sediments. With inclusion of the new method to analytically express a sound velocity profile shape based on measurements, the approximate solution provides a full analytic expression of the reflected field based on a realistic geoacoustic model.

Various geoacoustic models, with emphasis on changes in the shape of the sound velocity profile in the sediment layer, are examined and their parametric dependences on the associated reflected fields are investigated. The conditions necessary for the shape of the profile to be important are also quantitatively defined and are demonstrated in theoretical data as well as in real data.

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BAROCLINIC INSTABILITY
OF A MERIDIONALLY VARYING BASIC STATE

Stephen P. Meacham

Several problems are addressed herein. They are loosely connected by the theme of resonant triad interactions. The main topic is the finite amplitude evolution of weakly unstable, linear eigenmodes in a meridionally varying version of Phillips' two-layer model. It is shown in chapter four that interactions between neutral modes and the unstable mode strongly influence the evolution of the latter and are capable of stabilizing it before significant changes occur in the zonally averaged flow. The evolution of the unstable wave in the absence of such resonant triad effects is also considered and it is shown by example that the combined influence of changes to the mean flow and higher harmonics of the unstable wave is sufficient to equilibrate the unstable wave. (The higher harmonics are unimportant in the meridionally uniform version of this model.) The enhanced importance of neutral sidebands and the details of the evolution are interpreted as being consequences of the structure of the eigenmodes of the linear problem. It is shown in chapter three that, near minimum critical shear, meridional variation of the potential vorticity gradient of the basic flow can introduce dramatic changes in the structure of the normal modes.

Some aspects of resonant triad dynamics in a meridionally uniform, vertically sheared, two-layer model are considered in chapter two. It is shown that non-linear interactions between a resonant triplet of neutral waves can lead to baroclinic instability. It is also demonstrated that resonant interactions between a slightly supercritical unstable linear mode and two neutral waves can destabilize the weakly finite amplitude equilibration of the unstable mode that would occur in the absence of the sidebands. This demonstration is limited to the case in which the basic state is not close to minimum critical shear. Finally, the work of Loesch (1974), who examined the evolution of a weakly unstable mode and a pair of neutral waves in a basic flow that is close to minimum critical shear, is repeated with the difference that critical layer effects are included.

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BIOCHEMICAL CHANGES ASSOCIATED WITH
EMBRYONIC AND LARVAL DEVELOPMENT
IN THE AMERICAN LOBSTER
Homarus americanus Milne Edwards

Glenn Craig Sasaki

Proximate analysis was carried out on developing Homarus americanus Milne Edwards larvae and eggs. Lipids were further analyzed for class and fatty acid composition. During embryogenesis, triacylglycerol supplied most of the energy and the fatty acid 20:5 was selectively utilized. Absence of prolonged cold incubation temperatures resulted in increased yolk reserves in newly hatched larvae. Weight, ash, protein, carbohydrate and lipid varied in association with the larval molt cycle. Scant metabolic reserves were accumulated in premetamorphic larvae while large triacylglycerol reserves were stored in post-metamorphic (fourth stage) animals. Absolute levels of metabolic reserves limited the extent of their utilization. Triacylglycerol was the preferred (first used) energy substrate but was sometimes limited in amount; hence protein was the major source of metabolic energy during starvation in premetamorphic larvae. Protein based gluconeogenesis and dietary intake of carbohydrate were responsible for most chitin synthesis as established carbohydrate reserves were not sufficient.

Triacylglycerol served mainly as an energy storage form. P. choline appeared to exist in two metabolic pools, one of which could be catabolized without concomitant tissue loss. P. ethanolamine and sterols were primarily associated with cellular membranes. During tissue catabolism (starvation), P. ethanolamine was catabolized but sterol was conserved. On average, P. ethanolamine fatty acids were the most unsaturated, followed by the fatty acids of P. choline and then triacylglycerol.

The type of fatty acid may influence food consumption and rates of absorption. Compared to a diet containing 16:0, one containing 20:5 was related to greater consumption and faster lipid absorption. The fatty acid pattern of the larvae was heavily influenced by diet. The fatty acids 20:4, 20:5, and 22:6 and sometimes 16:0 and 18:0 were conserved under starvation. Conservation of the saturated fatty acids was related to control of cellular membrane fluidity. 16:0 and 18:0 were probably used to compensate for the increased membrane unsaturation from the conserved, potentially essential 20:4, 20:5, and 22:6 fatty acids.

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INTERACTION OF HIGH FREQUENCY
INTERNAL WAVES AND THE BOTTOM BOUNDARY
LAYER ON THE CONTINENTAL SHELF

Lawrence P. Sanford

Intermittent, shoreward propagating packets of high frequency first mode internal waves are common on the continental shelf when the water column is stratified and may induce large fluctuations in near bottom velocity. Simple theoretical considerations here lead to an approximate boundary layer interaction problem. Examination of data from the pilot Coastal Ocean Dynamics Experiment (CODE-I) shows that near bottom velocity fluctuations in the high frequency internal wave band were dominated by shoreward propagating, intermittent mode 1 internal events. Predictions of CODE-I internal wave characteristics using the above approximate method are shown to be good.

A boundary layer model is developed, which allows for the nonlinear interaction of surface waves, internal waves, and a steady current over a rough bottom. Modeling results suggest that internal waves will significantly enhance the stress felt by the steady current and can increase the variability and decrease the reliability of boundary layer measurements by the "log profile" technique, when the waves are present. Theoretical dissipation of internal wave energy in the bottom boundary layer is found to be significantly enhanced in the presence of surface waves and currents, and may be important to the overall internal wave energy balance on the shelf.

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TIDAL DISTORTION IN SHALLOW
ESTUARIES

Paul E. Speer

The offshore tide becomes distorted as it propagates into shallow inlet/estuarine systems. Time asymmetries develop in the rise and fall of sea surface with consequent time and magnitude asymmetries in tidal currents. Flood-dominant estuaries are characterized by longer falling tides and stronger flood currents while ebb-dominant estuaries have longer rising tides and stronger ebb currents. The asymmetries are reflected in the non-linear growth of

harmonics and compound tides of the principal equilibrium tidal constituents. This dissertation consists of three papers which examine the development of tidal asymmetries in shallow estuarine systems: a study of the recent migration history of Nauset Inlet (MA), a shallow estuarine system located on Cape Cod; an analysis of the results of a series of field experiments conducted at Nauset; and a numerical model study of the types of estuarine characteristics controlling tidal asymmetry. The analysis of field results focuses on sea surface measurements. Non-linear distortion of the tide at Nauset is characterized by the strong growth of harmonics and compound constituents particularly in the quarter-diurnal band. Phase relationships between the forced constituents and their parents produce a flood-dominant estuary. Numerical modeling of M_2 tidal propagation in shallow estuarine channels utilizes the one-dimensional equations of motion. Shallow, frictionally dominated channels with moderate tidal flat areas develop a flood-dominant asymmetry while deeper channels with extensive tidal flats develop an ebb-dominant asymmetry. Model results are supported by observations of tidal asymmetry in natural estuaries. Implications of non-linear tidal distortion on bedload and suspended material transport are profound. Flood-dominant estuaries tend to import sediment if the supply is adequate whereas ebb-dominant estuaries can flush entering sediment effectively. Over long time periods, flood-dominant estuaries may eventually fill. Ebb-dominant estuaries may represent more stable long-term configurations.

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CHEMISTRY OF SUBMARINE HYDROTHERMAL
SOLUTIONS AT 21° NORTH, EAST PACIFIC
RISE AND GUAYMAS BASIN, GULF OF
CALIFORNIA

Karen L. Von Damm

Submarine hydrothermal solutions at 21° north latitude on the East Pacific Rise were sampled for the first time in November 1979 and again in November 1981. In the 1981 program, four vent fields were sampled and a maximum temperature of 350-355°C was measured for three of the areas (OBS, SW, and HG) and only 273°C for the fourth area (NGS). The temperatures were stable over the twelve days of the diving program. The hot springs are "black smokers" which are

forming constructional features of Fe, Zn and Cu sulfides and Ca and Ba sulfates. The solutions are seawater which has been heated during convection through the oceanic crust and has reacted with basalt. The hydrothermal solutions are acid (pH = 3.303.8, 25°C, 1 atm), reducing (H_2S = 6.6–8.4 mmol/kg, SO_4 <1 mmol/kg), and metal rich (Fe = 0.8–2.4 mmol/kg, Mn = 0.7–1.0 mmol/kg, Zn = 40–106 μ mol/kg, Cu = 0–44 μ mol/kg, Pb = 183–359 nmol/kg, Co = 22–227 nmol/kg, Cd = 17–180 nmol/kg and Ag = <1–38 nmol/kg). Mg and SO_4 are quantitatively removed from these solutions while other elements are highly enriched. Li increases to 0.9–1.3 μ mol/kg, K to 23.2–25.8 mmol/kg, Rb to 27–33 μ mol/kg and Ca to 11.7–20.8 mmol/kg. Sr both increases and decreases from the seawater concentration to 65–97 μ mol/kg. Na and Cl also increase and decrease; the gain can be attributed to a ~7 percent loss of water due to rock hydration. Silica increases to 15.6–19.5 mmol/kg. Silica increases along strike from the southwest to the northeast; variations in the other chemical components are not geographically consistent. Quartz geobarometry indicates a pressure of reaction between 300–600 bars, implying a depth of reaction within the oceanic crust of 0.5–3.5 kms, in agreement with the geophysical estimates. The silica data imply that the NGS vent is conductively cooling.

The Guaymas Basin, Gulf of California hydrothermal system was first sampled in January 1982. A total of ten vent areas were sampled with a maximum temperature of 315°C. In contrast to the 21°N systems where the solutions exit directly from basalt, the hydrothermal systems at Guaymas pass through and react with approximately 500 meters of sediment cover before they exit on the seafloor. This difference is reflected in the chemistry of these solutions. The sediment also provides a trapping mechanism for the metals in solution and a sediment-hosted type ore deposit may be forming at depth. These solutions differ from those at 21°N as they are less acid (pH = 5.9, 25°C, 1 atm), sulfur-rich (H_2S = 3.8–6.0 mmol/kg, SO_4 <1 mmol/kg) and metal-rich (Fe = 0.02–0.18 mmol/kg, Mn = 0.13–0.24 mmol/kg, Zn = 0–40 μ mol/kg, Cu <6 μ mol/kg, Pb = 230–652 nmol/kg, Ag <230 nmol/kg, Cd <46 nmol/kg and Co <5 nmol/kg). The higher pH and extremely high alkalinity (2.8–10.6 meq/kg) can be attributed to dissolution of $CaCO_3$ and thermal degradation of organic matter which occur in the sediment column. The organic matter degradation is also responsible for the very high levels of ammonium (10.3–15.6 mmol/kg) found in the solutions. The high pH and

alkalinity are responsible for the lower concentrations of the metals which form insoluble sulfides. The ammonium exchanges for K and Rb in the sediments raising their levels in solution to a maximum of 49.2 mmol/kg and 86 μ mol/kg, respectively; significantly higher than the values observed at 21° N. Li increases to 0.6–1.1 mmol/kg, Ca to 41.5 mmol/kg and Sr to 253 μ mol/kg. Na and Cl increase between 8–18 percent; this is attributed to hydration. Na is lost preferentially to Cl. Quartz geobarometry indicates a depth of reaction of ~0.5 kms into the oceanic crust.

These two sites demonstrate the importance of seawater reactions with basalt in altering the composition of seawater. The 21° N system is dependent only on reactions between seawater and basalt at elevated temperatures for its chemistry. The Guaymas system is a more complicated case in which reactions between the hydrothermal solutions and sediment overprint the basalt signature. The presence of large amounts of $CaCO_3$ and organic matter in the sediments at Guaymas is probably very important in determining the solution chemistry.

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GS-12

AUTHOR INDEX

Page No.

Page No.

Abers, Geoffrey GG-7
 Agrawal, Yogi C. OE-7,8,9
 Akens, John J. OE-17,18
 Alford, Jane B. C-5,8
 Allen, John A. B-8
 Allen, Sarah B-12
 Anderson, Donald M. B-17,18,22,23
 Andersson, Agneta C-3
 Asper, Vernon L.* OE-9
 Aubrey, D.G. GG-3,17,18,20,22,23,25,26;OE-9
 Aubry, Marie-Pierre GG-3,4,14,16
 Azam, Farooq C-3
 Backus, Richard H. B-28
 Bacon, Michael P. C-9
 Bailey, Conner MP-3,5
 Ballard, Robert D. OE-6,18
 Bankston, Donald C. C-17
 Barber, Valerie B-29
 Be, Allan W.H. GG-24
 Beardsley, Robert C. GG-22;PO-3
 Behringer, D. OE-14
 Belanger, Paul E. GG-15
 Belkin, Shimshon B-15
 Bellows, D.R. GG-13
 Benavides, Livia M.* C-3
 Bennett, Sara L.* PO-11
 Ben-Avraham, Z. OE-6
 Benoit, Gaboury J.* C-15
 Berggren, William A. GG-4,14,15,16
 Bernstein, Robert L. PO-10
 Berteaux, H.O. OE-8
 Birdsall, T. OE-14
 Bliven, L.F. OE-17
 Boehm, Paul D. C-8
 Bolmer, S.T. GG-12
 Borenstein, David OE-3
 Bowen, Robert E. MP-4,6,9
 Bowen, V.T. C-16
 Bowin, Carl GG-7,8
 Bowman, Thomas E. B-8
 Boyd, Steven H. B-29
 Boyer, G.L. B-20
 Boyle, Edward A. GG-15
 Bradley, Albert M. OE-10
 Bradshaw, Alvin L. C-8
 Brady, Esther C.* PO-9
 Breitinger, Ingrid C-4
 Bremer, Mary E. PO-11
 Brewer, Peter G. C-8,9
 Brink, Kenneth H. PO-3,4
 Briscoe, Melbourne G. PO-25,26
 Broadus, James M. MP-4,5,9
 Brocher, Thomas M. GG-4
 Brown, Ellen D.* PO-13;GS-3
 Brown, M. OE-14
 Brownawell, Bruce J.* C-3
 Brown-Leger, L. Susan B-7,8
 Bruland, Kenneth W. C-9
 Byrden, Wilfred B. GG-17

Bryden, Harry L. PO-9,10,13
 Brzezinski, Mark A. PO-15
 Bucklin, Ann B-24
 Buesseler, Ken O.* C-15
 Burckle, Lloyd GG-4
 Burt, W.V. B-15
 Butenko, Jorge GG-4
 Cacchione, D.A. OE-5
 Cannon, Glenn A. PO-3
 Canuel, Elizabeth A. C-7
 Capuzzo, Judith M. B-7,15
 Caron, David A.* B-19;GS-3
 Carpenter, Edward J. B-23
 Casey, J.F. GG-5
 Casso, Susan A. C-15
 Caswell, Hal B-24
 Chajes, M. OE-14
 Chandler, Richard S. GG-24
 Chapman, David C. PO-3,18
 Chausse, Dolores H. PO-26
 Cheney, Jerry B-26
 Chisholm, Sallie W. B-23
 Chu, Ka Hou* GS-5
 Churchill, James H. PO-4,23
 Cicin-Sain, Biliana MP-5,6,9
 Clarke, Allan J. PO-4
 Coats, D.W. B-18
 Cochran, J. Kirk C-16
 Collie, Jeremy S.* B-7
 Collins, Clayton W. Jr. OE-8,10
 Collins, John A.* GG-4
 Conners, M. Elizabeth B-11
 Copley, Nancy J. B-8
 Corliss, Bruce H. GG-14,15
 Cormier, Marie-Helene GG-8
 Cornuelle, B. OE-14
 Corwin, Nathaniel B-14
 Cowles, Timothy J. PO-15
 Csanady, Gabriel T. PO-5,6,22,25
 Curry, W.B. GG-19
 Dacey, John W.H. B-12,13;C-7
 Darling, S.D. B-20
 Davis, Cabell S. B-10,27,29
 de Baar, Hein J.W.* C-9;GS-5
 Degens, Egon T. C-4
 DeMaster, D.J. GG-6
 Dennett, Mark R. B-18,19,21
 Desaubies, Yves OE-11
 Detrick, Robert S. GG-8
 Deuser, Werner G. C-4
 Dick, Henry J.B. GG-5,14,17;PO-8
 Doering, Peter H. C-7
 Doherty, Kenneth W. OE-9
 Douth, James A. OE-12
 Drake, D.E. OE-5
 Driscoll, Mavis L.* GG-19
 Druffel, Ellen R.M. C-3,9,12,16
 Duedall, I.W. B-15
 Ducklow, Hugh W. PO-15

Duennebie, F.K. GG-13
 Dunn, Christopher Van Rensselaer . . . OE-9
 Dwiponggo, A. MP-3
 Ebbesmeyer, Curtis C. PO-15
 Ehrhart, Llewellyn M. MP-8
 Elthon, D.L. GG-5
 Emery, K.O. GG-3
 Emery, William J. PO-8
 Evans, Robert H. PO-15
 Ewing, J.I. GG-11
 Farrington, John W. . . . C-3,4,5,6,7,8
 Feder, Meir* OE-3
 Fenner, Julianne M. GG-14
 Feuer, A. OE-4
 Fisher, Robert L. GG-17
 Flagg, Charles N. PO-6
 Flierl, Glenn R. B-29
 Francheteau, J. OE-6
 Frazer, Nat B. MP-6,7,8
 Freadman, Marvin A. B-3
 Frisk, George V. OE-12,14
 Gagosian, Robert B. C-5,7,8
 Gaines, Arthur MP-5
 Gallagher, Scott M. B-4
 Gamble, John King MP-8
 Garcon, Veronique C. B-23
 Garner, Susan P. B-8
 Garside, Christopher PO-15
 Gawarkiewicz, Glenn G. PO-26
 Glaeser, R.M. OE-10
 Glazer, Alexander N. B-22
 Glenn, S.M. OE-5
 Glibert, Patricia M. B-18,19
 Goehringer, Dale B-12
 Goldman, Joel C. . . . B-18,19,20,21;C-11
 Golubic, Stjepko GG-21
 Goud, M.R.* GG-20
 Gould, Richard W. Jr. PO-15
 Grant, William D. OE-5,17
 Grassle, J. Frederick B-7,8
 Grassle, Judith P. B-8
 Griffin, Sheila M. C-16
 Gross, Thomas F. OE-17
 Hagström, Ake C-3
 Haidvogel, Dale B. PO-24
 Hailwood, E.A. GG-4
 Hall, Mindy M.* PO-10
 Hall, Sherwood B-20
 Hannan, Cheryl Ann* GS-6
 Harbison, G.R. B-28
 Harris, Stewart E. OE-18
 Hart, S.R. C-12
 Hays, Earl E. OE-12
 Heinmiller, R. OE-14
 Hekinian, R. OE-6
 Helfrich, John V.K. C-7
 Hemleben, Christoph C-4
 Hennessey, Timothy M. MP-6,9
 Hess, F.R. OE-9
 Hessler, Robert R. B-8
 Hill, Winfield GG-25
 Hitchcock, Gary L. . . . B-20,21;PO-15
 Hoagland, Porter III MP-4
 Hobbie, John E. B-11;C-7

Hogg, Nelson G. PO-10,18,19
 Hollister, Charles D. GG-6,22,24
 Honjo, Susumu GG-20;OE-9
 Hook, James E. GG-21
 Hooker, Stanford B. PO-26
 Howe, Bruce M. OE-16
 Howes, Brian L. B-12,13;C-7
 Hua, Bach Lien PO-14
 Huang, Rui Xin* GS-7
 Huang-ting, Shen GG-22
 Huc, Alain C-15
 Hulburt, Edward M. B-21,22
 Humphris, Susan E. C-10,13
 Hunt, John M. C-10,15
 Hutchison, I. GG-9
 Iliffe, Thomas M. B-8
 Ittekkot, Venugopalan C-4
 Jaffe, Jules S. OE-5,10
 Jannasch, Holger W. . . . B-15,16,17;C-11
 Jasper, John* C-15
 Jemsek, J.* GG-9,13
 Jenkins, William J. C-11,17
 Jousset-Dubien, J. C-15
 Joyce, Terrence M. PO-14,15,16
 Kaminski, Michael A.* GG-16
 Karson, Jeffrey A. GG-4,5
 Kawahara, Hiroshi* OE-12;GS-8
 Keffer, Thomas PO-24
 Keigwin, Lloyd D. Jr. . . . C-12;GG-14,15
 Keller, Gerta GG-14
 Kelly, Kathryn A. PO-22
 Kennelly, Maureen A.* . . . PO-14,15,16,24
 Kent, D.V. GG-16
 Kester, D.R. B-15
 Khan, M.J. GG-16
 King, Gary M. B-13
 Kingsley, Richard H. C-10,13
 Klotz, Alan V. B-3
 Knecht, Robert MP-5,9
 Knox, R. OE-14
 Koblinsky, Chester J. PO-10
 Kupferman, S.L. C-16
 Kurz, Mark D. C-12
 Lahey, William MP-9
 Landman, Neil H. C-16
 Langdon, Christopher PO-15
 Langel, R.A. GG-12
 Lawrence, J.R. C-12
 Lawrence, Martin W. OE-13
 Lee, Cindy C-3
 Lee, Dong-Kyu PO-16
 Leschine, Thomas MP-9
 Levy, Ellen PO-25
 Limeburner, Richard GG-22;PO-3
 Lindstrom, Eric J. PO-15
 Little, S.A.* GG-9
 Liu, H.-W. B-20
 Lively, John J. B-17
 Livingston, Hugh D. . . . C-5,13,15,16,17
 Livramento, Joaquim B. . . . C-4
 Loder, Theodore C. C-8
 Lohmann, G.P. GG-16,19
 Lott, D.E. C-17
 Loudon, K.E. GG-9

Luyten, James R. PO-11,21
 Lynch, James F. OE-12,13
 Lyne, Vincent D. PO-25
 Malanotte-Rizzoli, P. OE-14
 Malmgren, Bjorn A. GG-16
 Mann, Roger B-4,6
 Marahundin, Firial MP-3
 Maranda, Lucie B-22
 Marcus, Henry S. MP-9
 Marcus, Nancy B-24,25
 Marquet, William M. OE-18
 McCarthy, James J. PO-15
 McCartney, Michael S. PO-11
 McCave, I.N. GG-6,19,21,22
 McCormick, Stephen D. B-5,6
 McDowell, Scott E. PO-6
 McKee, Theresa PO-24
 McWilliams, James C. PO-14
 Meacham, Stephen P.* PO-19,20;GS-9
 Meade, Robert H. GG-22
 Melillo, A.J. GG-16
 Melillo, Jerry M. B-11
 Meo, Mark MP-10,11
 Metzger, K. OE-14
 Meyer, Peter S. C-12
 Miksic, John N. MP-3
 Millard, Robert C. Jr. PO-7
 Miller, Kenneth G. GG-7,16
 Miller, R.L. B-28
 Milliman, John D. GG-4,21,22
 Mitchell, James R. B-14
 Molongoski, John J. B-17
 Montgomery, Ellyn T. B-6;PO-25,26
 Mook, Douglas R. OE-14
 Moore, Karen E. B-14
 Moore, R.M. C-16
 Morris, Michael A. MP-11
 Morse-Porteous, Linda S. B-7
 Mottl, Michael J. B-16;C-11,12
 Mountain, Gregory S. GG-7,9
 Munk, W. OE-14
 Murray, Mark H. GG-13
 Musgrave, David L. PO-20
 Naiman, Robert J. B-5,6,11
 Nelson, David M. PO-15
 Nelson, Douglas C. B-17
 Niiler, Pearn P. PO-10,16
 Nittrouer, C.A. GG-6
 Olson, Donald B. B-28;PO-16,17
 Olson, Robert J. B-23
 Oppenheim, Alan V. OE-14
 Orbach, Michael K. MP-6
 Östlund, H. Gote C-17
 Oug, Linda B-22
 Owens, W. Brechner PO-7,13,14,15,17,26
 Palmieri, Julianne M. C-5
 Park, P.K. B-15
 Parker, Robert L. GG-11,12
 Payne, Richard E. PO-22
 Pedlosky, Joseph PO-20,21
 Peltzer, Edward T. C-5,8
 Pennington, Nancy J. PO-25,26
 Peterson, M.J. MP-7,9
 Petraitis, Peter S. B-25

Petrecca, Rosemarie B-7,8
 Pfirman, Stephanie* GG-23
 Pires, Ivon MP-5,12
 Price, Carl A. B-17
 Purdy, G. Michael GG-8,11,13
 Ramp, Steven R. PO-3
 Raymer, Mary E. PO-9,11
 Real, Leslie B-24
 Reardon, Ellen M. B-17
 Rehault, J.-P. GG-13
 Reichardt, P.B. B-20
 Richardson, James I. MP-8
 Richardson, Philip L. PO-12,25
 Riley, J.B.* OE-7,8
 Robertson, L.A. B-17
 Roemmich, Dean H. PO-11
 Rosenfeld, Leslie K.* PO-26
 Ross, David A. GG-7,17;MP-12,13
 Saltzman, E. C-12
 Sanders, Howard L. B-8
 Sanford, Lawrence P.* GS-10
 Sasaki, Glenn Craig* B-7;GS-9
 Sayles, F.L. C-13
 Scheltema, Rudolf S. B-9,10
 Schilling, Jean-Guy C-10,13;GG-8
 Schlitz, Ronald J. PO-3
 Schmidt-Gengenbach, Jutta B-25
 Schmitt, Raymond W. PO-16,17
 Schmitz, William J. Jr. PO-10,13,16
 Schneider, Jurg K. C-5
 Schouten, Hans GG-14;PO-8
 Schrey, Suzanne E. B-23
 Schwartz, Frank J. MP-7
 Slater, J.G. GG-9,13
 Seyfried, W.E. Jr. C-13
 Seymour, Richard J. GG-22
 Sharp, Arnold G. OE-18
 Shibata, Tsugio C-14
 Shimizu, Yuzuru B-22
 Sholkovitz, Edward R. C-15
 Shure, Loren GG-7,11,12
 Shusterich, Kurt M. MP-13,14
 Shwartz, Daniel K. OE-13
 Siedler, Gerold PO-8
 Signell, Richard P.* PO-26
 Sigurdsson, Haraldur C-12
 Silva, A.J. GG-6
 Silva, Maynard E. MP-9,14
 Sivaprasad, Kondagunta OE-13
 Slotine, Jean-Jacques E. OE-19
 Smith, Wendy M.* PO-21
 Solheim, Anders GG-23
 Solomon, Sean C. GG-13
 Speer, Paul E.* GG-18,23;GS-10
 Spencer, Ann PO-26
 Spencer, Wayne D. GG-18,25,26
 Spiesberger, John L. OE-14,15
 Spindel, Robert C. OE-14,16
 Spindler, Michael C-4
 Stalcup, Marvel C. PO-14
 Stegeman, John J. B-3
 Stephen, R.A. GG-9,12,13
 Stewart, W.K.* OE-19
 Stommel, Henry M. PO-10,18,19

Swift, James H.	C-17
Swift, Stephen A.*	GG-24
Takahashi, Kozo	GG-24
Tarbell, Susan A.	PO-26
Tate, G.B.	OE-5
Taylor, Craig D.	B-17
Teal, John M.	B-12;C-4
Terray, E.A.	OE-17
Thompson, Geoffrey	C-10,13,14;GG-8
Titus, M.	GG-5
Toole, John M.	PO-9,13
Toomey, Douglas R.*	GG-13
Townsend, H.A.	GG-4
Tripp, Bruce W.	C-4,6
Trowbridge, John H.	GG-18,25
Tucholke, Brian E.	GG-7,9,19
Tyack, Peter	B-14
Tyler, M.A.	B-18
Tynan, Cynthia T.	PO-26
Uchupi, Elazar	GG-7
Vaccaro, Ralph F.	B-14
Valiela, Ivan	B-12
Van Etten, Richard	B-12
Vargas, Jorge A.	MP-6
Volkman, Suzanne	B-12
Von Damm, Karen L.*	GS-10
Von Herzen, R.P.	GG-9,13
Voorhis, Arthur D.	OE-10
Wakeham, Stuart G.	B-13;C-4,6,7
Walden, Barrie B.	OE-18
Walden, R.G.	OE-8,10
Walsh, Chris	B-3
Wartzok, Douglas	B-14
Waterbury, John B.	B-17,22
Watkins, William A.	B-14
Watras, Carl J.	B-23
Watson, Winsor Hayes III	B-3
Webb, D.	OE-14
Weinstein, Ehud	OE-3,4
Weiss, Anthony J.	OE-4
Weller, Robert A.	PO-23
Westermeyer, William	MP-14
Whelan, Jean K.	C-15
Whitehead, John A. Jr.	GG-14;PO-7,8
Wiebe, Peter H.	B-27,29
Williams, Albert J. III	OE-5,11,17
Williams, D.L.	GG-13
Williams, Isabelle P.	B-7
Williams, Robert T.	C-8
Winget, Clifford L.	OE-10
Wirsan, Carl O.	B-15,16,17
Worcester, Peter F.	OE-14,16
Wunsch, C.	OE-14
Yentsch, Charles S.	PO-15
Yincin, Ye	GG-4
Yingst, J.Y.	GG-6
Yoerger, Dana R.	OE-19
Yu, Honghua	PO-3
Zafirou, Oliver C.	C-8,15
Zenk, Walter	PO-8
Zepp, R.G.	C-15
Zika, R.G.	C-15
Zuo-sheng, Yang	GG-22

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