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PREFACE

This volume contains all abstracts submitted for publication during calendar year 1986 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 Because some of the abstracts may not be published in the journal to which they have been submitted initially, we have purposely omitted identifying the journals.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, reading "Derek W. Spencer", is written over a horizontal line.

Derek W. Spencer
Associate Director for Research

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DEPARTMENT OF BIOLOGY

Richard H. Backus, Department Chairman

BIOLOGY

SECRET
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ANIMAL PHYSIOLOGY
AND BIOCHEMISTRY

BLOOD FLOW IN THE MUSCLE
OF FREE SWIMMING FISH

Francis G. Carey and Quentin H. Gibson

Measurement of the rate of temperature change in muscle as ambient temperature varies allows blood flow to be calculated. The procedure is simplified by making the temperature measurements in deeply sited tissues of large fish where convection by the blood is the dominant heat transfer process and heat transfer by conduction is minimal. Rates of blood flow in free-swimming swordfish, Xiphias gladius, and blue sharks, Prionace glauca, have been obtained by using acoustic telemetry techniques to measure water temperature and muscle temperature. Blood flow rates of $34 \text{ ml kg}^{-1} \text{ min}^{-1}$ for the blue shark and $15 \text{ ml kg}^{-1} \text{ min}^{-1}$ for the swordfish are generally comparable to blood flow measured in other fish by a variety of techniques. Temperature effects are considered and systematic variations of blood flow in the blue shark are related to changing activity as the fish swims up and down.

In press: Physiological Zoology.

Supported by: NSF Grants OCE80-18674, OCE83-11512, PCM83-08150 and GM 14276-22; and U.S. Public Health Service Grant DMB83-08454.

WHOI Contribution No. 6223.

THE OCCURRENCE OF LYSOZYME IN THE
COMMON COCKLE Cerastoderma edule (L.)
AND THE EFFECT OF THE TIDAL CYCLE ON
LYSOZYME ACTIVITY

Noellette Conway

A sample of cockles was removed from the mid-tide level at Booterstown Strand, County Dublin at two hour intervals, for a period of 24 hours. The gills, mantle and visceral mass tissues contained significant levels of lysozyme with the gills containing the highest, weight specific levels. A tidal rhythm of lysozyme activity in the gills, mantle and visceral mass was inversely related to the tidal cycle. The data were best described by a tidal curve shifted -5 hours out of phase, with maximum and minimum levels of activity occurring one hour after low and high

tide, respectively.

In marine bivalves lysozyme may be involved in the extracellular digestion and absorption of bacteria during low tide. In this context the present use of bivalves as biological indicators of bacterial pollution is discussed.

Supported by: Zoology Department,
Trinity College, Dublin and WHOI
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WHOI Contribution No. 6282.

METABOLITE AND ENZYME CONTENTS OF
FREEZE-CLAMPED LIVER OF THE
MARINE FISH Stenotomus chrysops

Neal W. Cornell, John J. Stegeman,
Michael J. Kerich and Bruce R. Woodin

1. Hepatic metabolites and enzymes in the marine fish, scup or porgy (Stenotomus chrysops), were determined in freeze-clamped tissue taken either within a day of removing fish from their natural habitat or after scup were held in captivity for 6-8 months. The same determinations were made for liver from fed or 48 hour-starved rats (Mus norvegicus albinus).

2. Compared with rat liver, both groups of fish had, per g of liver, higher contents of AMP, inorganic phosphate, glucose, glucose-6-phosphate, malate, glutamate, and NH_4^+ . ATP was lower in fish liver, and ADP, lactate and pyruvate contents were similar in rats and fish.

3. Fish held in captivity had significantly lower pyruvate, α -ketoglutarate, and cytosolic free NAD^+/NADH and higher cytosolic free $\text{NADPH}/\text{NADP}^+$. These decreases were similar to those seen when starved rats were compared with fed ones.

4. In scup liver, glucose-6-phosphate dehydrogenase was 3-8 times, malic enzyme about 2 times, and alanine aminotransferase 2-4 times higher than those activities in rat liver. Those results and a higher cytosolic free $\text{NADPH}/\text{NADP}^+$ are consistent with the liver being the major site of lipogenesis in fish.

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WHOI Contribution No. 6149.

STRONTIUM IS REQUIRED IN ARTIFICIAL
SEAWATER FOR EMBRYONIC SHELL FORMATION
IN TWO SPECIES OF BIVALVE MOLLUSCS

Scott M. Gallager, Joseph P. Bidwell
and Alan M. Kuzirian

Strontium is required in artificial seawater for the formation of the calcareous embryonic shell of the bivalves Mercenaria mercenaria (Linne, 1758) and Bankia gouldi (Bartsch, 1908). Embryos reared in defined media without strontium chloride become swimming larvae that appear normal except that the mineralized portion of the prodissoconch I shell is absent. Calcification is sensitive to small differences in strontium concentrations and a level of 6-8 ppm is required for normal development. Structural defects also result at high concentrations of this element, 3 to 10 times that of natural seawater, or when barium is substituted for strontium. Exposure to strontium is required only between Hours 15-30 of the 40-45 hour embryonic period. Shell mineralization is initiated at Hour 20 while the organic layer is observed with SEM at Hour 18 and appears complete by Hour 26. Larval shell growth (prodissoconch II) and statolith formation in M. mercenaria do not require the presence of strontium. These results are compared with those obtained earlier for the gastropod Aplysia californica (Cooper, 1863) and the implications are discussed.

In press: 5th International Symposium
on Biomineralization.

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WHOI Contribution No. 6354.

UPTAKE, TOXICITY AND DISTRIBUTION
OF BENZO[a]PYRENE, AND MONOOXYGENASE
INDUCTION IN THE TOPMINNOWS
Poeciliopsis monacha AND
Poeciliopsis lucida

Kathryn A. Goddard, R. Jack Schultz
and John J. Stegeman

Poeciliopsis lucida and Poeciliopsis monacha are freshwater viviparous fishes susceptible to tumorigenesis by brief exposure to waterborne procarcinogens. The hepatic monooxygenase system and the uptake, toxicity, and distribution of BP¹ were characterized as a first step in exploring relationships between xenobiotic metabolism and cancer in these

fishes. Waterborne BP was lethal at a dose of 3.75 mg/liter with 24 hr exposure. During a 24 hr exposure to 1.0 mg/liter (3.97 μ mol/liter) ³H-BP, an average of 8.27 nmol of BP was taken up per fish. Of this total, 64-70% was in the gall bladder or gut, indicating rapid metabolism and excretion. Basal levels of AHH activity were fairly high, about 0.6 nmol/min/mg. Maximal induction by BP occurred at a dose of 1.0 mg/liter, but with AHH activities only about twice the levels in untreated fish. Sensitivity to inhibition by ANF increased slightly in treated fish. Induced AHH as well as EROD activities declined slowly over seven days after a single treatment, approaching pre-exposure levels after seven days. Monoclonal and polyclonal antibodies to cytochrome P-450E, the AHH and EROD catalyst in the marine fish scup (Stenotomus chrysops), inhibited AHH and EROD activities in untreated Poeciliopsis, indicating structural similarity between the catalysts in these fish species. Untreated Poeciliopsis evidently contain a counterpart to scup cytochrome P-450E, the major PAH-inducible form in scup. High levels of basal activity and the inducibility of xenobiotic metabolism in these fishes could indicate a strong potential to form bioactive metabolites of procarcinogens.

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WHOI Contribution No. 6375.

EFFECTS OF ANIMAL BEHAVIOR ON SEDIMENT
TRAP COLLECTIONS: IMPLICATIONS FOR THE
CALCULATION OF ARAGONITE FLUXES

G. Richard Harbison and Ronald W. Gilmer

Collection of living organisms can seriously bias the results of sediment trap collections, and the behavior of planktonic animals may cause certain species to be collected preferentially. We studied the effects of the escape response of one genus of pteropod on the rates of its collection by sediment traps. This model system was chosen because a great deal is known about the field behavior of pteropods, and because a recent paper (Betzer et al., 1984, Science, 226, 1074-1076) has proposed that the dissolution of sinking pteropod shells could almost balance the alkalinity budget of the Pacific Ocean. In three sediment trap deployments off the coast of Greenland, we

found that large numbers of living Lima-
cina spp., in contrast to copepods and
larvaceans, were rapidly collected in a
few hours. Since this artifact leads to a
gross overestimate of aragonite flux, we
conclude that the assertion of Betzer et
al. (1984) is not proved. There are
likely to be a number of other planktonic
organisms whose behavior can bias sediment
trap collections. Therefore, the results
of short-term flux measurements made with
shallow sediment traps should not be in-
terpreted without proper controls and more
knowledge of the behavior of planktonic
animals.

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WHOI Contribution No. 6133.

HATCHETFISHES HOLD HORIZONTAL ATTITUDES WHILST DESCENDING DOWNWARDS DIAGONALLY

John Janssen, G. Richard Harbison
and James E. Craddock

Based on analysis of videotape
records, species of the genus Argyro-
pelecus are capable of swimming diagonally
downward at considerable speed without
altering their body posture. Morpholog-
ical evidence strongly suggests that they
are able to swim diagonally upward in a
similar way. Their distinctive hatchet-
like profile presents a streamlined air-
foil shape for both diagonal and hori-
zontal movements, even though the body is
not tilted. Modifications of the caudal
musculature probably enable all hatchet-
fishes (including members of the other two
genera, Polyipnus and Sternoptyx) to use
the tail for propulsion for both diagonal
and horizontal movements. The dorsal fin
probably aids in diagonally downward move-
ments, and the pelvic and anal fins in
diagonally upward movements, whilst the
pectoral fins serve as stabilisers for
these movements, and as an axis of rota-
tion for striking at prey. The seemingly
ungainly shape of the hatchetfish is the
result of achieving a streamlined, fish-
like shape for horizontal and diagonal
movements without tilting of the body,
presumably in order to maintain an
effective camouflage in midwater.

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WHOI Contribution No. 6134.

SPECIFICITY AND CROSS-REACTIVITY OF MONOCLONAL AND POLYCLONAL ANTIBODIES AGAINST CYTOCHROME P-450E OF THE MARINE FISH SCUP

Pamela J. Kloepper-Sams, Sang S. Park,
Harry V. Gelboin and John J. Stegeman

Monoclonal antibody 1-12-3 generated
against liver cytochrome P-450E (P-450E),
an aryl hydrocarbon of the marine fish
Stenotomus chrysops (scup), reacted only
with P-450E when tested in immunoblot
analysis with five P-450 fractions from
scup liver. This and six other MAb
against P-450E recognized purified P-450E,
as well as a single band in BNF-induced
scup microsomes that co-migrated with
authentic P-450E. Like MAb 1-12-3, poly-
clonal anti-P-450E reacted with P-450E but
not other scup P-450 fractions and reacted
strongly with a band coincident to P-450E
in BNF-treated scup microsomes. However,
the PAb also faintly recognized additional
microsomal proteins. MAb 1-12-3 recog-
nized P-450E induced by 3,3',4,4',5,5'
hexachlorobiphenyl and by PCB mixtures in
scup, and a single band induced by BNF or
MC in microsomes of other teleosts, in-
cluding two trout species, killifish and
winter flounder. The content of the
P-450E counterpart in these fish and also
in untreated scup coincided with induced
ethoxyresorufin O-deethylase activity.
Induced EROD activity in scup and trout
was strongly inhibited by MAb 1-12-3, fur-
ther demonstrating the relationship be-
tween P-450E and induced P-450 in trout.
MAb 1-12-3, two other MAb and anti-P-450E
PAb recognized a band co-migrating with
P-450c in BNF-induced rat microsomes. MAb
1-12-3 also recognized purified rat
P-450c. MAb 1-12-3 and anti-P-450E PAb
recognized a second band of lower M_r
than P-450c in BNF rat microsomes, which
may correspond to P-450d, the MC and
isosafrole-inducible rat isozyme. The
results firmly establish the identity of
scup P-450E, the relationship of BNF-
induced P-450 in other teleosts with
P-450E, and its immunochemical relation-
ship with rat P-450c. Furthermore, re-
sults with untreated fish suggest that
effects of environmental chemicals may be
detected by immunoblotting with monoclonal
anti-P-450E.

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WHOI Contribution No. 6305.

CYTOCHROME P-450 ISOZYMES FROM THE
MARINE TELEOST *Stenotomus chrysops*:
THEIR ROLES IN STEROID HYDROXYLATION
AND THE INFLUENCE OF CYTOCHROME b_5

Alan V. Klotz, John J. Stegeman,
Bruce R. Woodin, Elisabeth A. Snowberger,
Paul E. Thomas and Chris Walsh

Two new cytochrome P-450 forms were purified from liver microsomes of the marine fish *Stenotomus chrysops* (scup). Cytochrome P-450A ($M_r=52.5$ K) had a CO-ligated, reduced difference spectrum λ_{max} at 447.5 nm, and reconstituted modest benzo[α]pyrene hydroxylase activity (0.16 nmol/min/nmol P-450) and ethoxycoumarin O-deethylase activity (0.42 nmol/min/nmol P-450). Cytochrome P-450A reconstituted at optimal conditions catalyzed hydroxylation of testosterone almost exclusively at the 6 β position (0.8 nmol/min/nmol P-450) and also catalyzed 2-hydroxylation of estradiol. Cytochrome P-450A is active toward steroid substrates and we propose that it is a major contributor to microsomal testosterone 6 β -hydroxylase activity. Cytochrome P-450A had a requirement for conspecific (scup) NADPH-cytochrome P-450 reductase and all reconstituted activities examined were stimulated by the addition of purified scup cytochrome b_5 . Cytochrome P-450B ($M_r=45.9$ K) had a CO-ligated, reduced difference spectrum λ_{max} at 449.5 nm and displayed low rates of reconstituted catalytic activities. However, cytochrome P-450B oxidized testosterone at several different sites including the 15 α position (0.07 nmol/min/nmol P-450). Both cytochromes P-450A and P-450B were distinct from the major benzo[α]pyrene hydroxylating form, cytochrome P-450E, by the criteria of spectroscopic properties, substrate profiles, minimum molecular weights on NaDodSO₄-polyacrylamide gels, peptide mapping and lack of cross-reaction with antibody raised against cytochrome P-450E. Cytochrome P-450E shares epitopes with rat cytochrome P-450c, indicating it is the equivalent enzyme, but possible homology between scup cytochromes P-450A or P-450B and known P-450 isozymes in other vertebrate groups is uncertain, although functional analogues exist.

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WHOI Contribution No. 6159.

MONOCLONAL ANTIBODIES TO LIVER
MICROSOMAL CYTOCHROME P-450E OF THE
MARINE FISH, *Stenotomus chrysops* (scup)

Sang S. Park, Haruko Miller,
Alan V. Klotz, Pamela J. Kloepper-Sams,
John J. Stegeman and Harry V. Gelboin

Hybridomas were prepared from myeloma cells and spleen cells of BALB/c female mice immunized with hepatic cytochrome P-450E purified from the marine fish, *Stenotomus chrysops* (scup). Nine independent hybrid clones produced MAbs, either IgG₁, IgG_{2b}, or IgM, that bound to purified cytochrome P-450E in radioimmunoassay. Antibodies from one clone (Mab 1-12-13), also strongly recognized rat cytochrome P-450_{MC-B} (P-450_{BNF-B}; P-450c). The nine antibodies inhibited reconstituted aryl hydrocarbon hydroxylase (AHH) and ethoxycoumarin O-deethylase of scup cytochrome P-450E to varying degrees, and inhibited AHH activity of β -naphthoflavone-induced scup liver microsomes in a pattern similar to that in reconstitutions, indicating that cytochrome P-450E is identical to the AHH catalyst induced in these fish by β -naphthoflavone. Mab 1-12-3 also inhibited the reconstituted AHH activity of the major BNF-induced rat isozyme. Conversely, Mab 1-7-1 to rat cytochrome P-450_{MC-B} had little effect on AHH activity of cytochrome P-450E, and did not recognize cytochrome P-450E in radioimmunoassay nor in an immunoblot. Scup cytochromes P-450E and rat cytochrome P-450_{MC-B} thus have at least one common epitope recognized by Mab 1-12-3, but the epitope recognized by Mab 1-7-1 is absent or is recognized with low affinity in cytochrome P-450E. The various assays indicate that the nine MAbs against cytochrome P-450E are directed to different epitopes of the molecule. These MAbs should be useful in determining phylogenetic relationships of the BNF or MC-inducible isozymes and their regulation by environmental and other factors.

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WHOI Contribution No. 6145.

PATTERNS AND REGULATION OF ESTRADIOL
METABOLISM BY HEPATIC MICROSOMES
FROM TWO SPECIES OF MARINE TELEOSTS

Elizabeth A. Snowberger
and John J. Stegeman

Estradiol (E_2) metabolites formed in vitro by microsomes from the marine teleosts winter flounder (*Pseudopleuronectes americanus*) and scup (*Stenotomus chrysops*) included at least seven products detected by thin layer chromatography (TLC) and high performance liquid chromatography (HPLC). The least polar metabolite was shown to be estrone by chromatographic and mass spectrometric identity with authentic estrone. Chromatographic analyses coupled with dual-label experiments also indicated formation of the catechol-estrogen 2-hydroxyestradiol (2-OH- E_2), which was the most prominent metabolite determined by TLC. Analysis of microsomal E_2 2-hydroxylase activity by measuring the specific release of 3H_2O from [$2-^3H$]- E_2 indicated that it is mediated by cytochrome P-450. E_2 2-hydroxylase activity normalized to microsomal protein was lower in females than males for microsomes from both mature scup and winter flounder. Activity normalized to liver weight or body weight in female winter flounder was also lower than in males. However, activity normalized to cytochrome P-450 content did not show sex differences in either species. E_2 2-hydroxylase activity per nmol cytochrome P-450 was reduced in scup treated with β -naphthoflavone (BNF), which induces the hydrocarbon hydroxylase cytochrome P-450E. Studies employing reconstituted P-450E and microsomes preincubated with polyclonal antibodies against P-450E confirmed that this isozyme does not catalyze E_2 2-hydroxylase activity in microsomes. However, preliminary work with scup cytochrome P-450A suggests that it may be an E_2 2-hydroxylase. The studies establish that catecholestrogen formation is prominent in fish liver, and that it is sexually differentiated, but further investigation is required to define the catalysts, as well as the significance and regulation of this function.

In press: General and Comparative
Endocrinology.

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WHOI Contribution No. 6306.

CYTOCHROME P-450 ISOZYMES AND
MONOOXYGENASE ACTIVITY IN AQUATIC ANIMALS

John J. Stegeman
and Pamela J. Kloepper-Sams

The roles of different forms of cytochrome P-450 in activation and deactivation of toxic chemicals, synthesis and breakdown of steroid hormones, and other functions, indicate the significance of these enzymes. Monooxygenase systems have been studied in species from several phyla of aquatic organisms. However, cytochrome P-450, the dominant catalyst in xenobiotic monooxygenase activity, is best-studied in fish. Forms of cytochrome P-450 have been purified from several teleost species, including scup (*Stenotomus chrysops*), rainbow trout (*Salmo gairdneri*) and cod (*Gadus morhua*). Cytochrome P-450E from scup, cytochrome P-450 LM_{4b} from trout and cytochrome P450c from cod have properties similar to each other and appear to be homologous hydrocarbon or BNF-inducible isozymes. Partially purified cytochrome DBA-P-450-I from little skate, *Rajia erinacea*, is possibly an elasmobranch counterpart of these teleost forms. Cytochrome P-450E from scup is immunologically related to the major BNF-inducible isozyme (cytochrome P-450c or BNF-B) in rats, indicating homology between the fish and mammalian BNF-inducible isozymes. Several other cytochrome P-450 forms with interesting or unusual properties have been purified from aquatic species. Mammalian homologues are not yet known for these isozymes. Further studies of cytochrome P-450 forms in aquatic species should establish additional homologies and the regulation of these forms by chemical and biological variables, possibly providing fundamental insights into the function and evolution of these proteins.

In press: Environmental Health
Perspectives.

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WHOI Contribution No. 6247.

ENVIRONMENTALLY-INDUCED CYTOCHROME
P-450 IN WINTER FLOUNDER
(*Pseudopleuronectes americanus*) FROM
COASTAL MASSACHUSETTS EVALUATED BY
CATALYTIC AND MONOCLONAL ANTIBODY PROBES

John J. Stegeman, Frances Y. Teng
and Elisabeth A. Snowberger

Levels of hepatic microsomal EROD and AHH activities, and sensitivity to inhibition by ANF, were consistent with in-

duction of cytochrome P-450 by environmental chemicals in winter flounder from near the Deer Island sewage outfall in Boston Harbor, off Plymouth Beach, on Nantucket Shoals and at the outer New Bedford Harbor in Buzzards Bay, Massachusetts. Levels of activity were higher in fish from Boston Harbor and Plymouth Bay than from Nantucket Shoals and Buzzards Bay. Levels of EROD and AHH activities were correlated in fish from the latter site, with some individuals there showing little evidence of induction. Immunoblot analysis of flounder liver microsomes with a monoclonal antibody (1-12-3) against the 8-naphthoflavone (BNF)-inducible cytochrome P-450 isozyme (P-450E) from the marine fish scup, revealed a single cross-reacting protein in untreated fish from all four field sites. A similar protein was induced in BNF treated winter flounder. We conclude that this protein is the flounder counterpart of cytochrome P-450E, and the data indicate environmental induction of this flounder isozyme. Levels of monooxygenase activity in Buzzards Bay fish correlated positively with the amount of flounder cytochrome P-450E counterpart, supporting the conclusion that there was a wide range in the extent of induction in animals in Buzzards Bay. Induced cytochrome P-450 could function in activating environmental carcinogens, a probable factor in the tumorigenesis in winter flounder in Boston Harbor. Monoclonal antibodies as employed here should be useful in further analysis of such induced cytochrome P-450 in these and other fish.

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WHOI Contribution No. 6274.

SWIMMING MUSCLE HELPS WARM THE BRAIN OF LAMNID SHARKS

Nancy G. Wolf, Peter R. Swift and Francis G. Carey

1. Experiments with heat generation by model brains in lamnid sharks indicate that metabolic heat produced by the brain alone is probably not sufficient to cause the brain temperature elevations observed in these sharks.

2. A large vein in the red-fiber axial muscle of these sharks leads to the myelonal vein which in turn runs to the cranium. This red muscle vein is valved to direct blood flow anteriorly and provides a route for transfer of warm blood from the red muscle to the central nervous system.

3. Temperature profiles along the neural canal show that warm blood enters the myelonal vein from the red muscle vein.

4. The red swimming muscle acts as an accessory source of heat for the brain. Heat extracted from warm venous blood originating in the red muscle could provide a valuable addition to the heat budget of the head.

Supported by: NSF Grants OCE83-11512 and PCM83-08150; a Fellowship from the Leopold Schepp Foundation; and WHOI.

WHOI Contribution No. 6396.

BENTHOS

BENTHOPELAGIC MACROZOOPLANKTON COMMUNITIES AT AND NEAR DEEP-SEA HYDROTHERMAL VENTS IN THE EASTERN PACIFIC OCEAN AND THE GULF OF CALIFORNIA

Carl J. Berg, Jr. and Cindy Lee Van Dover

Benthopelagic zooplankton communities at hydrothermal vents on the East Pacific Rise and in Guaymas Basin are enriched in terms of both biomass and abundance with respect to non-vent areas, but depleted relative to biomass estimates of surface zooplankton communities. Composition of the zooplankton community varied among vent areas, particularly in the relative contribution of benthic-associated components (e.g., lysianassid amphipods). Larval and juvenile stages of many benthic species, including *Calyplogena* spp., two undescribed species of limpets, *Dahlella caldariensis*, *Bythograea* sp., *Munidopsis* sp., epicaridean isopods, and lysianassid amphipods, were collected in the water column. This is the first significant collection of larval and juvenile invertebrates in deep-sea waters, and is undoubtedly a consequence of the nature and extent of development of adult populations of invertebrates at hydrothermal vents.

In press: Deep Sea Research.

Supported by: NSF Grants OCE78-08855 and OCE81-17119.

WHOI Contribution No. 6206.

FOOD CONSUMPTION BY THE YELLOWTAIL
FLOUNDER IN RELATION TO
PRODUCTION OF ITS BENTHIC PREY

Jeremy S. Collie

The yellowtail flounder (Limanda ferruginea) consumes a small but significant proportion of the production of its invertebrate prey. Using two different methods, I calculated the rate of food consumption by yellowtail flounder at three sites off the New England coast. The bioenergetic method sums the food required to satisfy the metabolic requirements of the fish. The second method is based on the weight of stomach contents and the rate of food evacuation from the stomach. The bioenergetic method gave consistently higher results (1.4 to 1.6 kg fish⁻¹ yr⁻¹) than the stomach-content method (0.5 to 0.8 kg fish⁻¹ yr⁻¹). Yellowtail flounder abundance was estimated with a method that uses the commercial catch data to standardize the survey, relative-abundance index. I multiplied the consumption rates per fish by flounder density to obtain estimates of consumption per unit area, which range from 1.2 to 6.3 g WW m⁻² yr⁻¹. Annual production of six important prey species was calculated from benthic samples collected concurrently at the same sites. Yellowtail flounder consumption as a percentage of prey production was 6 to 12%, 2 to 5%, and 1 to 3%, for the amphipods Unciola inermis, Erichthonius fasciatus and Ampelisca agassizi, respectively; 11 to 34% and 7 to 21% for the polychaetes Chone infundibuliformis and Nephtys incisa, respectively; and less than 1% for the sand dollar, Echinarrachnius parma.

In press: Marine Ecology (Progress Series).

Supported by: U.S. Department of the Interior, MMS Contract 14-12-0001-29192.

WHOI Contribution No. 6207.

FOOD SELECTION BY YELLOWTAIL FLOUNDER
(Limanda ferruginea) ON GEORGES BANK

Jeremy S. Collie

Yellowtail flounder stomachs and benthic grab samples were collected concurrently at three sites on four quarterly dates from August 1982 to May 1983. Stomach contents and grab samples were sorted, weighed and important prey species measured. Yellowtail flounder feed mainly on benthic macrofauna; in most cases a few

amphipod and polychaete species constituted the bulk of the diet. I calculated selection indices to compare the species and size composition of the stomach contents with that of the benthic macrofauna. The selection indices are consistent among the four sampling dates and can largely be explained by prey life history and prey size. A lognormal curve, fitted by least squares, accounts for 87% of the variation in the mean size-selection indices. According to this curve, the preferred prey size of three-year-old yellowtail flounder is 13 mg.

In press: Canadian Journal of Fisheries and Aquatic Sciences.

Supported by: U.S. Department of the Interior, MMS Contract 14-12-0001-29192.

WHOI Contribution No. 6180.

PREMIERES OBSERVATIONS SUR LA
MEIOFAUNE DES SITES HYDROTHERMAUX DE LA
DORSALE EST-PACIFIQUE (GUAYMAS,
21°N ET EXPLORER RIDGE)

Alain Dinet, Frederick J. Grassle
and Verena Tunnicliffe

First observations on the meiofauna from hydrothermal vents of the East Pacific Rise (Guaymas, 21°N and Explorer Ridge). The main characteristics (i.e. abundance and species diversity) of the meiofauna collected at three hydrothermal sites of the East Pacific Rise are presented. Qualitatively, few differences are observed among the populations of the different areas which are basically composed of nematodes, siphonostomes, poecilostomes and harpacticoid copepods, ostracods and macrofaunal juveniles (polychaetes and limpets). As a whole, species diversity and abundance of these meiofaunal assemblages are low as compared with normal abyssal occurrences. Outstanding features of meiofaunal assemblages studied are confirmed through the species composition of the corresponding meiofauna which is moreover very patchily distributed. The physico-chemical variability of the vent waters encountered on Explorer Ridge shows that very few meiofaunal species seem to be able to adapt to H₂S-rich hydrothermal environments. The Guaymas Basin meiofauna is patchily distributed and the species composition varies according to the pattern of flux of hydrothermal fluid through the soft sediments.

Supported by: NSF Grants OCE81-15251 and OCE83-11201.

WHOI Contribution No. 6158.

PREDICTION OF HYDROTHERMAL VENT LOCATIONS
FROM BRACHYURAN CRAB DISTRIBUTIONS

Cindy Lee Van Dover, Peter J. S. Franks
and Robert D. Ballard

Mapping the distribution of hydrothermal vents along a spreading center is a prerequisite for developing models of oceanic heat budgets or hydrological and geochemical balances. Models of biological processes, such as colonization and maintenance of hydrothermal vent communities, will also rely on knowledge of spatial relationships among vents. We applied a model of symmetrical, exponential decreases in brachyuran crab density with distance from vent centers to a video census of crab density along the neovolcanic zone of the East Pacific Rise to predict the number of vents and their locations. The model, calibrated by data from 2 known vents, accurately locates one other known vent, and predicts the locations of three additional vents presumably skirted by the towed camera sled. Analysis of crab distributions may thus be a valuable tool for mapping locations of hydrothermal vents using remotely operated camera gear.

Supported by: ONR Contract N00014-82-C-0019; Navy Chair Grant N00014-85-C-0242; NSF Grant OCE83-11201; WHOI Education Office; and NSF Graduate Fellowship.

WHOI Contribution No. 6331.

A NEW TRICHOMYCETE COMMENSAL WITH A
GALATHEID SQUAT LOBSTER FROM DEEP-SEA
HYDROTHERMAL VENTS

Cindy Lee Van Dover and
Robert W. Lichtwardt

A new species of eccrinid fungus (Trichomycetes) is described. The fungus is a commensal in the cardiac and pyloric stomachs of the galatheid squat lobster Munidopsis subsquamosa (Decapoda, Anomura) collected from deep-sea (2600 m) hydrothermal vents. This is the first record of a trichomycete from depths greater than 50 m. About 40% of the galatheids examined were heavily infested; this proportion varied among the subsamples collected from various vent sites. No fungal thalli were observed in the smallest galatheids.

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17, 461-468, 1986.

Supported by: Personal funds.

WHOI Contribution No. 6184.

REPRODUCTION AND RAPID GROWTH IN A
DEEP-SEA APLACOPHORAN MOLLUSC,
Prochaetoderma yongei

Amelie H. Scheltema

Prochaetoderma yongei, an aplacophoran mollusc with a wide geographic distribution between 450 and 2200 m depth and high densities in the North American Basin, grows to adult size within two months and sexual maturity within one year. Gametogenesis is asynchronous within individuals from a single sled-trawl sample. Periods of increased recruitment and numbers of ripe individuals occur; whether these recurrent periods are irregular or cyclic at regular intervals is not known. Males usually outnumber females in all size classes. The peak class in length-frequency distributions contains individuals less than one year old. Repopulation of a disturbed area by this species may require about a decade. The rapid growth to maturity by P. yongei and its ability to colonize are attributes adapted to transient or disturbed environments, but its low egg numbers and lack of synchrony in egg development are not.

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WHOI Contribution No. 6357.

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

EPIPELAGIC MEROPLANKTON OF TROPICAL
SEAS: ITS ROLE FOR THE BIOGEOGRAPHY
OF SUBLITTORAL INVERTEBRATE SPECIES

Rudolf S. Scheltema

Epipelagic meroplankters are the larvae of benthic invertebrates that have been carried offshore from the continental shelf or the coast of oceanic islands either by eddy diffusion or advective processes. The existence of invertebrate larvae of benthic species far out in the open ocean has been known since the Plankton Expedition, the results of which were

reported in a series of volumes published near the end of the last century (Hacker 1898; Simroth 1895; Mortensen 1898), but the possible significance of these early observations was not considered by biologists at that time. Not until the last two decades have systematic investigation of the epipelagic meroplankton been undertaken (Mileikovsky 1966, Robertson 1964; Scheltema 1964, 1966, 1968, 1971a, b). These studies, as were those of the Plankton Expedition, were largely restricted to the North and South Atlantic Oceans.

Teleplanic larvae may show special adaptations for a long planktonic life. Among gastropods many species have long periostriical spines and very light, sometimes completely uncalcified, shells (Pechenik et al. 1984; Richter 1984) and long velar lobes that are used for swimming as well as feeding.

In the present account, knowledge about the occurrence of meroplankton throughout tropical waters of the Atlantic, Pacific and Indian Ocean is summarized both from published accounts and newly reported data. The overall significance of long distance dispersal by teleplanic larvae of gastropod molluscs is briefly discussed and related to the role of past geologic events and ecologic constraints that determine the geographic range of tropical species.

In press: Proceedings of the International Conference on Pelagic Biogeography, Amsterdam, Netherlands.

Supported by: NSF Grant OCE84-10262.

WHOI Contribution No. 6151.

ON DISPERSAL AND PLANKTONIC LARVAE OF BENTHIC INVERTEBRATES: AN ECLECTIC OVERVIEW AND SUMMARY OF PROBLEMS

Rudolf S. Scheltema

The question of how the larvae of benthic marine invertebrates are dispersed can be addressed from a number of different perspectives and at a variety of spatial and temporal scales. In some instances, dispersal is only a few centimeters or meters; in others, larvae may be transported thousands of kilometers across wide expanses of ocean. The time interval over which dispersal occurs may be a few minutes, a tidal cycle, many months, or even a year. An attempt is made to show how planktonic larvae are dispersed over various spatial and temporal scales and to consider the circumstances and possible consequences of such dispersal. The eco-

logical, biogeographic, genetic, and evolutionary consequences of larval dispersal are at present only dimly understood.

In press: Bulletin of Marine Research.

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WHOI Contribution No. 6261.

THE EASTERN PACIFIC AS A BARRIER TO THE DISPERSAL OF PLANKTONIC LARVAE OF BENTHIC INVERTEBRATES

Rudolf S. Scheltema

Thorson (1961) believed that "under average conditions even long-distance larvae have a much too short pelagic life to survive the critical distance across the eastern Pacific..." Zinsmeister and Emerson (1979) considered the possibility of larval dispersal across the eastern Pacific barrier and concluded that the paucity of Indo-Pacific molluscs in the eastern Pacific is owing to the "vast expanse of open water" and "lack of suitable habitats with available ecological niches...." However, no serious attempt has ever been made to determine whether or not the larvae of shoal water invertebrates actually occur in the open waters of the tropical east Pacific Ocean. Plankton samples taken from a region between Central or South America and the easternmost islands of the central Pacific show that teleplanic larvae of benthic invertebrates do in fact exist within the "east Pacific barrier" but that their occurrence there is significantly less than in the central Pacific with its many islands. The evidence suggests that the eastern Pacific acts as a "filter" rather than a "barrier" and that some larvae successfully cross the 5000 km of open ocean from time to time. Such a conclusion is supported by faunal data which show a small but persistent Indo-Pacific element in the eastern Pacific. The results also suggest a difference in the capacity for various taxa to cross the east Pacific "barrier."

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WHOI Contribution No. 6281.

DIFFERENTIATION IN GROSS AND
REPRODUCTIVE MORPHOLOGY AMONG PANAMANIAN
POPULATIONS OF THE BEACH ISOPOD
Excirolana braziliensis

James R. Weinberg
and Victoria R. Starczak

Specimens of the isopod Excirolana braziliensis, collected between 1969-1986 from three Panamanian beaches, were analyzed for differences in individual morphology within and among populations. Two beaches are in the Pacific (LB, BS) and one is in the Caribbean Sea (SH). All are near the entrance to the Panama Canal. ANOVA was used to test for sources of morphological variation, after adjusting for body size with Principal Component Analysis. There was no significant variation between individuals within beaches due to sex or location. Morphology of individuals from different beaches was significantly different and the interpopulation differences have persisted over seasons and years. Specimens from the Caribbean population (SH) were similar to one Pacific population (BS) in gross morphology, but these populations were significantly different in a male reproductive character. In contrast, SH differed from the second Pacific population (LB) in gross morphology, but they did not differ in male reproductive morphology. In addition to comparing specimens collected from the field, we measured F_1 's, derived from laboratory cultures of each population, to determine whether morphological differences were inherited. Analysis of F_1 morphology suggested that the morphological differences between populations were inherited. The results demonstrate that there is significant morphological variation in this species, and that the variation can be explained statistically by considering just one factor, populations (beaches). Because of this simple result, this is an appropriate organism for a large-scale, regional investigation of evolutionary divergence between marine populations which are geographically isolated by the Isthmus of Panama.

Supported by: NIEHS Training Grant ES07142 and Postdoctoral Fellowships from the Smithsonian Institution and the Woods Hole Oceanographic Institution.

WHOI Contribution No. 6363.

ECOSYSTEM STUDIES

RIVERINE SYSTEMS

ALTERATION OF CARBON CYCLING BY
BEAVER: METHANE EVASION RATES FROM
BOREAL FOREST STREAMS AND RIVERS

Tim E. Ford and Robert J. Naiman

In boreal forest drainage networks beaver (Castor canadensis) apparently influence the biogeochemical cycling of carbon by creating conditions for sediment accumulation in streams, providing anoxic conditions suitable for significant methanogenesis. To test this assumption we measured methane evasion rates in streams ranging in size from first to sixth order in the Matamek River drainage network, Quebec, Canada. Evasion rates varied between 0.04 and 4.41 g C(CH₄) m⁻² yr⁻¹. There was no correlation between stream size or water temperature and evasion rate. However, methane evasion was 33 fold greater in beaver ponds than at other sites, representing 3.6% of the measured annual carbon output. In contrast, methane evasion accounted for only 0.05-0.5% of the annual carbon output from sites not modified by beaver.

Supported by: Matamek Research Program and NSF Grant BSR81-05677.

WHOI Contribution No. 6360.

LONGITUDINAL PATTERNS OF ECOSYSTEM
PROCESSES AND COMMUNITY STRUCTURE
IN A SUBARCTIC RIVER CONTINUUM

Robert J. Naiman, Jerry W. Melillo,
Maurice A. Lock, Tim E. Ford
and Seth R. Reice

Ecosystem processes and community structure in running waters of the boreal forests of Quebec, Canada, are strongly influenced by climate and channel geomorphology. Here we present a concise overview of a project examining longitudinal trends as small streams gradually coalesce into large rivers, summarizing our results in a series of budgets and predictive equations describing changes in organic carbon dynamics and community structure. There were significant trends with stream order for 70% of the 73 components, processes, and ratios examined. Of 46 independent components examined, 63% showed a significant trend with stream order. As stream size increased from 1st to 9th order there was a decrease in total

carbon inputs (i.e., precipitation, throughfall, primary production and allochthonous materials) followed by a gradual increase due to greater primary production in streams > 6th order. The standing stock of carbon decreased exponentially downstream, and total carbon outputs (i.e., respiration, leaching, methane evasion, and insect emergence) increased slightly downstream. Nevertheless, some ecosystem-level processes, as well as community structure, showed equivocal trends, which were apparently due to the hierarchical scale of examination and the relative degree of physiochemical versus biological control of the processes and communities. The data, when placed in a watershed perspective, showed that total carbon inputs were evenly distributed by stream order throughout the 19,871 km² Moisie River drainage network, most carbon was stored in the small 1st-3rd order streams, whereas the majority of organic carbon was metabolized in the 7th-9th order rivers. Fluvial transport of organic carbon to the Gulf of St. Lawrence was nearly three times that of the measured total annual input, suggesting that inputs of dissolved organic carbon in groundwater were more important than previously expected.

Ecosystem-level measurements of carbon retention and utilization also showed significant trends with stream order. The spiraling length for carbon increased exponentially from 8-15 km in small streams to 426 km in the 9th order river. There was a concomitant decrease in reach retention with stream order while the rate coefficient of respiration and rate of downstream movement increased with order. The stream metabolism index, a measure of ecosystem efficiency, increased from 1st to 7th order, thereafter decreasing as streams became larger. These trends with stream order were related to physical gradients in channel dimensions, hydrology, riparian influences, and sunlight. We conclude that these subarctic lotic ecosystems have numerous strong relationships with stream order and that the dynamics can be described by a relatively small set of predictive equations.

In press: Ecology.

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WHOI Contribution No. 6179.

SALT MARSH SYSTEMS

PUTATIVE EFFECTS OF FIDDLER CRABS ON THE VEGETATION OF SALT MARSHES

Ivan Valiela, Brian Howes,
John M. Teal and Dale Goehringer

Results of new experiments in a Massachusetts salt marsh and a re-examination of previous work on a Rhode Island salt marsh indicate that burrowing by fiddler crabs does not seem to play a prominent role affecting growth or productivity of the salt marsh grass *Spartina alterniflora*. Manipulation of fiddler crab populations and burrow densities in both Massachusetts and Rhode Island studies did not greatly affect vegetation (height, stem density, or % flowering of *Spartina alterniflora*) or sediment properties (profiles of sediment redox potential, pH, or water movement). These results were corroborated by a survey of burrow densities and grass height and by data from long-term study plots in Massachusetts. Control of vegetation growth and composition in salt marshes is most likely carried out by factors other than crab activity.

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WHOI Contribution No. 6280.

MARINE MAMMALS

POPULATION BIOLOGY, SOCIAL BEHAVIOR, AND COMMUNICATION IN WHALES AND DOLPHINS

Peter Tyack

The major taxonomic division of the cetaceans separates the baleen whales from the toothed whales and dolphins. These two groups differ in life history and in social organization. Even though they grow to a larger size, young baleen whales tend to develop more rapidly than dolphins and toothed whales. Except for the mother-calf bond, most groups of baleen whales are short lived, on the order of hours, and individual specific associations appear to be exceptions to the norm. Most toothed whales live in more structured groups in which young animals have a long period of dependency and social learning. The signals that have been described for different cetacean species have functions suited to the kinds of interaction that

predominate in their societies.

Supported by: NSF Grant BNS85-08047.

WHOI Contribution No. 6302.

USE OF A TELEMETRY DEVICE TO IDENTIFY
WHICH DOLPHIN PRODUCES A SOUND:
WHEN BOTTLENOSED DOLPHINS (*Tursiops*
truncatus) ARE INTERACTING THEY MIMIC
EACH OTHER'S SIGNATURE WHISTLES

Peter Tyack

A small telemetry device, called a "vocalight," was developed to identify which dolphin within a group produces a sound. The vocalight attaches to a dolphin's head using a suction cup and lights up a variable number of light emitting diodes depending upon the loudness of sounds received at a hydrophone within the suction cup. If vocalights matched for sensitivity are put on each dolphin within a group, observers can identify which dolphin produces a sound.

The vocalight was used to study the whistle repertoires of two bottlenosed dolphins, *Tursiops truncatus*, at the Sealand Aquarium in Brewster, Massachusetts. 77% of the identified whistles (219 out of 284) fell into two primary categories, type 1 and type 2. The remaining 23% of whistles fell into five secondary categories. Of the primary whistles produced by one dolphin, 78% were of type 1 (22% type 2), while 69% of primary whistles from the other dolphin were of type 2 (31% type 1). The result that each of the dolphins favored a different primary whistle supports the findings of Caldwell and Caldwell (1965), that each dolphin produces an individually distinctive whistle. But when they were interacting, both dolphins appeared to imitate the other's signature whistle.

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WHOI Contribution No. 6362.

Steno bredanensis IN THE
MEDITERRANEAN SEA

William Watkins

Steno bredanensis (Lesson 1828), the rough toothed dolphin, has generally been considered to be only an occasional visitor to the Mediterranean Sea (cf. Walker 1964) and not a consistent component of the Mediterranean fauna (Duguy and Robi-

neau 1973, 1982; Duguy and Cyrus 1974; Duguy 1978, 1983; Duguy et al 1983; Cagnolaro et al 1983). Five specimens have been positively identified from these waters previously.

To add considerably to this record, we report here observations of a large aggregation totalling approximately 160 animals in eight groups of about 20 *Steno* each. These sightings were made during a cruise for the Woods Hole Oceanographic Institution in the Sicily Channel on 4 September 1985 in water of about 500-m depth, approximately 170 km southeast of Cape Passero (Sicily) and 130 km southeast of Malta (35°28'26"N, 15°53'04"E).

In press: Marine Mammal Science.

Supported by: NSF Grant BNS82-14089.

WHOI Contribution No. 6242.

THE SOUNDS OF SPERM WHALE CALVES

William A. Watkins,
Karen E. Moore, Christopher W. Clark
and Marilyn E. Dahleim

The development of the click sounds of sperm whales (*Physeter catodon*) has been investigated through comparisons of these vocalizations from calves of different sizes. The observations include sounds from four small stranded calves held for short periods in aquaria at Miami, Florida, and Seattle, Washington, and in a bay on Long Island, New York. These vocalizations were compared with those of larger calves encountered at sea. All the calves produced typical sperm whale sounds -- clicks with broadband spectra, often produced in short series. Vocalizations from the smaller calves sometimes included slightly noisy, tonal components -- similar noisy components accompanying click sounds were also occasionally heard in the presence of calves at sea, and they were interpreted as the result of improperly formed clicks. The smallest calves produced few temporally repetitive click patterns, but the larger (older) ones produced sequences with stereotyped "coda"-like temporal patterns. The use of such patterned click sequences increased with the apparent age of the whales. None of the calves appeared to use their sounds in ways that were related to echolocation. In the larger calves, the sounds appeared more organized in sequences similar to the communication signals of adults.

In press: NATO Advanced Study
Institute Series, Animal Sonar
Systems, Vol. III, Plenum Press,

NATO Conference, 10 September 1986.

Supported by: The Woods Hole Oceanographic Institution.

WHOI Contribution No. 6203.

MARINE POLLUTION

THE EFFECTS OF FENTHION AND FENVALERATE ON BIOENERGETICS AND POPULATION DYNAMICS OF PLANKTONIC CRUSTACEANS

Judith M. Capuzzo

The effects of the pyrethroid pesticide fenvalerate and the organophosphate pesticide fenthion on planktonic crustaceans were investigated in continuous flow bioassays. Fenvalerate was more toxic than fenthion in acute bioassays with 96-h LC_{50} values ranging from 5.4 ng/l for Stage I larvae of Homarus americanus to 46.0 ng/l for adult Heteromysis formosa; LC_{50} values for adult Acartia tonsa were 14.7 ng/l fenvalerate and 102.5 µg/l fenthion. Sublethal effects on respiration rates and O:N ratios were observed at concentrations as low as 0.6 ng/l fenvalerate and 0.7 µg/l fenthion. Metabolic changes paralleled delays in development for larvae of H. americanus and reductions in egg production and larval viability of A. tonsa. The most sensitive indicators of acute toxic response of Acartia to both pesticides were gross and net growth efficiencies (K_1 and K_2) and instantaneous birth rates, parameters which integrate metabolic responses, survival, and reproduction. Reductions in both bioenergetic parameters and birth rates were evident with sublethal exposure to both contaminants. Disruptions in reproduction and development were also observed in chronic assays of fenvalerate on Acartia tonsa. With exposure to 6.3 ng/l for 42 d, the first generation of Acartia tonsa had slightly reduced growth rates and slightly delayed maturation in comparison with control animals; second generation copepods, however, failed to develop beyond naupliar stage II. Chronic exposure to 0.6 ng/l also resulted in reproductive and developmental impairment, although some second generation copepods did develop to maturity. Comparison of instantaneous rates of population growth between control copepods and those exposed to 0.6 ng/l fenvalerate reflect reductions in both survival and reproductive potential of exposed copepods.

Supported by: EPA Cooperative Agreement CR-810313-01-0 with the Environmental Research Laboratory at Gulf Breeze, Florida.

WHOI Contribution No. 6116.

MICROBIOLOGY

A NEW SULFUR-REDUCING, EXTREMELY THERMOPHILIC EUBACTERIUM FROM A SUBMARINE THERMAL VENT

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

A newly described bacterial isolate, designated Strain NS-E, differs from presently known extremely thermophilic bacteria in various characteristics. It is a strictly heterotrophic eubacterium of marine origin and has a temperature range for growth of 50–95°C with an optimum at 77°C and a pH of 7.5. Its DNA base composition is 41.3 mol % guanine + cytosine. It is obligately anaerobic, utilizes various sugars as well as yeast extract and reduces elemental sulfur facultatively to hydrogen sulfide. In 24 hr cultures cell densities are up to four-fold higher in the presence than in the absence of elemental sulfur. Sulfide concentrations of 1.0 and 10.0 mM limit growth by 65 and 95 percent, respectively. Oxygen sensitivity is apparent only at or above that range of temperature at which growth occurs.

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WHOI Contribution No. 6061.

Staphylothermus marinus SP. NOV.
REPRESENTS A NOVEL GENUS OF EXTREMELY THERMOPHILIC SUBMARINE HETEROTROPHIC ARCHAEABACTERIA GROWING UP TO 98°C

Gerhard Fiala, Karl O. Stetter, Holger W. Jannasch, Thomas A. Langworthy and Jerzy Madon

Two isolates of a new type of extremely thermophilic S^0 -dependent archaebacteria with a GC-content of 35 mol% have been obtained from geothermally heated sediments at the beach of Vulcano, Italy, and from a submarine hydrothermal vent at the East Pacific Rise. The organ-

isms are strictly anaerobic heterotrophic immotile cocci, about 0.5 to 1 μ m in diameter, occurring singly, in short chains and, characteristically, in large clusters of up to 100 cells. Giant cells up to 15 μ m in diameter are formed at high yeast extract concentrations. Acetate, isovalerate, CO_2 and H_2S were found as metabolic products. The isolates grow between 1 and 3.5% NaCl and pH 4.5 to 8.5. The optimal growth temperature is 92 or 85°C, depending upon nutrition. The two isolates are considered to represent a new genus named Staphylothermus with the type species Staphylothermus marinus.

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WHOI Contribution No. 6150.

REGULATION OF GROSS GROWTH EFFICIENCY AND AMMONIUM REGENERATION IN BACTERIA BY SUBSTRATE C:N RATIO¹

Joel C. Goldman, David A. Caron and Mark R. Dennett

Natural assemblages of marine bacteria were cultured on combinations of C and N sources (amino acids, glucose and NH_4^+) to span a range of substrate C:N ratios from 1.5:1 to 10:1. Catabolic metabolism of the N component of amino acid substrates led to NH_4^+ regeneration during exponential growth. The efficiency of this regeneration (R_N) and also of the carbon gross growth efficiency (GGE) generally was independent of the sources of C and N, but increased as the C:N ratio of the bacterial biomass (C:N_b) decreased relative to the C:N ratio of the substrate (C:N_s). The elemental chemical composition (C:N:P ratio) of the bacterial biomass was relatively invariant at about 45:9:1 and GGE varied from a threshold value of about 40-50 percent at $\text{C:N}_s > 6:1$ up to 94 percent when C:N_s was 1.5:1. Hence, R_N varied from 0 percent when C:N_s was 10:1 up to 86 percent when C:N_s was 1.5:1. Inorganic sources of both N and P were taken up only in stoichiometric quantities during this phase of growth. Regeneration of NH_4^+ during the stationary phase, as well as of PO_4^{3-} occurred, most likely due to endogenous metabolism, but the magnitude of this regeneration seemed to increase greatly only when C:N_s was $> 6:1$. Considering that both amino acids frequently do not provide all of the N required and that carbohydrates often are the major C source for growth of marine

bacteria, we speculate that C:N_s of available substrates in marine waters is $> 10:1$. Hence, actively growing bacteria may be inefficient remineralizers of N in the microbial loop.

Supported by: NSF Grant OCE85-11283.

WHOI Contribution No. 6377.

EFFECTS OF HYDROSTATIC PRESSURE ON GROWTH OF MARINE BACTERIA

Holger W. Jannasch

This introductory paper to the Symposium on High Pressure Biology updates and summarizes information from last years' research on pressure effects on microbial growth and discusses present-day concepts of barotolerance and barophilism.

In press: Current Perspectives in High Pressure Biology, Academic Press, London.

Supported by: NSF Grants OCE83-08631 and OCE84-16206.

WHOI Contribution No. 6249.

LEBEN IN DER TIEFSEE: NEUE FORSCHUNGSGEBNISSE

Holger W. Jannasch

An account of the last years' progress in research on the biology of deep sea hydrothermal vent populations is presented with emphasis on the microbial chemosynthetic processes.

In press: Verhandlungen der Gesellschaft Deutscher Naturforscher und Ärzte, Vol. 114.

Supported by: NSF Grant OCE83-08631.

WHOI Contribution No. 6277.

INORGANIC ^{14}C AS A PROBE OF GROWTH RATE-DEPENDENT VARIATIONS IN INTRACELLULAR FREE AMINO ACID AND PROTEIN COMPOSITION OF NH_4^+ -LIMITED CONTINUOUS CULTURES OF Nannochloris atomis (BUTCHER)

Steven E. Lohrenz and Craig D. Taylor

Growth rate-dependent variations in intracellular free amino acid and protein composition were characterized and compared to their ^{14}C content as a function

of time in NH_4^+ -limited continuous cultures of the marine chlorophyte alga, *Nannochloris atomis* (Strain GSB Nanno). The relative abundances of cellular carbon in free amino acids and protein were positively correlated with relative growth rate (μ/μ_{max}). There was also a positive correlation between relative growth rate and the proportion of cellular nitrogen in free amino acids, but not in protein. Significant changes in the composition of the intracellular free amino acid pool accompanied the growth rate-related decline in pool size. The percentage of intracellular free amino carbon contained in glutamate increased from 9 to 53% and the glutamine/glutamate carbon pool ratio decreased as relative growth rate decreased. The percentage of intracellular free amino acid carbon contained in proline decreased from 76% to 21%, while small increases were observed for glycine + alanine, valine, and beta-aminobutyrate as relative growth rate decreased.

Equilibration of the intracellular free amino acid pool with inorganic ^{14}C was incomplete even after incubation for 25% of the generation time. Equilibration rates of glutamate, glutamine, glycine + alanine, and valine were positively correlated with growth rate. Incomplete equilibration led to underestimates of free amino acid carbon pool sizes based on ^{14}C content. However, because the saturation rates of glutamate and glutamine were similar, their ratio of ^{14}C pools could be used as an index of the growth rate-dependent changes in the ratio of their cellular carbon pools.

Isotope disequilibrium resulted in an initially higher relative abundance of ^{14}C in alcohol soluble low molecular weight material than the corresponding relative abundance of cellular carbon as determined from ^{14}C distributions in equilibrium-labeled cells. Most of the short term time-dependent variation in the distribution of ^{14}C in low molecular weight material was associated with the free amino acids. For incubations up to 25% of the generation time, the distribution of ^{14}C in protein was lower than the equilibrium distribution. Discrepancies between short term distributions of ^{14}C and cellular carbon distributions diminished if free amino acids and protein were considered together as a unit of cellular material. Growth rate-dependent changes in distributions of cellular carbon in free amino acids + protein were reflected by changes in the corresponding ^{14}C distributions.

The techniques described provide the ability to specifically assay growth rate-dependent variations in algal metabolism and biochemical composition without

the interference of detritus and non-algal biomass.

In press: Journal of Experimental Marine Biological Ecology, 105, 1987.

Supported by: NSF Grant OCE82-15854; WHOI Education Office.

WHOI Contribution No. 6196.

SOLUBILITY PROPERTIES OF OXYGEN AND HELIUM IN HYPERBARIC SYSTEMS AND THE INFLUENCE OF HIGH PRESSURE OXY-HELIUM UPON BACTERIAL GROWTH, METABOLISM, AND VIABILITY

Craig D. Taylor

One approach to the isolation of deep sea bacteria is to streak undecompressed and concentrated samples onto the surface of solid nutrient media which is in equilibrium with an oxygen-containing helium atmosphere at high pressure. Because of discrepancies in the literature, an independent investigation quantifying the effects of high pressure upon the aqueous solubility and fugacity of oxygen was undertaken and results applied to the operation of culture systems employing high pressure gases. Physiological studies with a barotolerant microorganism revealed that an oxy-helium atmosphere at 500 atm pressure did not significantly reduce culture viability or interfere with colony formation, and, in fact, dramatically enhanced growth and metabolism rates relative to high pressure control cultures incubated in the absence of an atmosphere. Results will be discussed with respect to application of high pressure gas systems for isolation of deep sea bacteria.

Supported by: NSF Grants DES75-15017, OCE75-21278 and OCE84-11580.

WHOI Contribution No. 6269.

BIOLOGICAL AND ECOLOGICAL CHARACTERIZATION OF THE MARINE UNICELLULAR CYANOBACTERIUM *Synechococcus*

John B. Waterbury, Stanley W. Watson, Frederica W. Valois and Diana G. Franks

This monograph describes the morphology, physiology, taxonomy, spatial and temporal patterns of abundance, annual and diurnal cycles and contribution to primary production of the marine unicellular cyanobacterium, *Synechococcus*.

In press: Photosynthetic
Picoplankton, T. Platt and W. K.
W. Li, eds. Canadian Bulletin of
Fisheries and Aquatic Sciences,
Bulletin #214, 1986.

Supported by: NSF Grants OCE78-19595,
OCE80-19057, OCE82-14889 and
OCE84-16960.

WHOI Contribution No. 6250.

MEMBRANE LIPIDS OF A PSYCHROPHILIC AND BAROPHILIC DEEP-SEA BACTERIUM

Carl O. Wirsen, Holger W. Jannasch,
Stuart G. Wakeham and Elizabeth A. Canuel

In a psychrophilic and barophilic
marine bacterial isolate of the genus
Alteromonas, the ratio of total unsatur-
ated versus saturated fatty acids in the
membrane lipids increased when the organ-
ism was grown at increasing hydrostatic
pressures and decreasing temperatures.
This regulatory capacity, as well as the
presence of relatively large amounts of
20:5 polyunsaturated fatty acid, appear to
be functional in maintaining membrane
fluidity within a range of pressures dis-
tinctly below and above the specific
optimum and at typical deep sea tempera-
tures.

In press: Current Microbiology.

Supported by: NSF Grant OCE84-16206
and ONR Contract N00014-85-C-0001.

WHOI Contribution No. 6225.

ACTIVITIES OF SULFUR-OXIDIZING BACTERIA AT THE 21°N EAST PACIFIC RISE VENT SITE

Carl O. Wirsen, Jon H. Tuttle
and Holger W. Jannasch

The incorporation of inorganic and
organic carbon into cell material as well
as the activities of carboxylating enzymes
(ribulose biphosphate carboxylase and
phospho-enol pyruvate carboxylase) were
measured in waters emitted from "warm"
vents at the 21°N ocean spreading site
(depth 2600 m) of the East Pacific Rise.
Both obligately and facultatively chemo-
autotrophic bacteria were present and com-
prised a significant but variable portion
of the total microbial population as in-
dicated by comparisons of microscopic cell
counts with liquid enrichments and colony
counts on media containing reduced sulfur
compounds. The proportion of chemoauto-
trophic sulfur oxidizing bacteria maxi-

mally reached 79% of the total microbial
population based on ribulose biphosphate
carboxylase activity. Variability of
chemoautotrophic activity occurred between
vents at different locations, but was also
observed in one individual vent. Maximum
rates of CO₂ incorporation in warm vent
water were similar to levels measured pre-
viously in the O₂/H₂S interface of the
Black Sea. In shipboard experiments,
these rates were virtually unaffected by
in situ pressures (ca. 260 atm). Rate
measurements at various temperatures as
well as the observed mesophilic character-
istics of all isolates obtained suggest
that the microbial chemoautotrophic
activity decreases rapidly as freshly
emitted vent water is diluted with cold
ambient deep-sea water.

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449-456, 1986.

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WHOI Contribution No. 6071.

PHYTOPLANKTON

THE DINOFLAGELLATES

Donald M. Anderson

The dinoflagellates (Division Pyrro-
phyta, Class Dinophyceae) are one of the
more important groups of phytoplankton in
the ocean. Their adaptation to a wide
variety of environments is evidenced by a
tremendous diversity in form and nutrition
and by an extensive fossil record dating
back several hundred million years. As
swimming cells, they can flourish under
conditions that are unsuitable for many
non-motile phytoplankton, a success due in
part to unique behavior patterns. Some
produce toxins that are dangerous to man
and other components of the marine food
chain; others are bioluminescent and emit
light; some function as parasites or sym-
bionts that rely on host organisms for
part of their nutrition; many are photo-
synthetic, but an equal number obtain
their carbon by ingesting other phyto-
plankton. It is thus no surprise that
these organisms have been extensively
studied, classified as plants by some
workers and as animals by others. This
chapter will describe the morphological,
behavioral, physiological, and ecological
characteristics of this group, empha-
sizing where possible the attributes that

make dinoflagellates unique and important members of the marine phytoplankton community.

In press: Marine Photosynthesis.
R. Alberte and R. Barber, eds.
Oxford University Press.

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WHOI Contribution No. 6108.

LOCALIZATION OF SAXITOXIN WITHIN
THE DINOFLAGELLATE Gonyaulax tamarensis

Donald M. Anderson and Toni Po-On Cheng

Gonyaulax tamarensis (synonyms Protogonyaulax tamarensis and Alexandrium tamarense) is one of several marine dinoflagellates that produce a suite of neurotoxins collectively called the saxitoxins. Blooms of this organism are often associated with outbreaks of paralytic shellfish poisoning, commonly called PSP or the red tide. One of the least understood aspects of this phenomenon is the physiological role of the toxin molecule in dinoflagellate metabolism. We report here the immunocytochemical localization of saxitoxin in two types of cellular sites - one within the dinoflagellate nucleus on or close to the permanently-condensed chromosomes and the other on the periphery of small granules thought to be starch grains. Different binding affinities were observed at these two sites using high and low antibody dilutions; no binding was observed in a non toxic strain. This is the first direct evidence for localization of saxitoxin within a dinoflagellate. The binding of the toxins to specific cellular sites not only provides new insights to guide future studies of toxin biosynthesis but also has important implications with respect to the retention and accumulation of these toxins in the food chain. The strong labelling in the nuclear region suggests that the saxitoxins may bind to nucleic acids in a manner analogous to the polyamines and other cations.

A postembedding immunofluorescence technique was employed whereby thin sections of fixed and embedded cells were incubated with various dilutions of antisera raised against highly purified saxitoxin isolated from G. tamarensis. Labelling was visualized using epifluorescence microscopy and FITC-labelled goat antibody to rabbit IgG. As some of the toxin may have been lost from the cells during fixation, the observed labelling might represent a partial picture of the saxitoxin distribution.

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WHOI Contribution No. 6395.

AN ENDOGENOUS ANNUAL CLOCK IN THE TOXIC
MARINE DINOFLAGELLATE
Gonyaulax tamarensis

Donald M. Anderson and Bruce A. Keafer

Blooms of the toxic dinoflagellate Gonyaulax tamarensis (synonyms Protogonyaulax tamarensis and Alexandrium tamarense) cause outbreaks of paralytic shellfish poisoning (PSP) in coastal waters throughout the world. Gulf of Maine episodes occur between April and November, a seasonality due in part to life cycle alternations between motile, vegetative cells and resting cysts which overwinter in bottom sediments. Newly-formed cysts have a mandatory 2-6 month dormancy period during which germination is not possible, but once mature, the resting state will continue if temperatures are unfavorable or oxygen unavailable. We now report another factor controlling germination of cysts of G. tamarensis from deep coastal waters -- an endogenous annual clock that can override an otherwise favorable environment for germination. Similar annual variability in germination has not been observed thus far for cysts of this species from shallow estuaries. These results represent the first conclusive demonstration of an endogenous circannual rhythm in a marine plant. They are evolutionarily and ecologically significant because an endogenous annual clock will release motile cells into deep and relatively invariant bottom waters at those times when temperature and light at the surface are suitable for growth. In shallow waters where seasonal variability is large and extends to bottom sediments, a strategy similar to that of the seeds of terrestrial plants would be more appropriate, namely a direct coupling between germination and the external environment.

In press: Nature.

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WHOI Contribution No. 6173.

THE CONTINUING ENIGMA OF CIGUATERA

Donald M. Anderson and Phillip S. Lobel

Research on ciguatera fish poisoning has expanded significantly over the last decade. In large part, this increase in effort is due to the identification of several benthic dinoflagellates as the toxin producers, a discovery soon followed by a series of field and laboratory studies on their distribution, abundance, growth characteristics and toxin production. Equally important have been advances in the analytical techniques and equipment needed to chemically characterize the toxins. Much of that work benefitted significantly from the rapid progress in chemical research on the numerous other toxins produced by marine dinoflagellates.

Despite this surge in activity the general state of knowledge on ciguatera remains relatively poor, both in terms of toxin chemistry and the physiological ecology of the causative dinoflagellates. Some important generalizations are gaining acceptance, but discrepancies and disagreements abound. One of the objectives of this review is to place the many recent papers on this topic in a current perspective that not only identifies common observations or conclusions but also accentuates those areas that require more research effort to resolve disagreements or contradictions.

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WHOI Contribution No. 6248.

THE EFFECTS OF DARKNESS AND ANAEROBIOSIS ON DINOFLAGELLATE CYST GERMINATION

Donald M. Anderson, Craig D. Taylor and E. Virginia Armbrust

The importance of light and anaerobiosis on the germination of marine dinoflagellate resting cysts was examined. When anaerobic conditions were maintained throughout 7 weeks of incubation, germination of all species was completely inhibited although the cysts remained viable. Longer incubations are not expected to alter these results. Light requirements were far more variable. Germination rates in the light varied by a factor of 20 between species; dark germination rates varied by a similar factor but were generally much lower. Only one species re-

quired light to germinate, three species germinated faster in the light than in the dark, and one germinated at comparable rates in the light and in the dark. Brief exposure of the cyst suspensions to light at the beginning of the experiments made it impossible to say whether germination of these species is possible in constant darkness. It is clear, however, that extended light exposure (and presumably photosynthesis) is an absolute requirement only for *Gonyaulax polyedra*, although it can significantly accelerate germination of most of the other species.

The inhibitory effects of darkness and anaerobic conditions reported here help to explain the subsurface accumulation of dinoflagellate cysts in marine sediments and the persistence of benthic cyst populations at times when temperatures favor germination. They also emphasize that several environmental variables other than temperature must be favorable before dinoflagellates can excyst and resume a motile, vegetative existence. These constraints are sufficiently severe that many cysts will never germinate once they reach bottom sediments.

In press: Limnology and Oceanography.

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WHOI Contribution No. 6143.

GREEN LIGHT-MEDIATED PHOTOMORPHOGENESIS IN A DINOFLAGELLATE RESTING CYST

Brian J. Binder and Donald M. Anderson

Developmental responses to light are well known and ubiquitous among higher plants, but examples of such responses among the algae are less common. Those responses which have been reported in this group are generally photoperiodic or require long-term light exposures; most involve macrophytes. This report documents a non-photosynthetic, low threshold, photomorphogenic response in a unicellular alga, the dinoflagellate *Scrippsiella trochoidea*. In contrast to the reported behavior of other dinoflagellate species, resting cysts of *S. trochoidea* require light to germinate. This requirement is satisfied to a large extent by low photon fluences delivered in exposures as short as one second. Green light is most effective in eliciting the response. Given the importance of dinoflagellates as primary producers in many aquatic ecosystems and the potential role of resting cysts in controlling the dynamics of natural dino-

flagellate populations, the present observations are of obvious ecological significance. The primitive phylogenetic standing of dinoflagellates and the relative rarity of green light-mediated photomorphogenic responses in eukaryotes generally suggest that this phenomenon may hold considerable evolutionary and physiological interest as well.

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WHOI Contribution No. 6167.

PHYSIOLOGICAL AND ENVIRONMENTAL CONTROL OF GERMINATION IN Scrippsiella trochoidea (DINOPHYCEAE) CYSTS

Brian J. Binder and Donald M. Anderson

Germination in dinoflagellate resting cysts may be regulated by a number of environmental and physiological factors. In the present study, the effects of aging, temperature, and growth medium on germination in culture-produced resting cysts of the marine dinoflagellate Scrippsiella trochoidea (Stein) Loeblich are addressed. Cysts undergo a mandatory period of dormancy lasting approximately 25 days, during which germination does not occur. The duration of this period is not affected by temperature. Once the dormancy period is completed, germination is regulated by external factors. Cysts germinate optimally in nutrient replete medium at temperatures greater than approximately 14°C. At lower temperatures or in nutrient-depleted media, germination rate is dramatically slowed, although the final germination frequency appears unchanged. The large Q₁₀ of this temperature effect (~11) suggests that the reduction in germination rate at lower temperatures is not merely the reflection of generally reduced metabolic rates, but rather the result of a temperature response specific to germination. At the highest temperatures tested (22-25°C), germination rate remains maximal although vegetative growth is greatly reduced. A shift in temperature or nutrient conditions, per se, is not necessary for germination. The relatively short dormancy period combined with the absence of a requirement for a dramatic shift in environmental conditions could facilitate rapid cycling between resting and vegetative stages in natural S. trochoidea populations. At the same time, the dramatic re-

duction in germination rate at low temperatures would permit cysts of this species to serve as overwintering cells as well.

In press: Journal of Phycology.

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WHOI Contribution No. 6214.

TEMPORARY CYST FORMATION AND WALL REGENERATION IN THE DINOFLAGELLATE Gonyaulax tamarensis

Lawrence Fritz, Donald M. Anderson and Richard E. Triemer

This paper uses ultrastructural observations to describe the process of temporary cyst formation and regeneration to the motile condition in Gonyaulax tamarensis. The process of temporary cyst formation in this organism is a cyclical process not complicated by cell division. A single motile cell will form one temporary cyst which is capable of regenerating only a single motile cell. This cyclical process of cyst formation and motile cell regeneration is easily induced in laboratory populations and is thus a good system for studying wall development in dinoflagellates.

In press: Journal of Phycology.

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WHOI Contribution No. 6246.

NITROGEN AS A LIMITING NUTRIENT: STUDIES IN THE LABORATORY AND RELATIONSHIPS IN THE LABORATORY AND RELATIONSHIPS TO NATURAL ASSEMBLAGES

Patricia M. Glibert

In this chapter the concept of nutrient limitation of marine primary productivity is reviewed. In so doing, the distinction between limitation of phytoplankton biomass and phytoplankton growth rate is emphasized. Different laboratory approaches for studying the physiological response of a phytoplankton species to a limiting factor are evaluated. Finally, the advantages and limitations of the available techniques for assessing the rate of phytoplankton uptake are discussed.

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WHOI Contribution No. 6113.

CLONAL COMPARISONS OF GROWTH AND
PHOTOSYNTHETIC RESPONSES TO NITROGEN
AVAILABILITY IN MARINE Synechococcus SPP.

Patricia M. Glibert, Todd M. Kana,
Robert J. Olson,
David L. Kirchman and Randall S. Alberte

Growth, photosynthesis and fluorescence of the phycoerythrin-containing clones of marine Synechococcus, WH7803 and WH8018, were investigated as a function of nitrogen nutritional status in batch culture. Cultures were grown for ca. 5 divisions prior to exhaustion of the NO_3^- supply, allowed to become nitrogen deficient for 48 h, then resupplied with fresh media. Cell division appeared to become arrested immediately upon nitrogen depletion in Clone WH7803, and growth resumed almost immediately after the 48 h starvation period when nitrogen was resupplied. In sharp contrast, Clone WH8018 showed continued, but slow, cell division during the 48 h period of nitrogen depletion and displayed a lag phase (>24 h) before growth resumed when nitrogen was resupplied. Fluorescence of phycoerythrin and chlorophyll changed only slightly during nitrogen depletion in WH7803, but decreased sharply in WH8018 during this period. In both clones, the photosynthesis vs. irradiance parameters declined proportionately during nitrogen depletion, suggesting independent regulation of growth and photosynthesis.

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Marine Biological Ecology, 101,
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NAGW-460.

WHOI Contribution No. 6182.

NUTRIENT CYCLING IN A MICROFLAGELLATE FOOD
CHAIN: IV. PHYTOPLANKTON-MICROFLAGELLATE
INTERACTIONS

Joel C. Goldman, David A. Caron
and Mark R. Dennett

The phagotrophic microflagellate Paraphysomonas imperforata was capable of grazing with equal efficiency two marine phytoplankton species, the diatom Phaeodactylum tricornutum and the chlorophyte

Dunaliella tertiolecta, that are grossly different in size, shape, and morphology, and which were first grown under different degrees of nitrogen and phosphorus limitation. Growth rates of the microflagellate were maximal and independent of species type or nutritional state, whereas ingestion rates on a cell basis were a function of species type. When considered on the basis of total limiting-nutrient in the prey, the major determinant of ingestion rate was whether N or P was the limiting nutrient. Clearance rates were independent both of prey species and form of limiting nutrient, but were influenced by total prey biomass concentration. Patterns of nutrient limitation appeared to be a function of the physiological state of the prey: lags in NH_4^+ regeneration until the end of exponential growth occurred when the prey were N-limited and phosphorus regeneration was negligible during the entire growth cycle of the microflagellate when the prey were P-limited. There was, however, evidence for dark uptake of NH_4^+ by both species when N-limited, which could have biased the observed lags in nutrient regeneration. Nitrogen regeneration efficiencies during exponential growth varied from 0 to 58% of initial prey nitrogen, depending on the nutritional state of the prey. Phosphorus regeneration efficiencies varied from 0 to 16% under similar P-limiting conditions. After extended periods in the stationary phase, regeneration efficiencies reached as high as 70% for nitrogen and up to 50% for phosphorus. The contribution of microflagellates to nutrient regeneration in pelagic waters is largely a function of the reliability and accuracy of size fractionation results. Because protozoa are able to convert prey nutrients to their own biomass with great efficiency, the microbial loop must include many grazing steps and be highly complex in order for 90+% nutrient regeneration to occur. Similarly, to accommodate rapid and efficient nutrient regeneration with contemporary estimates of new primary production, these two processes must occur on different spatial and temporal scales.

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and OCE85-11283; and WHOI Mellon
Study Award.

WHOI Contribution No. 6339.

EXPONENTIAL GROWTH RATES OF
PHYTOPLANKTON CALCULATED FROM CARBON-14
UPTAKE RATES: A CLARIFICATION

W. K. W. Li and Joel C. Goldman

Phytoplankton growth rates can be estimated from measurements of light-dependent (^{14}C) bicarbonate uptake (photosynthesis) rates using the integrated (logarithmic) form of the exponential growth law. A clarification of this method is presented here in view of confusions in the recent literature.

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WHOI Contribution No. 6194.

PRIMARY PRODUCTION OF PROTEIN: I.
COMPARISON OF NET CELLULAR CARBON AND
PROTEIN SYNTHESIS WITH ^{14}C -DERIVED
RATE ESTIMATES IN STEADY-STATE CULTURES
OF MARINE PHYTOPLANKTON

Steven E. Lohrenz and Craig D. Taylor

Measurements of total inorganic ^{14}C -carbon fixation and ^{14}C -carbon incorporation into protein were compared with calculated net synthesis of total cellular carbon and protein carbon respectively in NH_4^+ -limited continuous cultures of 4 marine phytoplankton species: the marine chlorophyte *Nannochloris atomis*, the diatom *Chaetoceros simplex*, the chrysophyte *Chattonella luteus*, and the cryptomonad *Chroomonas salina*. Net synthesis rates were estimated from dilution rates and steady state concentrations of total cellular carbon and protein in the chemostat cultures. For 3 out of the 4 species, there was good agreement between the increase in total fixed ^{14}C -carbon over 3 h and the calculated net synthesis of newly fixed cellular carbon. Observed increases in fixed ^{14}C -carbon in cultures of *C. salina* exceeded calculated values indicating degradative loss of unlabeled cell material. Extracellular release of fixed ^{14}C -carbon was significant for *C. luteus* as shown by a higher rate of production of acid non-volatile ^{14}C relative to total particulate ^{14}C (i.e. retained on Whatman GF/F glass fiber filter). As a result of incomplete equilibration of protein precursors with the exogenous ^{14}C -labeled inorganic carbon pool, incorporation of ^{14}C -carbon into protein of all species was less than calculated net synthesis of protein carbon for up to 3 h after isotope addition.

Comparisons of net synthesis and incorporation of ^{14}C -carbon into individual protein amino acid residues revealed that precursor sources of protein-bound glycine and alanine rapidly attained isotopic equilibrium with the ^{14}C -labeled inorganic carbon pool for all growth conditions and in all species examined. Precursor equilibration dynamics of protein-bound glutamate and aspartate were generally slower than glycine and alanine. Rates of incorporation of ^{14}C -carbon into protein of *N. atomis* decreased more rapidly in response to interruption of the supply of fresh media to the chemostat culture than did rates of total ^{14}C -carbon fixation. *C. simplex* was also sensitive to interruption of media inflow, as indicated by continuous decreases in ^{14}C -carbon incorporation into protein-bound glycine and alanine. These results emphasize the importance of time-course sampling and keeping incubations as short as possible for measurements of ^{14}C -carbon incorporation into protein. Characteristics of incorporation of ^{14}C -carbon into protein-bound glycine and alanine make them select tracers for measuring protein synthesis in mixed autotrophic populations using short-term incubations. The relative uniformity of the amino acid composition of proteins provides a basis for extrapolating synthesis rates of glycine and alanine to total protein production rates, thereby leading to a determination of the proportion of primary production associated with protein synthesis. This will provide information about the physiological state of phytoplankton populations and their role in influencing the trophodynamic flux and composition of particulate organic matter.

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WHOI Contribution No. 6197.

PRIMARY PRODUCTION OF PROTEIN: II.
ALGAL PROTEIN METABOLISM AND ITS
RELATIONSHIP TO THE COMPOSITION OF
PARTICULATE ORGANIC MATTER IN THE
SURFACE MIXED LAYER OF SALT POND, MA

Steven E. Lohrenz, Craig D. Taylor
and Brian L. Howes

The proportion of primary production allocated to synthesis of particulate protein amino acids (PPAA) was determined in natural microbial populations and compared to simultaneous measurements of the proportion of particulate organic carbon (POC) associated with PPAA. This approach was used to ascertain whether the protein

content of the particulate organic matter pool reflects the metabolism of the sampled autotrophic population. Water column sampling was conducted in the epilimnion of a marine pond throughout the summer of 1983. Depth profiles of conventional specific gravity indicated a mixed layer depth of between 1 and 3 meters and profiles of chlorophyll *a* and total pigments were relatively uniform throughout the upper mixed layer. In situ time course productivity measurements at 1 m demonstrated close correspondence between rates of increase in non-volatile ^{14}C in acidified samples and ^{14}C retained on glass fiber filters, indicating no significant accumulation of ^{14}C -labeled dissolved organic carbon. Consecutive morning and midday production measurements revealed no consistent trends in rates with time of day. Significant correlations were found between the diffuse attenuation coefficient and the natural logarithm of assimilation number, and between the rate of primary production and ammonium and nitrate concentrations. These correlations suggest light and nitrogen limitation influenced phytoplankton population metabolism. A bloom dominated by the brown flagellate *Olisthodiscus magnus* Hulburt occurred in late August. Before and after the *O. magnus* bloom, the POC pool and the POC pool/POC production ratio were relatively constant, suggesting a close coupling between POC synthesis and removal. PPAA synthesis and the PPAA carbon pool accounted for similar proportions of primary production and the POC pool respectively (5 to 15%), supporting the view that algal biosynthesis significantly influenced the composition of particulate organic matter, and that processes removing PPAA and POC were non-selective. During the bloom, POC production and removal became uncoupled as inferred from a large increase in the POC ratio. As the bloom population declined, the proportion of primary production allocated to PPAA synthesis was higher than the PPAA fraction of the POC pool, indicating that the protein content of particulate organic matter did not reflect the biosynthetic characteristics of the sampled autotrophic population. The lack of agreement was explained by either differential changes in synthesis of PPAA and POC resulting from mixing across the vertical light gradient, or increased senescence of the bloom population whose composition may have differed from that of active algal species better adapted to low light and nutrient levels. Selective losses of PPAA from the POC pool may have also contributed to the observed differences.

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WHOI Contribution No. 6378.

PLANKTON ECOLOGY

GRAZING OF ATTACHED BACTERIA BY HETEROTROPHIC MICROFLAGELLATES

David A. Caron

Four species of heterotrophic microflagellates were examined for their ability to graze attached and unattached bacteria. The species tested displayed pronounced differences in their ability to graze the bacterium *Pseudomonas halodurans* attached to chitin particles. Two species of microflagellates (*Monas* sp. and *Cryptobia* sp.) efficiently grazed unattached bacteria but showed little or no ability to graze attached or aggregated cells. In contrast, *Rhynchomonas nasuta* and *Bodo* sp. showed marked preferences for attached and aggregated bacteria and a limited ability to graze unattached cells. The density of attached bacteria was reduced by an order of magnitude due to grazing by *Bodo* and *R. nasuta*, even though the density of unattached bacteria was ~5 to 90X the density of attached cells. The maximum densities attained by microflagellates in the cultures were related to the density of unattached bacteria for *Monas* and *Cryptobia* but not for *Bodo* and *R. nasuta*. Growth of the latter two species appeared to be related to the density of attached or aggregated bacteria. Based on the results of these experiments, it is concluded that the pelagic existence of microflagellates which graze attached bacteria may be strongly linked to the distribution of suspended particles and their associated bacteria. In addition, the removal of attached bacteria by microflagellates can significantly affect the density of bacteria attached to particles in the plankton. This activity may have important implications for the controversy concerning the relative importance of attached and free-living bacteria in the plankton.

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WHOI Contribution No. 6380.

ENRICHMENT OF MICROBIAL POPULATIONS IN
MACROAGGREGATES (MARINE SNOW) FROM
SURFACE WATERS OF THE NORTH ATLANTIC

David A. Caron, Paul G. Davis,
Laurence P. Madin and John McN. Sieburth

Marine snow particles (macroscopic detrital aggregates) were collected from surface waters throughout the western North Atlantic. Counts of phototrophic and heterotrophic picoplankton, phototrophic and heterotrophic nanoplankton, and phototrophic microplankton were made by epifluorescence microscopy. A Most Probable Number culture technique also was used to estimate the density of bacterivorous protozoa. All microbial populations enumerated were highly enriched on macroaggregates relative to their densities in the surrounding water. The degree of enrichment was greater in open ocean environments because microorganisms in the surrounding water were less abundant in the open ocean than in nearshore waters, and also because microbial density on marine snow was greater in the open ocean than in nearshore environments. Material released by ctenophores and appendicularia is a likely source of marine snow since it supported microbial populations of the same order of magnitude as were observed on SCUBA-collected particles. Heterotrophic nanoflagellates dominated the bacterivorous protozoa cultured from macroaggregates and the surrounding water, but dense populations of ciliates and amoebae also were present on particles. Protozoan populations on marine snow were so dense relative to the surrounding water as to suggest that detrital aggregates are responsible for the planktonic existence of some bacterivorous species.

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WHOI Contribution No. 6243.

EFFECTS OF TEMPERATURE AND SALINITY
ON THE GROWTH AND SURVIVAL OF THE
PLANKTONIC FORAMINIFER
Globigerinoides sacculifer

David A. Caron, Walter W. Faber
and Allan W. H. Be

Temperature and salinity are believed to be major factors influencing the geographical distributions of planktonic foraminifera. While there are ample data

to support the hypothesis that these physical parameters establish the overall ranges of these planktonic protists, there is virtually no information on how temperature and salinity affect the growth, reproduction and lifespan of individuals which occur within these geographical limits. SCUBA-collected specimens of the spinose planktonic foraminifer Globigerinoides sacculifer (Brady) were cultured in the laboratory at four temperatures (19.5-28°C) and six salinities (34.25-38.25‰) which span the range of these two variables at which G. sacculifer occurs commonly in the ocean. The effect of these two variables was apparent in the average final shell length of the specimens, and in the percentage of specimens forming sac-like chambers and kummerform (diminutive) chambers. In addition, pore diameter and shell porosity were greater at warmer temperatures. In contrast to their effects on shell size and morphology, however, temperature and salinity had virtually no effect on the percentage of organisms which underwent gametogenesis, the chamber formation rate or the estimated lifespan of the species. Growth parameters of G. sacculifer were less affected by temperature and salinity in the present study than by the frequency of feeding or the light intensity which were examined in previous studies. We conclude that, while the geographical distribution of G. sacculifer may be ultimately controlled by temperature and salinity, the effects of these physical parameters on life processes of this species are small relative to the effects of light and feeding frequency.

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United Kingdom.

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WHOI Contribution No. 6381.

GROWTH OF THE SPINOSE PLANKTONIC
FORAMINIFER Orbulina universa IN
LABORATORY CULTURE AND THE EFFECT OF
TEMPERATURE ON LIFE PROCESSES

David A. Caron, Walter W. Faber, Jr.
and Allan W. H. Be

SCUBA-collected specimens of the planktonic foraminifer Orbulina universa d'Orbigny were reared in the laboratory in order to examine the rate of increase in shell size, reproductive potential, shell morphology and lifespan of this species. Specimens were cultured at four temperatures (19.5, 22, 25, 28°C) that span the

range at which this species is abundant in the ocean, and using two feeding frequencies for one of the temperatures (28°C). Changes in the predicted lifespans of *O. universa* (9 to 16 days), the rate of chamber formation (0.54-0.78 chambers day⁻¹), average final shell length (594-669 µm) and the frequency of a second spherical chamber (4.5-22%) were significantly affected by culture temperature in this study. Longevity of the trochospiral (juvenile) stage of the foraminifer was affected more by temperature than was the longevity of the spherical (adult) stage. In contrast, temperature had no discernable effect on the percentage of foraminifera reaching the spherical stage, the frequency of gametogenesis, or on the total number of chambers formed in culture. The frequency of feeding of specimens cultured at 28° C affected the rate of chamber formation as well as the frequency of gametogenesis of these specimens. We conclude that, within the normal distributional range of this species, temperature has relatively little effect on survival and reproductive potential while feeding frequency may significantly affect reproductive potential. The main effect of temperature on *O. universa* in this study was a reduction in sphere diameter and an increase in the percentage of organisms forming a second sphere at suboptimal temperatures.

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WHOI Contribution No. 6382.

DYNAMICS OF PROTISTAN CARBON AND NUTRIENT CYCLING

David A. Caron and Joel C. Goldman

In the last decade there has been a marked increase in the number of studies on the flow of organic material and major nutrients through the microbial assemblages of aquatic ecosystems. From these studies it has been concluded that small (<5 µm) prokaryotic and eukaryotic microorganisms are a major component of these communities. Chroococcoid cyanobacteria and small eukaryotic algae, for example, are responsible for a major fraction of the primary production in these systems, and up to 10 to 50% of the energy fixed by these microbes passes through the bacterial assemblage. There is now a growing consensus that organisms which consume these small autotrophic and heter-

otrophic microorganisms are major effectors of energy and nutrient flow in aquatic environments.

Prominently figured in this reevaluation of aquatic food webs is the role of phagotrophic protists as the major consumers of bacteria, cyanobacteria and minute eukaryotic algae. Consequently, there is an increasing need to understand the processes by which these protists incorporate and remineralize organic carbon and essential nutrients (nitrogen and phosphorus) contained in ingested prey. Understanding the factors affecting the assimilation and remineralization of these materials, and the relationship between carbon and nutrient cycles within the protistan trophic link, is essential for modelling energy and nutrient flow in microplankton communities.

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WHOI Contribution No. 6383.

NUTRIENT REGENERATION BY MARINE PROTOZOA

David A. Caron and Joel C. Goldman

A clear recognition of the role which protozoa play as nutrient regenerators in aquatic ecosystems has been hampered in the past by an inability of researchers to resolve the relative contributions of protozoa and bacteria to this process in both laboratory microcosm and field studies involving natural assemblages of marine organisms. We have summarized the available data concerning nutrient regeneration by aquatic protozoa in order to evaluate their importance as mineralizers of nitrogen and phosphorus. Based on the results of recent laboratory studies with cultured protozoa, we conclude that weight-specific regeneration rates of protozoa are indeed higher than the rates reported for most zooplankton and benthic metazoa. Small protozoa may be particularly important as remineralizers because weight-specific regeneration rates are inversely related to protozoan cell volume. However, this negative relationship apparently is due to higher weight-specific metabolic rates of small protozoa and not to low gross growth efficiency as previously has been assumed. Reevaluation of the role of bacteria in nutrient cycles of aquatic ecosystems indicates that bacteria are often "sinks" and not sources of regenerated nutrients in these environments. A model is proposed which resolves much of the controversy concerning the relative importance

of bacteria and protozoa as nutrient regenerators in detrital food chains. We conclude that protozoa play a pivotal role in the regeneration of inorganic nitrogen and phosphorus in marine ecosystems.

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WHOI Contribution No. 6114.

EFFECT OF TEMPERATURE ON GROWTH,
RESPIRATION, AND NUTRIENT REGENERATION
BY AN OMNIVOROUS MICROFLAGELLATE

David A. Caron, Joel C. Goldman
and Mark R. Dennett

The effect of temperature on the rates and extent of carbon and nitrogen cycling by the heterotrophic microflagellate *Paraphysomonas imperforata* (diameter, 7 to 12 μ m) fed with the diatom *Phaeodactylum tricornutum* was investigated over an ecologically pertinent temperature range (14 to 26°C). All physiological rates investigated increased with increasing temperature. Q_{10} values were similar for all rate changes and were comparable to those which have been reported for other protozoa. In contrast to all rates, microflagellate gross growth efficiency and cell volume were unaffected by temperature. Decreases in the concentration of particulate carbon and particulate nitrogen from grazed diatom cultures also were similar when summed over the entire growth phase of the microflagellate population. Therefore, the proportions of ingested carbon and nitrogen which were incorporated or remineralized by the microflagellate were independent of temperature between 14 and 26°C. At temperatures above 18°C, growth rates of *P. imperforata* were greater than the maximum growth rates reported for most phytoplankton. We conclude that the impact of *P. imperforata* on natural phytoplankton communities is not controlled by temperature above 18°C but may be affected by the rate at which zooplankton or microzooplankton prey on the microflagellate, as well as the inability of the microflagellate to graze efficiently when phytoplankton are present at low cell densities.

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EXPERIMENTAL DEMONSTRATION OF THE ROLES
OF BACTERIA AND BACTERIVOROUS PROTOZOA
IN PLANKTON NUTRIENT CYCLES

David A. Caron, Joel C. Goldman
and Mark R. Dennett

We have used a model food chain composed of a natural bacterial assemblage, a pennate diatom and a bacterivorous microflagellate to investigate the factors controlling the relative importance of bacteria and protozoa as sources for regenerated nitrogen in plankton communities. In bacterized diatom cultures in which diatom growth was nitrogen-limited, the carbon:nitrogen (C:N) ratio of the bacterial substrate greatly affected which population was responsible for the uptake of nitrogen. When nitrogen was added as NH_4^+ and the cultures were supplemented with glucose, the bacteria competed successfully with the algae for NH_4^+ and prevented the growth of algae by rapidly assimilating all NH_4^+ in the cultures. Bacterivorous protozoa inoculated into these cultures grazed the bacterial population and remineralized NH_4^+ , thus relieving nitrogen limitation of algal growth and allowing an increase in algal biomass. In contrast, bacteria in cultures supplemented with the amino acid glycine (C:N = 2) were major remineralizers of nitrogen, and the influence of protozoan grazing was minimal. We conclude that the relative importance of bacteria and protozoa as nutrient regenerators in the detrital food loop is dependent largely on the overall carbon:nutrient ratio of the bacterial substrate. The role of bacterivorous protozoa as remineralizers of a growth-limiting nutrient is maximal in situations where the carbon:nitrogen ratio of the bacterial substrate is high.

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WHOI Contribution No. 6384.

PROTOZOAN RESPIRATION AND METABOLISM

David A. Caron, Joel C. Goldman
and Tom Fenchel

Protozoan respiration represents the sum of the dissimilatory processes which take place during metabolism in order to meet the energy demands of motility, food capture/absorption, osmotic regulation, growth, reproduction, etc. In most protozoa these processes take place aerobically and the respiration rate can be measured conveniently as O_2 uptake or CO_2 generation. In the former case, carbon utilization can be estimated from the rate of oxygen utilization via the respiratory quotient (RQ).

All major eukaryote metabolic pathways of energy generation have been demonstrated in the protozoa. Indeed, all enzymes of the glycolytic and Krebs cycle are present, and oxidative phosphorylation is carried out as effectively in these unicellular organisms as in mammalian mitochondria (Danforth, 1967; Hill, 1972; Wichterman, 1986). These enzymatic pathways are present in species from all major protozoan taxa and, therefore, the degree to which specific pathways function in particular species appears to be more related to ecological strategy than phylogeny.

From an energetics point of view, respiration represents that portion of the energy contained in the ingested food which is not assimilated, egested or excreted. Assuming that the latter two quantities are small (which may not always hold true), respiration can be expressed as the fraction of the ingested food which is not incorporated into biomass, or

$$R = I \times (1 - GGE) \quad (1)$$

where R is the amount of carbon respired, I is the amount of carbon ingested and GGE is the gross growth efficiency of the protozoan (fraction of prey carbon converted to protozoan carbon). The gross growth efficiencies which have been reported for protozoa are relatively high, and values of 40 to 60% appear to be typical. Based on these efficiencies, it is clear that protozoa transform a substantial portion of the carbon contained in their food into protozoan biomass, thus placing an upper limit on the amount of organic carbon that will be respired.

From an ecological perspective, it has been recognized that protozoan respiration in aquatic environments may constitute an important portion of the total system respiration. The bases for this realization are much the same as those outlined in the previous chapter on nutrient regeneration. Through the use of improved count-

ing techniques it has been shown that the densities of protozoa in the ocean are greater than previously believed (Davis et al., 1978; Dale and Burkill, 1982; Davis and Sieburth, 1982; Haas, 1982; Caron, 1983; Sherr and Sherr, 1983; Davis et al., 1985; Gifford, 1985; Sherr et al., 1986). Also, protozoa are now considered to be the primary consumers of bacterioplankton (Haas and Webb, 1979; Fenchel, 1982d; Linley et al., 1983; Sherr et al., 1984; Sieburth, 1984; Andersen and Fenchel, 1985) and of chroococcoid cyanobacteria (Johnson et al., 1982; Iturriaga and Mitchell, 1986), and they may be important consumers of phytoplankton (Heinbokel, 1978; Heinbokel and Beers, 1979; Capriulo, 1982; Azam et al., 1983; Goldman and Caron, 1985; Suttle et al., 1986; Parslow et al., 1986). Finally, the weight-specific metabolic rates of protozoa generally are greater than those of larger zooplankton. Therefore, given equivalent amounts of growing protozoan and zooplankton biomass, more carbon typically will be processed (respired or incorporated) by the protozoa.

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WHOI Contribution No. 6385.

12-KHZ NONMIGRATORY DEEP SCATTERING LAYERS OF SARGASSO SEA ORIGIN IN WARM-CORE RINGS

Maureen H. Conte, James K. B. Bishop
and Richard H. Backus

Nonmigratory deep 12-kHz sound scattering layers (NMDSLs) were entrained with Sargasso Sea/Gulf Stream waters during the formation of warm-core rings 82B and 82H. Ring water was easily distinguished from Slope Water at night by the presence of these strong NMDSLs between 200 and 550 meters. The distribution of NMDSLs in 82H as a function of temperature and salinity matched Sargasso Sea distributions, indicating that Sargasso Sea water was present in the center of 82H at the time of its formation. However, the distribution of NMDSLs in the center of 82B in April was more consistent with Gulf Stream/Sargasso Sea edge water, indicating that Sargasso Sea water was not present in the center of 82B at the time of its formation.

NMDSLs were a persistent feature of the lower thermocline and upper thermocline of 82B. The distribution of NMDSLs in the upper thermocline approximately paralleled the decrease in the depth of the thermocline and became shallower with increasing

distances from ring center. NMDSLs disappeared at the ring edge when the base of the thermocline became shallower than about 100 meters. Between April and June, the distribution of the NMDSLs within 30 km of ring center changed very little, whereas the NMDSLs in the thermocline of greater distances from ring center showed greater dispersion with respect to temperature. NMDSL distribution following several Gulf Stream interactions in July was significantly shallower and colder. The continued presence of the lower NMDSLs in the thermocline, even though it was nearly 100 meters shallower, indicates that the remaining thermocline was not significantly exchanged with Gulf Stream or Slope Waters during the interactions. The changes in NMDSL temperature distribution found in August suggest that core waters (<30 km from ring center in June) were resorbed by the Gulf Stream and that only waters of >30 km radius remained to reform the ring.

We found no evidence that the animals comprising the NMDSLs adjusted their vertical distributions in response to environmental parameters; rather, the temporal changes we observed are best explained by physical processes which affected ring structure. No qualitative decrease in NMDSL intensity was observed in 82B between April and August, suggesting that these animals can tolerate a significant decrease in depth and T,S properties.

The gonostomatid Cyclothone braueri and/or the physonect siphonophores are suggested as possible sources of the NMDSLs.

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WHOI Contribution No. 6251.

OCEANIC DIMETHYLSULFIDE: PRODUCTION DURING ZOOPLANKTON GRAZING ON PHYTOPLANKTON

John W. H. Dacey and Stuart G. Wakeham

About half of the biogenic sulfur flux to the earth's atmosphere each year arises from the oceans. Dimethylsulfide, which constitutes about 90% of this marine sulfur flux, is presumed to originate from the decomposition of dimethylsulfonio-propionate produced by marine organisms, particularly phytoplankton. The rate of DMS released by phytoplankton is greatly increased when the phytoplankton are subjected to grazing by zooplankton. DMS production associated with such grazing may be the major mechanism of DMS production in many marine settings.

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ARE MARINE PLANKTONIC CILIATES SUSPENSION-FEEDERS?

Diane K. Stoecker

Many marine planktonic ciliates (primarily tintinnids and oligotrichs) feed on relatively large particles, distinguish among particles based on criteria other than size, and can dramatically increase their clearance rates at low food concentrations. Thus, the feeding behavior of many planktonic ciliates is not adequately described by a simple suspension-feeding model. Experimental methodologies which rely on the assumption that ciliates only distinguish among particles based on size, or on the assumption that clearance rate is independent of particle concentration, may be incapable of accurately measuring grazing rates of planktonic ciliates. The grazing strategies of planktonic ciliates appear to be different from those of other zooplankters and may make ciliate-microbial interactions unique.

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WHOI Contribution No. 6234.

PREDATION BY Acartia tonsa DANA ON PLANKTONIC CILIATES AND ROTIFERS

Diane K. Stoecker and David A. Egloff

The calanoid copepod, Acartia tonsa, has higher clearance for planktonic ciliates and rotifers than for phytoplankton. Adult copepods have a maximum clearing rate of about 200 ml copepod⁻¹d⁻¹ for large ciliates, with lower clearing rates for smaller ciliates. Nauplii have higher clearance for small than for larger ciliates. Addition of ciliates or rotifers to the diet of A. tonsa enhances egg production; this effect is due to improved food quality. These data demonstrate that microzooplankton can be an important component of the diet of A. tonsa when phytoplankton are plentiful. Selective predation by copepods on ciliates and rotifers is expected to influence the dynamics of microzooplankton assemblages.

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A LARGE PERCENTAGE OF MARINE PLANKTONIC
CILIATES CONTAIN FUNCTIONAL CHLOROPLASTS

Diane K. Stoecker, Ann E. Michaels
and Linda H. Davis

Planktonic ciliates, primarily tintinnids and oligotrichs, are an important component of the microplankton in marine coastal waters. Their role as grazers of phytoplankton and bacteria has been recognized, but their role as chloroplast-bearing cells has not been widely appreciated. In surface waters during the spring and summer, approximately 42% of the planktonic ciliates have chloroplasts. The chloroplasts are functional in photosynthesis. During the autumn and winter, chloroplast-bearing species are less abundant, but still comprise at least 10% of the combined tintinnid and oligotrich fauna. The trophic position of ciliates in planktonic food webs needs to be reconsidered.

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WHOI Contribution No. 6285.

GRAZING BY THE JELLYFISH,
Aurelia aurita, ON MICROZOOPLANKTON

Diane K. Stoecker, Ann E. Michaels
and Linda H. Davis

The medusa of the scyphozoan, Aurelia aurita, is a seasonally important predator of copepods and fish larvae in coastal waters but little is known about its grazing on microplankton. Medusae preferentially remove large ($> 50 \mu\text{m}$) oligotrichs and copepod nauplii from natural microplankton assemblages. Clearance rates for phytoplankton, tintinnids, rotifers, and polychaete larvae are usually low. In feeding experiments in which mixtures of cultured prey were used, medusae selected small non-loricate ciliates over similar-sized algae, non-loricate ciliates over tintinnids, and large non-loricate ciliates over smaller ones. Observations of feeding medusae confirmed that post-capture selection of particles is important during microphagous feeding.

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WHOI Contribution No. 6308.

ALGAL CHLOROPLASTS ARE FUNCTIONAL
IN THE MARINE PLANKTONIC CILIATE,
Laboea strobila

Diane K. Stoecker and Mary W. Silver

The planktonic ciliate, Laboea strobila, contains chloroplasts derived from ingested algae. These chloroplasts are functional in the ciliate and have assimilation efficiencies equivalent to those of chloroplasts in phytoplankton. At saturating irradiance, the amount of carbon fixed h^{-1} equals 12.6% of the body carbon of the ciliate. In the absence of food, the survival of L. strobila is significantly higher in the light than in the dark. Because of mixotrophy, planktonic ciliates which sequester chloroplasts may be particularly efficient producers of animal biomass in the sea.

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WHOI Contribution No. 6367.

FEEDING BY LARVAL AND POST-LARVAL
CTENOPHORES ON MICROZOOPLANKTON

Diane K. Stoecker, Peter G. Verity,
Ann E. Michaels and Linda H. Davis

Feeding by the coastal ctenophore, Mnemiopsis leidyi, on microplankton was investigated. Larval ctenophores (tentaculate stage) grew best and had the highest survival rates when offered a mixture of ciliates and copepod nauplii. Larvae did not survive when offered phytoplankton alone. Clearing of planktonic ciliates by post-larval ctenophores was a function of the ciliate species and the size of the predator. Removal of small ciliates ($< 20 \mu\text{m}$ in size) and phytoplankton were negligible. Small post-larval ctenophores (volume $< 4 \text{ cm}^3$) had higher biovolume-specific clearing rates ($0.5\text{--}1.5 \text{ l/cm}^3/\text{d}$) than did larger ctenophores fed the same ciliate species. During in situ incubations, adult M. leidyi removed ciliates, rotifers, and copepod nauplii from natural microplankton assemblages. The data indicate that non-crustacean microzooplankton are an important component of the diet of larval and post-larval lobate ctenophores, particularly when copepod standing stocks are low.

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WHOI Contribution No. 6233.

THE DEMOGRAPHIC AND EVOLUTIONARY
CONSEQUENCES OF PLANKTONIC DEVELOPMENT

Hal Caswell

Over half of all marine invertebrate species have incorporated a planktonic larval stage into an otherwise benthic life cycle (Thorson 1950). The biogeographic implications of this life history pattern are profound (e.g. Scheltema 1978, Jablonski and Lutz 1983). Species with long planktonic larval stages tend to have greater geographical ranges and longer geological durations than those with restricted larval duration (see, e.g., Scheltema 1978 and Jablonski 1982 for data on gastropods). The relation of dispersal and gene flow also has important implications for patterns of local adaptation and speciation (Scheltema 1978). Hansen (1983), for example, finds that tropical neogastropods with non-planktrophic development have exhibited greater speciation rates than those with planktotrophic development, presumably because the greater dispersal abilities of the latter make geographical isolation more difficult.

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WHOI Contribution No. 6091.

MATRIX MODELS AND THE ANALYSIS
OF COMPLEX PLANT LIFE

Hal Caswell

The life cycle is the fundamental unit of demographic analysis. Evaluating the demographic consequences of the vital rates (a general term subsuming rates of growth, survival, development, reproduction, and so on) requires an analytical framework that can include the entire life cycle. Evaluating the evolutionary consequences of changes in the vital rates requires a relation between the vital rates and a measure of fitness and perturbation analysis which reveals the effects on fitness of possible modifications of the rates. Fitness, being a measure of the relative rate of incorporation of genotypes into future generations, is itself a fundamentally demographic idea. Demographic and evolutionary considerations thus converge upon the need for a description of the life cycle from which analyt-

ical conclusions can be drawn.

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WHOI Contribution No. 6202

LIFE HISTORY SHIFTS IN THE ATLANTIC
SALMON (*Salmo salar* L.): GROWTH,
POPULATION STRUCTURE, AND
REPRODUCTIVE STRATEGY

Hal Caswell, W. Linn Montgomery
and Robert J. Naiman

Between 1967 and 1982, the Atlantic salmon population of the Matamek River, Quebec, exhibited a dramatic set of life history shifts. During this time, parr body size increased, the parr sex ratio became more dominated by males, and the incidence of male precocious sexual maturation increased dramatically. Precocity was more frequent at upstream sites and was positively related to body size. The age of emigrating smolts declined, but the survival at sea of the younger smolts declined. Among adults, the proportion spawning as grilse increased, due to an increase in the proportion of grilse spawning as females. We suspect, though we cannot prove conclusively, that these changes are the result of selection due to the intense high-seas fishery on adult salmon.

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WHOI Contribution No. 6373.

SAMPLE SIZE AND SENSITIVITY IN THE
DETECTION OF COMMUNITY IMPACT

Hal Caswell and James R. Weinberg

Power is a measure of the sensitivity of a statistical test. Considerations of power are, or should be, a primary concern in designing monitoring programs. Increasing the number of samples increases power, but at an obvious increase in the cost of collecting and processing those samples. Here we consider the effects of community structure (specifically species diversity and density) on the power of

simple two-sample tests to detect changes in several indices of community structure. Our results show that tests based on community-level diversity indices have higher power than those based on the abundance of single indicator species, especially if those species are rare. Different indices respond differently to changes in the overall species pool and the density of the community. Our approach could be used to derive quantitative estimates of sample size necessary to obtain given levels of power using only very coarse resolution biological data.

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WHOI Contribution No. 6260.

A STAGE-BASED POPULATION MODEL FOR LOGGERHEAD SEA TURTLES AND IMPLICATIONS FOR CONSERVATION

Deborah T. Crouse, Larry B. Crowder
and Hal Caswell

Management of many species is currently based on an inadequate understanding of their population dynamics. Lack of age-specific demographic information, particularly for long-lived iteroparous species, has impeded development of useful models. We use a Lefkovich stage-class matrix model, based on a preliminary life table developed by Frazer (1983a), to point to interim management measures and to identify those data most critical to refining our knowledge about the population dynamics of threatened loggerhead sea turtles (*Caretta caretta*). Population projections are used to examine the sensitivity of Frazer's life table to variations in parameter estimates as well as the likely response of the population to various management alternatives. Current management practices appear to be focused on the least responsive life-stage, eggs on nesting beaches. Alternative protection efforts for juvenile loggerheads, such as using turtle excluder devices (TED's), may be far more effective.

In press: Ecology.

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WHOI Contribution No. 6386.

ELASTICITY AS A MEASURE OF THE RELATIVE CONTRIBUTION TO POPULATION GROWTH RATE IN MATRIX MODELS

Hans de Kroon, Anton Plaisier,
Jan van Groenendaal and Hal Caswell

In their study of the population dynamics of three closely related species of *Ranunculus*, using a stage-classified matrix projection model, Sarukhan & Gadgil (1974) tried to measure the extent to which the species are dependent on sexual as opposed to vegetative reproduction. They argued that this could be quantified by multiplying each mode of reproduction in the projection matrix (one at a time) by a certain factor and comparing the resulting shifts in population growth rate (λ). To make the results comparable for different species, the growth rates were normalized to unity. Hence, a proportional change in λ resulting from a proportional change in each of the reproductive pathways was used to establish their impact on the growth rate of the population.

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1986.

Supported by: NSF Grant BSR82-14583
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WHOI Contribution No. 6105.

THE LIFE TABLE CONSEQUENCES OF LARVAL DEVELOPMENT MODE: AN INTRASPECIFIC COMPARISON OF PLANKTOTROPHY AND LECITHOTROPHY

Lisa A. Levin, Kathy D. DePatra,
Elizabeth L. Creed and Hal Caswell

This paper examines the demographic consequences of planktotrophic and lecithotrophic development in a poecilogonous polychaete. Two strains of *Streblospio benedicti* (Spionidae) were reared in the laboratory from birth through death at 20°C, 34 o/oo. Survivorship and reproductive data were collected weekly and were used to construct life tables and population projection matrices for each development mode. Planktotrophic females reproduced earlier, and had higher fecundity and a shorter generation time than lecithotrophic females, but also exhibited higher mortality early in life. Despite the opportunistic nature of the planktotrophic life history traits, the finite rate of increase (λ) in the lecithotrophic strain (1.319/wk) exceeded that of the planktotrophic strain (1.205/wk). Net reproductive rate (R_0) was also higher

for the lecithotrophs (93.4) than for the planktotrophs (17.6). Peak reproductive values were attained earlier in planktotrophs than in lecithotrophs. Sensitivity analyses indicate that λ is most sensitive to changes in larval and juvenile survivorship. The potential population growth rates obtained in this study agree well with those estimated for other opportunistic polychaete species such as *Capitella* sp. I and *Polydora ligni*. Under uniform conditions the two strains of *S. benedicti* achieved similar growth rates with very different life history traits. We hypothesize that each combination of traits may be adaptive under different circumstances in the field. Dispersal characteristics were not examined in this study, but probably play a key role in defining the conditions under which each reproductive strain is most successful.

Supported by: NSF Grants OCE84-00123 and BSR82-14583; and NOAA Grant NA83AA-D-00058.

WHOI Contribution No. 6273.

Z O O P L A N K T O N

PARTICULATE MATTER DISTRIBUTIONS, CHEMISTRY AND FLUX IN THE PANAMA BASIN: RESPONSE TO ENVIRONMENTAL FORCING

James K. B. Bishop, Jeanne C. Stepien
and Peter H. Wiebe

Multidisciplinary studies of the particle cycle were carried out during two cruises in July-August and November-December 1979 at 5°N 82°W in the Panama Basin as part of the Sediment Trap Intercomparison Experiment (STIE) and Composition, Flux and Transfer Experiments (C-FATE). Measurements included: primary production; new production; hydrography; nutrient distributions; 12-kHz echo sounding; macrozooplankton biomass and group abundances; microzooplankton group abundances; vertical distributions, chemistry, and morphology of suspended and sinking particulate matter; and vertical particulate matter fluxes.

Comparisons were made among particle fluxes determined by several means. Size distributions of fecal matter and fecal pellets determined on samples from the Large Volume in-situ Filtration System (LVFS) were used in settling models to calculate vertical particle fluxes. These results were compared with fluxes estimated from measurements of new production,

with fluxes determined by short-term deployments of sediment traps in the upper 300 m, and with fluxes recorded by moored time-series traps at 1268 m.

Previous C-FATE results had shown that the rates of primary production and new production are determined by the physical and chemical environment of the euphotic zone at this location. Results presented here indicate that new production and particle flux are in balance in the euphotic zone on the time scale of days. The data also demonstrate that particulate matter distributions, chemistry and fluxes in the water column extending from the euphotic zone to 1000 m are closely related to rates of primary production and new production in the euphotic zone. Finally, the data show that the vertical particle flux gradient in the upper 1000 m is determined by the instantaneous distributions, feeding activities, and migratory behavior of zooplankton and fish present in the water column.

In press: Progress in Oceanography.

Supported by: ONR Contract N00014-80-C-0098; NSF Grants OCE80-17468, OCE85-13420 and OCE85-08350; and Lamont Doherty Geological Observatory.

WHOI Contribution No. 6296.

BIOMASS OF THE MICRONEKTON IN GULF STREAM RING 82-B AND ENVIRONS: CHANGES WITH TIME

Steven H. Boyd, Peter H. Wiebe,
Richard H. Backus, James E. Craddock
and Mary Ann Daher

Micronekton biomass was sampled in warm-core Gulf Stream ring 82-B (at ages 2, 4 and 6 months), the Slope Water, the Gulf Stream and the Sargasso Sea during three multi-ship cruises. There was no significant diel difference in the 0-1000 m integrated biomass for fishes or invertebrate micronekton in 24 paired day/night tows and no evidence for diel vertical migration across the 1000 m level. Biomass showed a consistent upward shift at night. Although it varied with hydrographic regime and sampling date, median biomass depth shift for invertebrates averaged 184 m and 137 m for fishes. For total micronekton, median biomass depth ranged from 550-750 m by day and 300-600 m by night. Fish biomass was always centered deeper than 250 m, while the center of invertebrate biomass rose above that level in only one of 12 night tows.

In April, ring core biomass for fishes

and invertebrates (2.2 and 11.9 cc/m² respectively) was significantly lower than that for the high velocity region (3.6 and 19.8 cc/m²) or that for the Slope Water (4.7 and 20.8 cc/m²). By June, ring-core standing stocks had doubled while high-velocity region had been reduced to half of the April levels. No significant changes in Slope Water biomass occurred over the April-August period. Fluctuations in ring core micronekton biomass were probably due to both in situ processes and advective exchange.

On the average, invertebrate biomass was about 4 times that of fish biomass. Total micronekton was 20 to 30% of the macrozooplankton biomass in April and June, and 7 to 16% in August. Vertically, the invertebrate fraction overlapped the macrozooplankton more than did the fish fraction. Greater overlap of micronekton and macrozooplankton occurred at night.

In press: Deep Sea Research.

Supported by: NSF Grants OCE80-17248,
OCE85-08350 and OCE80-17270.

WHOI Contribution No. 6258.

INTRODUCTION TO A COLLECTION OF PAPERS ON WARM-CORE RINGS

Peter H. Wiebe and Trevor J. McDougall

A joint meeting of Japanese, Australian and United States scientists was held in Tokyo, Japan from 20 to 24 May 1985 to discuss and compare the characteristics of warm-core rings and fronts that occur in oceanic waters offshore of each of the respective countries. Among the topics discussed were: (1) the fundamental processes of formation and decay of warm-core rings; (2) the interaction of rings with the parent current system, the host water mass, and adjacent continental shelf waters; (3) similarities and differences between warm and cold-core rings in the respective regions; (4) sampling design and techniques and data processing strategies; and (5) oceanographic processes best studied in rings, but which occur throughout the world's oceans.

The papers in this volume reflect the very significant progress made in our understanding of the structure and dynamics of these most energetic of meso-scale eddies. The Tokyo workshop ended with an in-depth discussion of the problems that remained unresolved. The majority require new field studies in geographical areas largely unsampled and in times of the year (e.g., winter) when major alterations to ring structure occur,

but few observations have been made.

In press: Deep-Sea Research.

Supported by: NSF Grants INT84-15111
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WHOI Contribution No. 6322.

DEPARTMENT OF CHEMISTRY

Robert B. Gagosian, Department Chairman

CHEMISTRY

COASTAL RESEARCH
CENTER

NO. 2 FUEL OIL COMPOUND RETENTION AND
RELEASE BY *MYTILUS EDULIS*: 1983 CAPE COD
CANAL OIL SPILL

John W. Farrington, Jia Xiaoping,
C. Hovey Clifford, Bruce W. Tripp,
Joaquim B. Livramento, Alan C. Davis,
Nelson M. Frew and Carl G. Johnson

SCOPE: OPPORTUNITIES FOR INTERNATIONAL
STUDY OF GLOBAL ENVIRONMENTAL ISSUES

Ruth S. DeFries, John W. Farrington
and Edith Brown Weiss

We are now facing a new generation of environmental problems which are of concern not only to the United States but to the other countries in the world community. Some of these are regional and/or global in scope: transboundary air pollution, such as acid rain, which crosses national frontiers in North America and in Europe (CEQ, 1983; Wetstone and Rosencranz, 1983); Arctic haze (Rahn, 1984; Anon., 1985); disposal of hazardous wastes (OECD, 1984); marine pollution (NRC, 1984). Other problems are more locally based but generate broad concern either because many countries share the problem or because it has important international implications for the environment: surface and ground water pollution; soil erosion; deforestation; and the loss of genetic resources.

There is now a widespread recognition that the human species has the capacity to alter the environment in ways that may be harmful both to present and to future generations, and that new approaches are needed to address these problems (Holdgate, Kassas and White, 1982; Brown et al., n.d.; and World Resources Institute, 1984). In the words of Gro Harlem Bruntland, "We must change our perceptions so that sustainable development and the conservation of our planetary heritage come to the forefront. We must come to see that many of our current approaches add up to a sort of piracy against our children that a truly civilized world can no longer afford or tolerate" (Bruntland, 1985).

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National Academy of Sciences.

WHOI Contribution No. 6221.

Retention and release of No. 2 fuel oil compounds by *Mytilus edulis* contaminated by a small oil spill in the Cape Cod Canal in 1983 has been studied for the population "in situ" and for a subsample transplanted to a clean laboratory seawater system. Compounds analyzed include C₁₃ to C₂₄ n-alkanes; pristane; phytane; C₂-, C₃-naphthalenes; fluorene; phenanthrene; C₁-, C₂-, C₃-phenanthrenes; fluoranthene; pyrene and dibenzothiophene. Biological half-lives were determined for the compounds from Day-3 to Day-29 following the spill and ranged from 1.5 days for C₂-naphthalenes to 9.9 days for C₂-phenanthrenes. Biological half-lives for the unresolved complex mixture determined by gas chromatographic analyses were 17 days for the alkane-cycloalkane fraction and 35 days for the aromatic fraction. Results compared favorably with data from a small oil spill contaminating the same mussel population at the same time of the year in 1978, although marked differences were noted for certain parameters.

Gas chromatographic-mass spectrometer analyses of C₂- and C₃-phenanthrenes revealed changes in relative abundance of compounds within isomer groups from samples at Day-29 to the time when no further detection of fuel oil was noted. These results suggest a release or metabolism of these compounds which is molecular structure specific.

This study also demonstrated the feasibility of training an analyst unfamiliar with analyses of hydrocarbons in tissues to conduct high resolution glass capillary GC analyses and some aspects of GCMS data systems output within a period of four to five months.

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WHOI Technical Report 86-8.

CHAPTER 1:
BIOAVAILABILITY OF POLYNUCLEAR
AROMATIC HYDROCARBONS IN THE
AQUATIC ENVIRONMENT

Anne E. McElroy, John W. Farrington
and John M. Teal

This chapter serves two purposes. The primary goal is to review what is known about the bioavailability of polynuclear aromatic hydrocarbons or polycyclic aromatic hydrocarbons (PAH) and their metabolites in the aquatic environment. Emphasis will be placed on the physical/chemical, biological, and environmental factors which drive these processes. Secondly, this discussion will provide a rationale for why it is important to study metabolism when considering the fate of PAH in aquatic systems. The chapter is divided into three main sections. The first introduces PAH, their sources, transformations and sinks, and the physical/chemical factors which influence their cycling in the environment. The second section reviews information gathered from field studies on the bioavailability of PAH to aquatic organisms. Information derived from laboratory investigations on processes influencing bioavailability is discussed in the third section. Due to the complexity of the many parameters which influence the fate of compounds such as PAH in the environment, studies of these processes in the field are required to obtain a realistic assessment of the environmental fate of PAH. For the same reasons it is very difficult and often impossible to do controlled experiments in the field. In organizing this chapter we chose to focus on field collected data on PAH bioavailability, and then to supplement this discussion with information derived from laboratory studies. This organization may seem awkward at times, but we think it best serves the purposes of the chapter within the context of this book.

Published in: CRC Press Book: Metabolism of Polynuclear Aromatic Hydrocarbons in the Environment. U. Varaasi, ed.

Supported by: NOAA Contract 83-ABD-00012; and Andrew W. Mellon Foundation.

WHOI Contribution No. 6394.

MARINE AND TERRIGENOUS LIPIDS IN COASTAL
SEDIMENTS FROM THE PERU UPWELLING REGION
AT 15°S: STEROLS AND TRITERPENE ALCOHOLS

John K. Volkman, John W. Farrington
and Robert B. Gagosian

The distributions of 4-desmethyl sterols in 3 surface sediments and 4 deeper sediments from the Peru coastal zone at 15°S have been determined. Major sterols in the surface sediments include cholesterol, which is mainly derived from zooplankton, and two C₂₈ sterols: 24-methylcholesta-5,24(28)-dien-3β-ol and 24-methylcholesta-5,22E-dien-3β-ol. Both marine sterols are derived from diatoms, but they are transported to the sediments in faecal pellets from anchovies. Their concentrations decrease by almost an order of magnitude with depth due to the effects of diagenesis. Lipids from higher plants were also detected: long chain fatty acids and alcohols and various triterpenoid alcohols, including lupeol and α- and β-amyrin. The concentrations of most terrigenous lipids varied by less than a factor of 3 with depth, and these changes were not correlated with changes in the concentrations of total organic carbon. Below 3 cm, higher plant lipids predominated in the extractable lipid distributions due to the more rapid degradation of marine lipids. Using concentration data for selected terrigenous markers, we show that there are significant marine sources of the higher plant sterols 24-ethylcholesterol, 24-ethylcholesta-5,22E-dien-3β-ol and 24-methylcholesterol. A high proportion of many of the terrigenous lipids in these sediments are probably transported into the coastal zone by rivers and not from the atmosphere.

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WHOI Contribution No. 6393.

I N S T R U M E N T S A N D
S T A T I S T I C S

A WHOLE CORE SQUEEZER FOR INTERFACIAL
PORE WATER SAMPLING

Michael Bender, William Martin,
Jennifer Hess, Fred Sayles,
Lary Ball and Claude Lambert

A description is given of the "whole core squeezer," a simple pore water sampler designed for collecting samples with millimeter depth resolution near the sediment-water interface. A variety of tests have been done to determine how accurately true gradients are reproduced by whole core

squeezing. Tracer studies show that any mixing associated with the sampling process does not "smear" the profiles by more than a few millimeters. Benthic fluxes of SiO_2 calculated from interfacial concentration gradients resolved with the whole core squeezer in San Clemente Basin are in good agreement with "bell jar" values measured using the benthic chambers of the Bottom Lander. Oxygen profiles determined with the whole core squeezer are very similar to values determined by Reimers (personal communication) using an oxygen electrode. These comparisons confirm that interfacial gradients and fluxes of O_2 , NO_3^- , SiO_2 , and other particle-unreactive ions and molecules can be determined using the instrument. On the other hand, the composition of squeezed pore waters is very susceptible to rapid alteration by solid-solution reactions. Therefore the method is not suitable for determining pore water profiles of trace metals and other particle-reactive chemicals.

In press: Deep-Sea Research.

Supported by: NSF Grant OCE83-12142.

WHOI Contribution No. 6321.

ORGANIC AND BIOLOGICAL CHEMISTRY

SEASONAL VARIATIONS IN ISOTOPIC COMPOSITION AND DEEP-WATER FLUXES OF THE TESTS OF PERENNIALY ABUNDANT PLANKTONIC FORAMINIFERA OF THE SARGASSO SEA: RESULTS FROM SEDIMENT-TRAP COLLECTIONS AND THEIR PALEOCEANOGRAPHIC SIGNIFICANCE

Werner G. Deuser

A six-year series of sediment-trap samples from the deep Sargasso Sea provides data on seasonal stable-isotope and flux variations of the tests of planktonic foraminifera. Three species, *Globigerinoides ruber* (white var.), *Globigerinella aequilateralis*, and *Orbulina universa* are abundant throughout the year and undergo consistent annual cycles in number, mass, average weight and oxygen and carbon isotopic composition of tests approaching the seafloor. Comparisons of their oxygen isotopic composition with that calculated from hydrographic data for Station 'S' for the same six-year period allows the assignment of average depths of origin of the settling tests to within 25m. Tests of *G.*

ruber form in the upper 25m and deviate from isotopic equilibrium with ambient seawater by an average of -0.20‰ . Tests of *G. aequilateralis* form between 50 and 75m, and thin-walled *O. universa* tests between 25 and 50m. Secondary wall thickening of *O. universa* takes place in deeper water. Both *G. aequilateralis* and *O. universa* tests form in or very close to oxygen-isotopic equilibrium. The annual flux variations of the three species do not significantly bias the isotopic composition of multiannual accumulations of their tests toward certain seasons. Therefore, all three species are good paleoceanographic indicators: isotopic analyses of multispecimen samples give information on mean annual hydrography, whereas the spread among analyses of individual tests can indicate the amplitude of the annual temperature-salinity variation. (Effects of salinity variations below 50m are negligible in the Sargasso Sea.) The carbon-isotope composition of the tests of these three species appears largely controlled by internal biological factors rather than external factors. Thus the annual carbon isotope cycles of *G. aequilateralis* and *O. universa* are out of phase even though their tests form in the same water during winter. The $\delta^{13}\text{C}$ of *G. ruber* tests may respond to ^{12}C and nutrient depletion in the surface water and, therefore, might be useful as an indicator of the intensity of past primary productivity. The large tests of *G. aequilateralis* have a $\delta^{13}\text{C}$ which is correlated to the flux of organic carbon to the deep water. It is conceivable that these tests record the intensity of photosynthetic carbon fixation at the depth of the chlorophyll maximum, but the utility of these relationships for paleoceanographic purposes needs to be established by studies in other oceanographic settings.

In Press: Journal of Foraminiferal Research, Vol. 17.

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WHOI Contribution No. 6112.

THE IMPORTANCE OF ATMOSPHERIC INPUT OF TERRESTRIAL ORGANIC MATERIAL TO DEEP SEA SEDIMENTS

Robert B. Gagosian and Edward T. Peltzer

The concentrations of lipids were determined in atmospheric particle, gas and rain samples collected from the tropical North Pacific to assess lipid sources, transport mechanisms and fluxes

to the ocean surface. Four lipid compound classes (aliphatic hydrocarbons, fatty alcohols, fatty acid esters, and salts) all unequivocally show a terrestrial vascular plant source. These aerosol lipids originate from wind erosion of Asian and American soils and direct emission from vegetation.

The major fluxes result from rain rather than dry deposition. These fluxes are large enough to have a major potential impact on the inventory of terrestrially derived lipid material found in deep-sea sediments. This has been shown for *n*-alkanes, fatty alcohols, fatty acids, total lipids and for organic carbon. By comparing atmospheric and sediment trap fluxes with sediment accumulation rates, it is suggested that some biogenic terrestrial material is more protected from degradation than marine derived material.

In Press: Adv. Organic Geochemistry
volume on the Twelfth International
Meeting on Organic Chemistry, 1985.

Supported by: NSF Grants OCE84-15724
and OCE84-06666.

WHOI Contribution No. 6153.

LONG RANGE TRANSPORT OF TERRESTRIALLY- DERIVED LIPIDS IN AEROSOLS FROM THE SOUTH PACIFIC

Robert B. Gagosian, Edward T. Peltzer
and John T. Merrill

Terrestrially produced particulate organic matter can be transported relatively fast in the atmosphere long distances over the ocean. It has been hypothesized that this atmospheric transport may be an important pathway for quickly introducing continentally-derived organic material to the surface waters of the open ocean. After rapid transport through the water column to the sediment surface, these terrestrial organic substances could account for an important fraction of the organic carbon found in the sedimentary record. The atmospheric fluxes of these organic substances are large enough to have a major potential impact on the inventory of terrestrially-derived lipid material, originating from vascular plant waxes, found in deep-sea sediments. In this manuscript we present the first use of organic compound biological source marker information in conjunction with long range meteorological trajectory analysis to elucidate specific terrestrial source regions and to determine the transport pathways of organic material through the atmosphere to remote marine locations.

In Press: Nature.

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OCE84-06666 and OCE84-05608.

WHOI Contribution No. 6295.

ω -OXOCARBOXYLIC ACIDS IN THE REMOTE MARINE ATMOSPHERE AND THE IMPLICATION FOR PHOTO-OXIDATION OF UNSATURATED FATTY ACIDS

Kimitaka Kawamura and Robert B. Gagosian

Specific organic compounds have been used as tracers of biological and anthropogenic source inputs to the marine atmosphere. This tracer approach uses the unique molecular signatures or fingerprints for various lipid compound classes of marine and terrestrial plants to identify the sources of the organic substances in aerosols. However, many of these substances are not stable and undergo transformation reactions. For example, unsaturated fatty acids, which are major constituents in marine and terrestrial plants, have not been frequently detected in remote marine aerosols. The mechanism for the transformation of unsaturated fatty acids in the atmosphere has not been elucidated. In this paper, we report the discovery of a homologous series of 1-oxocarboxylic acids (C_4 - C_{14} ; C_9 being maximum) in marine aerosols. We propose that these compounds are oxidation products of unsaturated fatty acids in the marine environment. The discovery of 1-oxoacids, along with additional aerosol, seawater, and rain data for mono- and di-carboxylic acids, has led us to postulate a photoinduced oxidative reaction scheme for unsaturated fatty acids in the marine atmosphere and surface seawater.

In Press: Nature.

Supported by: NSF Grant OCE84-06666.

WHOI Contribution No. 6176.

IDENTIFICATION OF ω -OXOCARBOXYLIC ACIDS AS ACETAL ESTERS IN AEROSOLS USING CAPILLARY GAS CHROMATOGRAPHY-MASS SPECTROMETRY

Kimitaka Kawamura and Robert B. Gagosian

An homologous series of ω,ω -dimethoxycarboxylic acid methyl esters (acetal esters) has been identified in the most polar methyl ester fraction separated from remote aerosol samples by liquid chromatography. These compounds were separated by silica gel column chromatography and their

structures determined by capillary gas chromatography (GC) and GC-mass spectrometry with a synthesized standard. Acetal esters are originally present in the samples as ω -oxocarboxylic acids, which are derivatized to acetal esters during treatment with boron trifluoride in methanol. This method enables the determination of ω -oxocarboxylic acids in environmental samples as acetal esters.

In Press: Journal of Chromatography.

Supported by: NSF Grant OCE84-06666.

WHOI Contribution No. 6286.

IN SITU PRODUCTION OF TERRESTRIAL COSMOGENIC HELIUM AND SOME APPLICATIONS TO GEOCHRONOLOGY

Mark D. Kurz

The concentrations of cosmogenic ^3He have been measured in a series of basaltic drill core samples from Hawaiian volcanoes of Haleakala and Mauna Loa. The ^3He concentration in the surface of a radio-carbon dated Mauna Loa flow (20,000 years) gives reasonable agreement with a theoretical production rate of $140 \text{ atoms g}^{-1}\text{yr}^{-1}$, and suggests that the uncertainty in this rate is roughly 10%. The results illustrate the feasibility of using ^3He to measure exposure ages of young basaltic lava flows and for measuring erosion rates. Erosion rates calculated from the three Haleakala cores range from 7 to 11 meters/million years. The drill core data demonstrate that accurate depth control is crucial to the use and evaluation of cosmogenic helium. Depth profiles from several of the older cores display a non-exponential depth dependence of ^3He below 170 g cm^{-2} , which is attributed to the contribution from $^6\text{Li}(n,\alpha)\text{T}$, where the neutrons are from stopped muons. This has important implications for depth dependence of cosmogenic ^3He because muons are weakly attenuated compared to the nucleonic component that produces spallation.

In press: Geochimica et Cosmochimica Acta.

Supported by: NSF Grants NSF OCE85-16082 and EAR86-10611; and NASA Grant NAG-969.

WHOI Contribution No. 6335.

NATURAL RADIONUCLIDE GRADIENTS IN TWO Mn OXIDE DEPOSITS FROM THE MAR: POSSIBLE RELATIONSHIPS WITH INTENSITY AND/OR INCREASING DISTANCE FROM A HYDROTHERMAL SOURCE

Claude Lalou, Evelyne Brichet and
Geoffrey Thompson

Two apparently very different Mn oxide deposits were dredged during cruise AII-78 in 1973 from the western flank of the Mid-Atlantic Ridge (MAR), about 135 km from the spreading axis, at $22^{\circ}53'\text{N}$, $45^{\circ}56'\text{W}$, on a basement about 7 my old and from depths between 2910-3860 m. One of them (AII-78-9-21) is postulated to be of hydrothermal origin. It has an Mn/Fe ratio of 1.4×10^3 and is especially pure Mn in the form of todorokite. The other (AII-78-9-12) is postulated to be of hydrogenous origin. It has a Mn/Fe ratio of 0.75, typical of many ferromanganese crusts in the Atlantic, and mineralogically is composed of δMnO_2 , interlayered with amorphous iron oxide and/or goethite. Because the origin, genesis and growth rates of marine metallic deposits remain somewhat controversial, we took the opportunity of having two apparent end products in the same dredge haul to establish if they are genetically independent or part of a continuum. We will show that the similarities and differences in the U and Th distributions with depth in each sample do not allow use of the decrease of the ^{230}Th activity within each crust as a chronometer to calculate growth rates, and are better explained by a chemical gradient due to the proximity of a hydrothermal discharge.

Supported by: NSF Grant OCE85-10847.

WHOI Contribution No. 6227.

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

Edward T. Peltzer and Robert B. Gagosian

A procedure is described for the determination of organic compounds in aerosols and rain from the remote marine atmosphere. Five classes of naturally occurring lipids (n-alkanes, wax esters, fatty alcohols, sterols, and fatty acids) were quantified in the samples. Air samples ($4,000$ - $10,000 \text{ m}^3$) were collected on glass fiber filters under automatic control. Rain samples (1 - 5ℓ) were collected on an event basis. Filter and rain samples were extracted with methylene chloride and the extracts were fractionated into discrete chemical classes by adsorption chromatography with silica

gel. The fractions were derivatized (if necessary) and quantified by high resolution glass capillary gas chromatography (HRGC) and HRGC/mass spectrometry. A second filter extraction was required for quantitation of fatty acid salts. On-column injection of the fractions enabled the identification and quantification of a wide range of homologs within each compound class: C_{15} - C_{44} for n-alkanes, C_{39} - C_{62} for wax esters, and C_{13} - C_{36} for fatty alcohols and fatty acids. Internal standards were used to quantify recoveries and concentrations. Mean recoveries relative to the internal standards were 96.5% for C_{18} - C_{36} n-alkanes, 96.4% for C_{20} - C_{30} n-fatty acids, 92.5% for C_{14} - C_{30} n-fatty alcohols and 93.3% for cholesterol. The procedural blanks for the remote marine aerosol samples allow detection limits of 0.1-1.0 $pg\ m^{-3}$ for most compounds. These values are lower than any other method used at coastal marine, rural or suburban sampling locations.

In Press: *Analytica Chimica Acta*.

Supported by: NSF Grants OCE77-12914, OCE81-11947 and OCE84-06666.

WHOI Contribution No. 6307.

CAROTENOID DIAGENESIS IN RECENT MARINE SEDIMENTS-I. THE PERU CONTINENTAL SHELF (15°S, 75°W)

Daniel J. Repeta and Robert B. Gagosian

We report here the distribution of carotenoids in Peru surface sediments, including partial identification of 37 pigments, 33 of which have not been previously reported to occur in marine sediments. Our analysis demonstrates that zooplanktonic crustacea, diatoms, dinoflagellates, cryptomonads, purple nonsulfur photosynthetic bacteria, and unidentified species of photosynthetic bacteria are contributors to sedimentary organic matter. Fucoxanthin, fucoxanthinol, diadinoxanthin, peridinin and peridinol, the principal carotenoids of diatoms and dinoflagellates observed in sediment traps, are nearly absent from our sample, even though these phytoplankton are the primary source of organic matter. We attribute this to the presence of 5,6 epoxides in these pigments, a feature which causes rapid cleavage of the polyene and fragmentation to low molecular weight compounds.

In Press: *Geochimica et Cosmochimica Acta*.

Supported by: NSF Grant OCE83-10004.

WHOI Contribution No. 6361.

EVIDENCE FOR MICROBIOLOGICAL ACTIVITY IN LEG 95 (NEW JERSEY TRANSECT) SEDIMENTS

Martha E. Tarafa, Jean K. Whelan, Ronald S. Oremland and Richard L. Smith

Radioisotope tracer experiments were carried out on sediments recovered from DSDP Leg 95 from Holes 612 and 613 to test for viable micro-organisms having geochemical significance. Positive indications of anaerobic bacterial activity (sulfate reduction, acetate oxidation and methanogenesis) were found in sediments recovered from a maximum depth of 46 m at Site 612 and 134 m at Site 613. Further work is needed to identify the organisms responsible for geochemical processes in these sediments.

In Press: Initial Reports DSDP, 95.

Supported by: NSF Grant OCE82-00485.

WHOI Contribution No. 6156.

MATURITY OF ORGANIC MATTER AND MIGRATION OF HYDROCARBONS IN TWO ALASKAN NORTH SLOPE WELLS

Jean K. Whelan, John W. Farrington and Martha E. Tarafa

Plots of T_{max} and production index (P.I.) for seven Alaskan North Slope wells suggest that samples from the Ikpikpuk well are optimal for examination of thermal maturity and the Seabee well for migration-geochemical trends at all maturity levels. Vitrinite reflectance profiles for the two wells are identical and reach maximum values of 2.5% in the deepest rock units. Pyrolysis $Pl/org\ C$, T_{max} , and P.I. values all behave "normally" in Ikpikpuk but for Seabee show generally lower (by about 60°C) T_{max} values and higher and more scattered $Pl/org\ C$ and P.I. values.

Sorbed light hydrocarbon ratios including $C2/C3$; $iC4/nC4$; $iC5/nC5$; $22DMB/nC6$; $MCP/benz$; $benz/tol$; paraffin indexes 1 and 2 and $C1/(C1+C2+C3)$ are compared for both wells. Light hydrocarbon data for Ikpikpuk generally show smooth changes expected for maturation across the Kingak shale and Shublik formation with increasing paraffin indexes 1 and 2; decreasing $MCP/benz$; increasing $benz/tol$; increasing $C1/(C1+C2+C3)$; and a spike in $22DMP/nC6$ at the bottom of the over-mature Sadlerochit sandstone. These ratios are consistent with some localized lateral migration at the bottom of the Sadlerochit Group sand-

stone and at the top of the pebble shale unit. In contrast, Seabee ratios were very different and showed no particular trends with depth, although some increase in proportions of methane and benzene are observable in the deepest sections of the well.

The ratios of pyrolyzable $C1/(C1+C2+C3)$ for the Ikpikpuk well were similar to those for the generated sorbed gases within for the catagenetic and post mature sections of the well. Seabee showed pyrolyzable $C1/(C1+C2+C3)$ ratios similar to those from Ikpikpuk except for a less pronounced bottom hole increase in the ratio.

Migration phenomena with preferential retention of polar asphalts or pyrobitumens in strata through which or from which migration has occurred are postulated to be the cause of a low temperature P2 shoulder often observed in and below the catagenic zones of Ikpikpuk. GCMS data of pyrolyzable material show that maturation causes a decrease in alkane and alkene pyrolysis products as compared to aromatic and heterocyclic compounds. This low temperature shoulder appears to become the predominant P2 peak in sections of other wells, such as Seabee, which are extensively influenced by migration.

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WHOI Contribution No. 6146.

DIETARY CARBON SOURCES FOR DEEP-SEA ORGANISMS AS INFERRED FROM THEIR ORGANIC RADIOCARBON ACTIVITIES

Peter M. Williams, Ellen R. M. Druffel and Ken L. Smith, Jr.

A small but significant depletion of radiocarbon activity ($\Delta^{14}C/\text{‰}$) is present in surface, meso-, bathy- and abyssopelagic fishes and crustaceans collected from depth in the North Central Pacific (NCP) and in the Northeast Pacific (NEP) in the 1960s and 1970s compared to average values for dissolved inorganic carbon (DIC) and zooplankton found in the euphotic zone during this period. These low ^{14}C activities are postulated to result from 1) the ^{14}C gradient in DIC in the euphotic zone, and 2) the incorporation of low activity, pre-bomb peak carbon (pre-1969) from the surface ocean into chronologically old organisms. Based on the relative increase of ^{14}C activity in surface and deep organisms,

maximum estimates of the turnover times range from <1 to 9 years for the organic carbon in surface and mesopelagic animals and 4 to 18 years for bathy- and abyssopelagic animals from the NCP and NEP. These data suggest that the main source of dietary carbon for deep-sea organisms is from rapidly sinking organic detritus from the surface and from active (animal mediated) transport of living carbon. There may be a minor contribution (15%) to bathypelagic organisms from low ^{14}C activity chemolithotrophically-derived organic carbon, from heterotrophic uptake of mid-depth DIC or from recycled carbon.

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WHOI Contribution No. 6231.

RADIOCHEMISTRY

LEAD-210 AND POLONIUM-210 IN OCEAN WATER PROFILES OF THE CONTINENTAL SHELF AND SLOPE SOUTH OF NEW ENGLAND

Michael P. Bacon, Rebecca A. Belastock, Mark Tecotzky, Karl K. Turekian and Derek W. Spencer

Concentration profiles of ^{210}Pb and ^{210}Po were measured on a traverse of the continental shelf and slope during the first phase of the SEEP (Shelf Edge Exchange Processes) program. Results from the upper 100 m show low concentrations of dissolved ^{210}Pb over the shelf (<2 dpm/100 kg) and increasing concentrations progressing into the Slope Water, where concentrations >10 dpm/100 kg are found. This trend reflects the more efficient removal of ^{210}Pb from the water column over the shelf. The deep waters over the slope show the commonly observed ^{210}Pb deficiency, relative to ^{226}Ra , due to removal by chemical scavenging. Vertical profiles indicate somewhat intensified scavenging of ^{210}Pb near the sediment-water interface. Flux calculations for the shelf show an imbalance such that the input of atmospheric ^{210}Pb must be compensated by an export of ^{210}Pb off the shelf. This provides an important constraint on models that would predict the fate of materials

introduced to the continental shelf. Over the slope, on the other hand, a good vertical flux balance is maintained, indicating that inputs of ^{210}Pb to the Slope Water by cross-frontal particle transport or by exchange across the Gulf Stream may be unimportant. Results for ^{210}Po in the surface waters show strong depletion, relative to ^{210}Pb , in the dissolved form and enrichment in the particulate form, indicative of particulate transport out of the surface layer. Evidence for release of ^{210}Po is seen in a sub-surface layer, centered at 50-100 m, where ^{210}Po is enriched in the dissolved form and depleted in the particles. There is also evidence for a flux of ^{210}Po from the shelf sediments.

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WHOI Contribution No. 6338.

THE GLOBAL OCEAN FLUX STUDY (GOFS): STATUS OF THE U.S. GOFS PROGRAM

Peter G. Brewer, Kenneth W. Bruland,
Richard W. Eppley and James J. McCarthy

The proposed National Science Foundation budget for FY 1987 contains funding for a major new initiative (Waldrop, 1986), the Global Geosciences Program, which consists of separate but related research efforts that treat the earth as an integrated system of global oceanic and atmospheric circulation systems, and as a delicate and dynamic balance of biogeochemical fluxes which sustain life on our blue planet.

This essay concerns the status of one important element of this program, the U.S. segment of the Global Ocean Flux Study, which is now being planned with NSF and NASA support. What is the origin of such a program? What are its aims? How might it be accomplished? And why is it necessary at this time?

The origin of this program may be found in the excellent NAS publication "Global Ocean Flux Study: Proceedings of a Workshop, September 10-14, 1984" (NAS, 1984). The aims are to observe and understand the biogeochemical cycles of the ocean sufficiently well to predict the interaction between the oceanic, atmospheric and sedimentary cycles of the biologically active elements such as C, N, O and S. These are the master variables of ocean chemistry.

The clear necessity arises from abiding concerns over the impact of biogeochemical and climatic changes on the habitability of our planet. For those who must deal

with these issues the urgency is fueled by our vexing inability to have other than a crude understanding of the processes that control the time dependent biogeochemical variability of the ocean. As we review in detail the hypothesis made to understand the major biogeochemical cycles of the ocean one thing remains perennially true. It is hard to make the numbers add up.

The early prototype satellite (Coastal Zone Color Scanner) that has now delivered the first essential glimpse of global pigment data faces system failure and must be replaced by successor instruments. GOFS can be accomplished through a combination of sophisticated research cruises, satellite ocean color observations, moored and drifting instrumentation of novel design, and advanced numerical modelling and data assimilation techniques. It will require genuine and vigorous international cooperation for a decade or more.

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WHOI Contribution No. 6336.

THE MASS SPECTROMETRIC ANALYSIS OF DETERMINATION ^{239}Pu AND ^{240}Pu IN MARINE SAMPLES

Ken O. Buesseler and Justin E. Halverson

A thermal ionization mass spectrometric technique is presented for the detection of ^{239}Pu and ^{240}Pu in seawater, pore water, ocean sediments, sediment trap samples, and coral samples. Both sample preparation and purification procedures, as well as the procedure used to detect Pu by mass spectrometry (m.s.) are presented. The m.s. technique proves to be over an order-of-magnitude more sensitive than traditional alpha-counting techniques for the detection of Pu in environmental samples. Also, the ratio of $^{240}\text{Pu}/^{239}\text{Pu}$ is obtained with this technique.

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Radioactivity.

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WHOI Contribution No. 6400.

THE GEOCHEMISTRY OF FALLOUT PLUTONIUM IN
THE NORTH ATLANTIC: I. A PORE WATER STUDY
IN SHELF, SLOPE AND DEEP-SEA SEDIMENTS

Ken O. Buesseler and Edward R. Sholkovitz

The distribution of fallout plutonium between pore waters and sediments in the Northwest Atlantic is examined in order to constrain the potential for Pu migration from and within marine sediments. Along a transect of seven cores collected between Woods Hole and Bermuda, we find that the solid phase $^{239,240}\text{Pu}$, $^{210}\text{Pb}^{ex}$ and ^{137}Cs results do not suggest that any of these tracers are preferentially mobile within the cores. Pore water Pu activities appear to be controlled primarily by the distribution of Pu in the solid phase, with an operationally-determined distribution coefficient, K_d , in the range of $0.2\text{--}23 \times 10^4$. While the Pu pore water activity at the sediment-water interface is elevated over near bottom water activities, the potential for Pu remobilization out of the sediments is small ($0.3\text{--}24 \times 10^{-5}$ dpm $^{239,240}\text{Pu}/\text{cm}^2$ year). Previous studies which use solid phase Pu and $^{210}\text{Pb}^{ex}$ data to suggest Pu mobility have been re-examined. At MANOP site C (Cochran, 1985), the enhanced mobility of Pu due to the diffusion of Pu in pore waters is shown to be small relative to the inventory of Pu in the sediments. Sediment mixing models are not significantly altered by the inclusion of Pu diffusion terms.

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WHOI Contribution No. 6391.

THE GEOCHEMISTRY OF FALLOUT PLUTONIUM IN
THE NORTH ATLANTIC: II. $^{240}\text{Pu}/^{239}\text{Pu}$
RATIOS AND THEIR SIGNIFICANCE

Ken O. Buesseler and Edward R. Sholkovitz

In this study, a systematic decrease in the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio in sediments is found with increasing water depth along a transect of cores between Woods Hole and Bermuda. The $^{240}\text{Pu}/^{239}\text{Pu}$ atom ratios range from ≈ 0.18 on the shelf to ≈ 0.10 at 5000 m. A model will be presented which can account for the range of $^{240}\text{Pu}/^{239}\text{Pu}$ ratios found in this and other similar studies (Noshkin and Gatrousis, 1974; Scott *et al.*, 1983). In this model, we propose that there have been at least two distinct sources of fallout Pu to this region. The major source of Pu is global stratospheric fallout which is characterized by a $^{240}\text{Pu}/^{239}\text{Pu}$ ratio of 0.18. The second source of fallout Pu is characterized by a much lower $^{240}\text{Pu}/^{239}\text{Pu}$

ratio, and relative to global fallout, must have been more efficiently deposited to deep-sea sediments.

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WHOI Contribution No. 6392.

NATURAL AND ANTHROPOGENIC RADIONUCLIDE
DISTRIBUTIONS IN THE NORTHWEST
ATLANTIC OCEAN

J. Kirk Cochran, Hugh D. Livingston,
David J. Hirschberg and
Lolita D. Surprenant

In situ pumps which filter large volumes of sea water through a $1\text{ }\mu\text{m}$ cartridge prefilter and two MnO_2 -coated cartridges provide information on dissolved and particulate radionuclide distributions in the oceans. Two sites in the Northwest Atlantic show subsurface maxima of total ^{137}Cs , $^{239,240}\text{Pu}$ and ^{241}Am . The maxima for Pu and Am are $\sim 200\text{--}400\text{m}$ deeper than for Cs, implying some scavenging onto sinking particles and release at depth. Inventory calculations show, however, that 60–80% of the Pu and $\sim 70\%$ of the ^{241}Am present in the deep water ($>2000\text{--}3000\text{m}$) at these sites is supplied by advection. The depth distributions of ^{232}Th , ^{228}Th and ^{230}Th reflect their sources to the oceans. ^{232}Th shows high dissolved concentrations in surface waters presumably as a result of atmospheric or riverine supply. Concentrations decrease with depth to values ≤ 0.01 dpm/1000 ℓ . ^{228}Th shows high concentrations in near surface and near bottom water, due to the distribution of its parent, ^{228}Ra . Dissolved ^{230}Th increases with depth to $\sim 3000\text{m}$, below which values are nearly constant at $.6\text{--}.7$ dpm/1000 ℓ . The ratio of particulate to dissolved activity for both ^{230}Th and ^{229}Th is $\sim .15\text{--}.20$. This similarity precludes the calculation of sorption rate constants using a simple model of reversible sorption equilibrium. Moreover, ^{228}Th occasionally shows a higher particulate/dissolved ratio than ^{230}Th , suggesting uptake and release of ^{230}Th and ^{228}Th by different processes. This could occur if ^{228}Th , produced in surface water, were incorporated into biogenic particles formed there and released as those particles dissolved or decomposed during sinking. ^{230}Th , produced throughout the water column, may more closely approach a sorption equilibrium at all depths. ^{230}Th , ^{241}Am and $^{239,240}\text{Pu}$ are partitioned onto particles in the sequence $\text{Th} > \text{Am} > \text{Pu}$ with $\sim 15\%$ of the ^{230}Th on particles compared with $\sim 7\%$ for Am and $\sim 1\%$ for Pu. K_d values are $1.3\text{--}1.6 \times$

10^7 for Th, $5-6 \times 10^6$ for Am and $7-10 \times 10^5$ for Pu. The lower reactivity for Pu is consistent with analyses of Pu oxidation states which show ~85% oxidized (V+VI) Pu. However, the K_d value is probably an upper limit because Pu, like ^{228}Th , may be incorporated into particles in surface waters and released at depth only by destruction of the carrier phase.

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WHOI Contribution No. 6420.

RADIOTRACER STUDIES OF DEEP WATER FORMATION IN THE NORDIC SEAS

Hugh D. Livingston

The distributions of the radiotracers ^{137}Cs , ^{90}Sr , and ^3H which characterized surface and deep waters of the Nordic Seas in the time-period 1979-82 are presented and discussed in the context of regional circulation and deep water formation.

The data indirectly support the view that mid-gyre winter convection is the major process which is driving the transfer of surface water and associated properties into the deep Nordic Seas. Furthermore, the deep gyral circulation appears the active process which propagates these properties relatively rapidly within the regional deep-water waters.

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WHOI Contribution No. 6421.

CHERNOBYL FALLOUT STUDIES IN THE BLACK SEA AND OTHER OCEAN AREAS

Hugh D. Livingston, William R. Clarke,
Susumu Honjo, Errol Izdar, Tosun Konuk,
Egon T. Degens and Venu Ittekkot

The release of massive quantities of radionuclides to the lower atmosphere from the Chernobyl nuclear power station accident on 26 April 1986 has environmental radioecological implications which extend into the future. It is premature at present to make a comprehensive assessment of the oceanic impact of the release and the possible consequent potential marine radio-tracer applications. Clearly the Baltic Sea, being heavily impacted, is one area

where fallout was high enough to be used to conduct an extensive range of experiments. The Black Sea, Norwegian/Greenland/Barents Seas and Arctic Ocean are likely to have received substantial amounts of Chernobyl fallout. In addition to direct fallout, the Arctic Ocean can be expected to receive an advective input from the south as Atlantic water flows relatively rapidly into it. Likewise, the Norwegian Sea will receive water exported from the Baltic Sea outflow. The Black Sea receives large amounts of river input in the northwest - mostly from the Danube and Dnieper Rivers. Both these rivers drain watersheds heavily impacted by Chernobyl fallout - the latter including the freshwater environment directly around the Chernobyl site itself.

Dr. H. D. Livingston's laboratory at the Woods Hole Oceanographic Institution has started to collect samples this summer which can be used to assess the geographical impact of Chernobyl fallout in the areas noted above. This information will permit an assessment of what radio-tracer experiments become possible and will establish a partial base against which temporal changes may be noted.

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WHOI Contribution No.: 6256

DETERMINATION OF TRANSURANIC AND THORIUM ISOTOPES IN OCEAN WATER: IN SOLUTION AND IN FILTERABLE PARTICLES

Hugh D. Livingston and J. Kirk Cochran

A sensitive technique for the measurement of dissolved and particulate actinide concentrations and water column distributions is described. Pu, Am, and Th isotopes are collected using large-volume, wire-mounted electrical pumping systems. Particles were removed by filtration, and actinides by absorption on MnO_2 -coated filters. The very large volumes processed (up to 4000 liters) result in very sensitive and precise concentration measurements after analyses of the samples by standard radiochemical and alpha spectrometric techniques.

Supported by: Sandia Laboratories
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PARTICLE AND SOLUTION PHASE DEPTH
DISTRIBUTION OF TRANSURANICS AND ^{55}Fe
IN THE NORTH PACIFIC

Hugh D. Livingston, Don R. Mann,
Susan A. Casso, David L. Schneider,
Lolita D. Surprenant and Vaughan T. Bowen

In-situ large volume filtration and chemisorption techniques were used to collect samples from the North Pacific for radiochemical analyses of fallout transuranics and ^{55}Fe in filterable and filtered phases. The data cover several locations for surface collections and a detailed depth profile north of Hawaii at 30°N. The observed partition of these nuclides between suspended particulate and filtered phases is directly linked to the rates at which they are moved downward through the water column in association with sinking particles. Particulate phases in open ocean surface waters contain higher Pu (12%-35%) than subsurface particulates - which average about 6%. ^{241}Am was found to exhibit much stronger particle association - typically close to 50% in both surface and subsurface waters - in accord with its known greater particle reactivity. In the high Pu deep water layer, particle associated Pu dropped to close to 1% of total Pu concentration. Together with a correlated increase in the proportion of oxidized Pu in this layer close to the sediment-water interface, this is taken as clear evidence of remobilization of Pu from particles at, or near to, the interface. ^{55}Fe distributions on filtered particulates indicate a much deeper depth distribution relative to the transuranics. This may reflect both a higher particle association reactivity in respect to scavenging and a longer exposure history to scavenging (especially relative to ^{241}Am - produced by in-situ decay).

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WHOI Contribution No. 6224.

RARE EARTH ELEMENTS IN THE SEDIMENTS OF
THE NORTH ATLANTIC OCEAN, AMAZON DELTA,
AND EAST CHINA SEA: REINTERPRETATION OF
TERRIGENOUS INPUT PATTERNS TO THE OCEANS

Edward R. Sholkovitz

New and published data for the concentration and relative abundances of rare earth elements (REE) are synthesized for the sediments of the North Atlantic Ocean and East China Sea. The new data come from the shelf, slope, and abyssal regions off North America, the delta of the Amazon River, and the East China Sea shelf. Shale-normalized REE patterns are consistently and significantly (1.8 to 2.0 times) enriched in light REE (LREE) relative to heavy REE (HREE). This observation is consistent with both the limited data for riverine particles and the continental source rock to the N. Atlantic Ocean and casts doubt on the underlying assumption used in the interpretation of oceanic REE data - a flat shale normalized pattern for the terrigenous input of particulate REE to the oceans.

Profiles of REE from box cores on the slope off New England display no diagenetic signal associated with large diagenetically-induced surface enrichments in Mn. No cerium anomalies are observed in these sediments. An assessment of REE diagenesis and fluxes across the sediment/water interface must await pore water data.

The conclusion of Thomson et al. (1984) that there is preferential authigenic removal of light REE onto red clays in the Nares Abyssal Plain is reassessed. Based on the direct comparison of their grey and red clay REE data, with the exception of Ce, there is no distinguishable fractionation of LREE from HREE at this location.

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WHOI Contribution No. 6376.

$^{239,240}\text{Pu}$ IN ESTUARINE AND SHELF WATERS
OF NORTHEASTERN UNITED STATES

Edward R. Sholkovitz and Don R. Mann

The distribution of $^{239,240}\text{Pu}$ between dissolved and particulate forms has been measured from four estuaries on the northeast coast of the United States (Connecticut River, Delaware Bay, Chesapeake Bay and Mullica River). The data cover the whole salinity range from fresh-water input to shelf waters at 35‰ and includes one profile from a nearly-anoxic basin in the Chesapeake Bay. In the organic-rich Mullica River Estuary large scale removal of riverine dissolved $^{239,240}\text{Pu}$ occurs at low

salinities due to salt-induced coagulation, a mechanism analogous to that for iron and humic acids.

Within the 0 to 25-30‰ zone in the other three estuaries, the activity of dissolved $^{239,240}\text{Pu}$ increases almost conservatively. At higher salinities corresponding to shelf water there is a sharp increase in dissolved $^{239,240}\text{Pu}$ activity. The dissolved $^{239,240}\text{Pu}$ activity within each estuary appears to be inversely related to the flushing time of water. For example, Chesapeake Bay with a 6-12 month flushing time has much lower dissolved $^{239,240}\text{Pu}$ activities than does the Connecticut River Estuary with a few days flushing time. We interpret this and other data from the shelf waters to indicate that the sharp decrease in dissolved $^{239,240}\text{Pu}$ activities between shelf and estuarine waters is being driven by removal within the estuaries themselves rather than on the shelf.

Dissolved $^{239,240}\text{Pu}$ activities are lower in the nearly-anoxic bottom waters of Chesapeake Bay indicating enhanced removal by redox transformation of Pu.

The activities of particulate $^{239,240}\text{Pu}$ are highest in the more turbid waters of low salinity regime (0-15‰) but become increasingly insignificant with respect to dissolved $^{239,240}\text{Pu}$ as salinities increase.

In press: Estuarine, Coastal and Shelf Science.

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WHOI Contribution No. 6152.

SEA WATER AND GEOCHEMISTRY

WHAT CONTROLS THE VARIABILITY OF CARBON DIOXIDE IN THE SURFACE OCEAN? A PLEA FOR COMPLETE INFORMATION

Peter G. Brewer

The annual exchanges of carbon dioxide gas between the atmosphere and the surface ocean and the slow but inexorable oceanic uptake of fossil fuel CO_2 are among the most important problems addressed by ocean chemists today.

There is wide agreement as to experimental procedures in this field through the measurement of alkalinity, total CO_2 , pH and pCO_2 of ocean waters, together with physical properties and ^{14}C . More-over the uncertainties surrounding ocean

physical chemistry and the representation of the various thermodynamic constants necessary to define this system now appear to have been solved.

There is, however, widespread disagreement as to the relative importance of physical and biological controls on the CO_2 chemistry of the surface ocean. Indeed, one may divide the scientific papers in this field into two virtually distinct piles: those regarding biological controls as dominant, and those invoking the dominance of physical processes.

What appears to be true is that a complete experiment separating these effects has yet to be done, recognizing that the feedback between ocean mixing and biological productivity prevents, of course, a truly separate set of processes. The great variability of the ocean in space and time suggests the need for a well-coordinated program if progress is to be made in furthering our knowledge of this system.

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WHOI Contribution No. 6170.

HELIUM ISOTOPIC DISEQUILIBRIUM AND GEOCHRONOLOGY OF GLASSY SUBMARINE BASALTS

David W. Graham, William J. Jenkins,
Mark D. Kurz and Rodey Batiza

We have measured isotopic disequilibrium of $^3\text{He}/^4\text{He}$ between He trapped in vesicles and that dissolved in the glass phase of some young seamount basalts to determine $(\text{U}+\text{Th})/\text{He}$ ages. We use the $^3\text{He}/^4\text{He}$ in vesicles (extracted by crushing in vacuo) to correct the dissolved phase He (by fusion of the remaining powder) for the inherited component, and compute the radiogenic $[\text{He}]$. The method is applicable to rocks containing phases with different $(\text{U}+\text{Th})/\text{He}$, and the results have implications for dating lavas in the age range of 10^3 to 10^6 years and for reconstructing the geochemical history of young volcanic systems.

In Press: Nature.

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WHOI Contribution No. 6390.

IRON ENRICHMENTS IN HYDROTHERMAL PLUMES
OVER THE EAST PACIFIC RISE

Andrew Hudson, Michael L. Bender
and David W. Graham

Manganese, iron, and helium isotopes have been measured in samples taken near the crest of the East Pacific Rise at 19°S. Samples were enriched in Mn and in He isotopes, as is typical for waters in this area. Samples were also enriched in Fe; Fe enrichments covary with Mn and ^3He enrichments. The Fe/Mn ratio at four sites ranges from about 2-9, spanning the average value found for metalliferous sediments (3.5).

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WHOI Contribution No. 6115.

THE ROLE OF ATMOSPHERIC DEPOSITION
IN THE GEOCHEMICAL BUDGET OF
TRACE METALS IN THE SARGASSO SEA

Timothy D. Jickells, Thomas M. Church
and Werner G. Deuser

Atmospheric inputs (wet and dry) are compared to deep sea sedimentation rates of trace metals in the Sargasso Sea. The geochemical budgets for several of the elements mainly associated with crustal particles (Al, Mn, Fe and V) demand a significant lateral advective input. For Cd, Cu, Ni, Pb and Zn, this lateral input is small compared to the atmospheric inputs which dominate in this ocean area relatively remote from fluvial sources. Wet deposition dominates over dry deposition for all elements except Fe and Al. For Cd, Ni and Zn, the excesses of atmospheric inputs over removal by sedimentation are consistent with estimates of export from the Sargasso Sea accompanying remineralization of particulate organic matter in the southward flowing North Atlantic Deep Water.

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WHOI Contribution No. 6327.

ENHANCED SCAVENGING OF ^{210}Pb AND
 ^{210}Po BY PROCESSES ASSOCIATED WITH THE
EAST PACIFIC RISE NEAR 8°45'N

David Kadko, Michael P. Bacon and
Andrew Hudson

In 1977 and 1981, a hydrothermal plume was detected at the East Pacific Rise (EPR) near 8°45'N and at MANOP Site M, 25 km east of the EPR, by anomalous ^{222}Rn and Mn concentrations. In 1981, samples were also taken for ^{210}Pb , ^{210}Po and ^{226}Ra analyses to determine if enhanced scavenging of these elements occurred in the plume. At both the ridge crest and at Site M, the $^{210}\text{Pb}/^{226}\text{Ra}$ ratios range from 0.09-0.35, which are among the lowest values ever measured. It appears that removal of ^{210}Pb is occurring by processes operating at or near the seafloor. There is also significant $^{210}\text{Po}/^{210}\text{Pb}$ disequilibrium at both locations, which appears to increase away from the seafloor towards the plume (as indicated by elevated Mn concentrations). An in situ water column scavenging process is suggested by correlation of [$^{210}\text{Pb}-^{210}\text{Po}$] and Mn concentrations in the plume. The residence time of the ^{210}Po is only about 1 year, which is close to its residence time in surface waters but quite short compared to typical deep-sea values. Thus rapid scavenging of the polonium in the plume and relatively rapid settling of particles from the plume is suggested.

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Letters.

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WHOI Contribution No. 6337.

SEASONAL CYCLES OF PARTICLE AND SOLUTE
TRANSPORT PROCESSES IN NEARSHORE SEDI-
MENTS: $^{222}\text{Rn}/^{226}\text{Ra}$ and $^{234}\text{Th}/^{238}\text{U}$
DISEQUILIBRIUM AT A SITE IN
BUZZARDS BAY, MA

William R. Martin and Frederick L. Sayles

Radiochemical measurements leading to the estimation of particle mixing rates and irrigation rates in the sediments of a site in Buzzards Bay, Massachusetts, have been made over nearly two full seasonal cycles. Both particle mixing and sediment irrigation show significant seasonal variability at this site; the variability is consistent with biologically-driven transport mechanism. $^{234}\text{Th}/^{238}\text{U}$ disequilibrium measurements were used to estimate particle mixing rates. Based on three cores taken from December through March and four taken from

June through October, a cold-season average mixing rate of $5.6 \text{ cm}^2/\text{yr}$ and a warm-season average rate of $17 \text{ cm}^2/\text{yr}$ were found. Excess ^{234}Th inventories in the upper 5 cm of the sediments also varied seasonally, with a cold-season average value of 1.8 dpm/cm^2 , significantly less than both the warm-season value of 3.4 dpm/cm^2 and the predicted average value for Buzzards Bay ($\sim 3 \text{ dpm/cm}^2$). $^{222}\text{Rn}/^{226}\text{Ra}$ disequilibrium in sediment pore waters was used to estimate sediment irrigation. Based on a total of seven cores, three seasonal groupings of results were made: (1) December through March, when ^{222}Rn deficits could be explained by vertical molecular diffusion alone, (2) early summer (June), when irrigation was important to at least 20 cm, the maximum depth of the sampled region, and (3) early fall, when irrigation was important to about 10 cm. A nonlocal exchange/vertical molecular diffusion model (Emerson et al., 1984) was used to obtain quantitative estimates of irrigation rates; when the exchange parameter was allowed to vary exponentially with depth below the sediment-water interface, model Rn deficit profiles fit measured profiles quite well.

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WHOI Contribution No. 6213.

THE DISTRIBUTION AND BEHAVIOUR OF ^{230}Th AND ^{231}Pa AT AN OCEAN MARGIN, BAJA CALIFORNIA, MEXICO

Graham B. Shimmield, James W. Murray, John Thomson, Michael P. Bacon, Robert F. Anderson and N. Brian Price

Uranium, Th and Pa isotopes were measured in sediments collected by box core along a transect normal to the Baja California continental margin. Six cores were analyzed, ranging in depositional environment from manganese nodule-bearing, pelagic, red clay to hemipelagic sediments displaying Mn reduction in the upper 5 cm. In the hemipelagic cores, solid-phase Mn peaks due to diagenetic remobilization occur within the upper layers which are well mixed with respect to unsupported ^{230}Th and ^{231}Pa . The fact that ^{230}Th and ^{231}Pa are not concentrated at the Mn peaks suggests that little mobility of these nuclides occurs within the sediment column. Unsupported $^{230}\text{Th}/^{231}\text{Pa}$ activity ratios in the bioturbated layer of the sediments range from 10.9 to 6.6, generally decreasing towards the inshore stations. The flux of ^{230}Th and ^{231}Pa across the sediment/water

interface is almost in balance with the theoretical water column supply in the most distal core, but rapidly increases inshore. This evidence from the sediment column confirms that enhanced ^{230}Th and ^{231}Pa removal occurs at ocean margins, and that ^{231}Pa is removed from the water column to the sediments in preference to ^{230}Th .

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WHOI Contribution No. 6317.

AXIAL VOLCANISM ON THE EAST PACIFIC RISE, 10-12°N

Geoffrey Thompson and Wilfred B. Bryan

The East Pacific Rise axis, 10-12°N, consists of discrete topographic or tectonic units each of which has compositionally distinct magmas. The two major units have an axial bathymetric high, are bounded by transform or overlapping spreading centers, and are suggested to be discrete volcanoes. One shows systematic variation in magma composition along the rift consistent with injection of lava down rift and concomitant low pressure fractional crystallization with distance from the topographic high. The eastern and western limbs of a large overlapping spreading center about 11°45'N have compositionally distinct lavas suggesting separate magma sources. Axial eruptions in the vicinity of a large transform fault (Clipperton Fracture Zone), and at the tips of propagating rifts, show a large variation in composition suggesting a number of independent magma injections. Highly fractionated lavas with composition up to 59% silica are found near the Clipperton FZ. The northern axial portion has, in addition to normal tholeiitic eruptions, some lavas highly enriched in incompatible elements such as K, Ti, Sr, Ba, Zr and La. They are also isotopically enriched with respect to $^{87}\text{Sr}/^{86}\text{Sr}$ composition suggesting that the mantle beneath some selected portions of the axis is compositionally heterogeneous.

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WHOI Contribution No. 6425

DEPARTMENT OF GEOLOGY AND GEOPHYSICS

David A. Ross, Department Chairman

Department of Health and Human Services
United States Department of Health and Human Services

G E O L O G Y

HISTORICAL NOTE ON "EVOLUTION OCEAN BASINS" PREPRINT BY H. H. HESS

Carl Bowin

The now-famous December 1960 preprint of Harry Hammond Hess' paper titled EVOLUTION OCEAN BASINS, which first presented the concept of seafloor spreading, enjoyed rather broad distribution. Hess originally planned to publish that manuscript in the book "The Sea, Ideas and Observations" then being prepared by Editors Maurice Hill, E. Goldberg, Walter Munk and Columbus Iselin. The delay in completion of that volume, together with the intense interest created by the preprint, led Harry to have the paper published instead, more promptly, in the Geological Society of America book PETROLOGIC STUDIES: A VOLUME TO HONOR A.F. BUDDINGTON, in which it was titled "History of Ocean Basins," and to which an Abstract was added. Hess, to all his students and friends, was simply Harry, and to refer to him otherwise would be unnatural.

In that initial preprint I was the only person named in the Acknowledgments, and several people from time-to-time have asked me for insight into Harry's development of his ocean spreading hypothesis. Harry and I had had many conversations in those months preceding December 1960, and I was uncertain as to what aspects of our chats that he may have specifically had in mind, and I never asked him. I had just completed my dissertation in September 1960, entitled Geology of Central Dominican Republic (Bowin, 1960, 1966), and at Harry's asking, remained on at Princeton as an Instructor for a year.

Recently (October 1986), Alan Allwardt of the University of California at Santa Cruz called me regarding that Acknowledgment for a history of Harry Hess' seafloor spreading hypothesis he is preparing. From my review that following weekend of the letters, preprint and reprint materials in my possession I can now, I believe, see an important linkage between our conversations and the development of his hypothesis. During those conversations, I should add, I was very skeptical of his hypothesis and did not accept that the ocean crust was principally serpentinite, as that increased the difficulty of accounting for the origin of the significant volumes of tonalite, quartz tonalite, trondjemite, quartz trondjemite, keratophyre, and quartz keratophyre encountered in my thesis area (Bowin, 1960, p. 162; 1966, p. 25).

Prior to his December 1960 preprint draft, Harry believed that the elevation of ridges (mid-ocean and his mid-Pacific ridge, upon which he found, and named, guyots during the Second World War) was owing to serpentinitization of mantle material by water released from the upwelling limb of a large mantle convection cell (Hess, 1955a, b; 1959b; 1960b, p. 10-11; 1962, 605). The serpentinitization lowered the mantle density, causing uplift of the ridge, but would have had to extend to 20-km depth to account for the 2-km rise of a ridge. I have noted that he uses the phrase "Formerly the writer attributed..." in the preprint, and "Earlier I attributed..." in the 1962 paper in referring to his 1955 and 1959 papers. The use of "formerly" suggests that that was his view up to the writing of the preprint manuscript. Serpentinitization was the reversible reaction adopted that could account for subsequent deflation of the ridges, and hence the drowning of the flat-topped guyots. In his 1959 paper (Hess, 1959a, p. 345) promoting the AMSOC drill hole to the mantle (Project Mohole) he concluded that the apparent uniform thickness of oceanic crust results from it being serpentinite with its base indicating the level of an isotherm or past isotherm (500°C).

The day Fortran manuals arrived, I had begun using the IBM 650 digital computer that the off-campus Forrestal defense research laboratory made available off-hours to Princeton staff and students. A short time later I switched to the CDC 1604 at the Institute of Defense Analysis, available from midnight to 3 a.m. My objective was to calculate the time it took for the 1 1/2-inch-long chialstolite crystals to grow during contact metamorphism in the wall rock of a gabbro intrusion in northern Maine that I had mapped for a Master's thesis for Northwestern University. The heat flow conduction, temperature, and time relations being solved also had impact upon our discussions of Hess's serpentinitization hypothesis for ridge elevation. The increase in temperature gradient in the wall rock during contact metamorphism translated to an increase in temperature gradient and a rise in the 500°C isotherm above an upwelling convection cell to a very shallow level; i.e., above a 20 km depth required for uplift of the ridge by serpentinitization.

Hence, I now infer that prior to our heat-flow discussions, Harry's primary concern had been to raise the ridges and later have them go back down, and that serpentinitization had been the chosen mechanism. The rift zone down the mid-Atlantic ridge with its associated seismicity (Ewing and Heezen, 1956) was inferred to be due to

subcrustal drag on the base of the crust from the horizontal flow of the convection cell (Hess, 1959b, p. 34). That means the crust mainly stayed in place with the convection cell in the mantle moving laterally beneath it (the usual picture of Earth convection cells at that time). The active ocean rift zone was said (Ewing and Heezen, 1956) to be continuous with the African Rifts, and thus Hess appears to originally have envisioned only small separations along the mid-Atlantic rift. After our discussions, with a volume increase upon serpentinization ruled out as a cause for elevation of a ridge, Harry struggled to identify another mechanism for ridge uplift that could decay with time. Thermal expansion of hot mantle material in the upwelling convection limb presumably came to mind soon. I imagine him looking at one of his convection-cell illustrations (such as Hess, 1955b, Fig. 3, diagram 2), possibly with a central rift sketched in, and replacing, in his mind, the serpentinization 'root' by thermally expanded mantle (Hess, 1960b, p. 21; 1962, p. 611). Then the stroke of intuition struck, and the mental confining chains prohibiting large lateral crustal motions were broken. This intuition may have been aided by his having sketched on a 500°C isotherm at the base of the crust, possibly with it dropping below the crust on the flanks, leaving the base of the crust away from the crest as a "fossil" isotherm (Hess, 1959a, p. 345; 1960a; and as in Hess 1960b, Fig. 6) as suggested by Allwardt (personal communication, November 5, 1986). It is difficult to discern whether such a view preceded, or followed, his new visualization of ridge relationships. However, with the new intuition, the guyots could then be seen sinking, simply as they moved away from the hot ridge crest (Hess, 1960b, Fig. 9)! Such an image also explained the thickening of sediments away from the ridge axis and the overall thinness of the oceanic sedimentary column because of the youthful age of the central ocean floor. Seafloor spreading was born! And, the 1960 preprint quickly followed.

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WHOI Contribution No. 6374.

RECENT RELATIVE SEA-LEVEL CHANGE IN EASTERN NORTH AMERICA

Barbara V. Braatz and David G. Aubrey

Eigenanalysis of tide-gauge records between 1920 and 1983 in eastern North America reveals highly variable spatial

and temporal patterns of relative sea-level change. Auxiliary data from numerical modeling suggest that much of the long wave-length (thousands of km) spatial patterns of sea-level change are due to post-glacial isostatic adjustment of the land surface. Filtering the isostatic component from the rates of relative sea-level movement yields residual rates that fluctuate about a coastal mean of 1.0-1.5 mm/yr during this 64-year time interval. This mean rate is within the range of previous estimates of mean rate of eustatic rise in sea level during the past century. Some residual fluctuations (wavelengths of tens to hundreds of km) correlate with tilts of the land surface revealed by geodetic leveling transects, and appear to be related to regional geology (i.e., basement structures and tectonic provinces in Florida, Georgia, the Carolinas, and the Chesapeake Bay area; fault reactivation in northern New England and the Maritime Provinces). These results suggest that tide-gauge data can be used to determine neo-tectonic movements along this coastline. Analysis of the temporal patterns of relative sea-level change reveals a gradual increase in the rate of rise centered at about 1934, which may be due to steric expansion of the ocean. Broad peaks in the spectrum of temporal sea-level fluctuations at 3-, 6-, and 20-year periodicities (significant at the 80% level) may be a reflection of oceanographic, atmospheric, and astronomical forcing.

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WHOI Contribution No. 6205.

VARIATIONS IN OCEANIC LAYER 2 ELASTIC VELOCITIES NEAR HAWAII AND THEIR CORRELATION TO LITHOSPHERIC FLEXURE

Thomas M. Brocher and Uri S. ten Brink

Analysis of the travel-times and amplitude-range distributions of both compressional and shear wave arrivals on 15 closely-spaced refraction profiles reveals a pronounced, systematic, and symmetric dependence of average Layer 2 velocities on their distance to the north and south of the Hawaiian ridge. Beyond the flexural arch surrounding the ridge the velocity-depth solutions indicate a normal Layer 2. Within the arch, approximately 155 km from

the ridge, the average elastic velocities in Layer 2 are lowered by an average of 0.8 to 0.9 ± 0.2 km/s. Within 75 km of the ridge the average velocities are again normal. Elastic and elastic-plastic flexural models for the regional compensation of the Hawaiian islands predict tensional stress drops of 0.8 kBar in the upper lithosphere for the region having lowered velocities in Layer 2, which are similar in magnitude with laboratory measurements of the confining pressure drop necessary to reduce velocities in porous basalts by 0.5 km/s. A significant inverse relationship (correlation coefficient of 0.818) exists between the average elastic velocities in the upper 1.0 km of the igneous crust and the strain in the upper crust calculated from these flexural models. The correlation between lowered average velocities in Layer 2 and increased tensional stresses and strains suggest that significant crack opening in the upper crust accompanies the flexure. These observations are the first reported for a mid-plate load and corroborate previous suggestions from seismic and flexural data at subduction zones.

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WHOI Contribution No. 6132.

TECTONIC CONTROLS ON INITIAL CONTINENTAL RIFTING AND THE EVOLUTION OF YOUNG OCEAN BASINS -- A PLANETARY PERSPECTIVE

Wilfred B. Bryan

A review and comparison of planetary tectonic literature and terrestrial interpretations of both oceanic and continental tectonics suggests that the Earth, in common with other terrestrial planets, may have developed a global tectonic grid very early in its history. This grid, still preserved in ancient continental crustal fragments, is preserved by both vertical and lateral fracture propagation. It influences both the direction of initial continental rifting and the location and orientation of seafloor fracture zones in a developing young ocean basin. Seafloor spreading directions must continue to be controlled by the direction of easiest slip along major inter-continental wrench faults; the Atlantic Ocean appears to be still in this stage. Development of subduction zones around the margin of an ocean basin permits greater freedom in spreading direction. At this stage, as represented by the Pacific Ocean, ridge

jumps and changes in spreading direction may occur as in spreading geometry readjusts to more closely reflect stresses associated with underlying convection cells. At subduction zones, rejuvenation tectonics still operate; thick, cold oceanic crust may impose its tectonic grain on the relatively thin, overriding edge of the continental plate; but young, thin, and hot oceanic crust is forced to conform to the tectonic grain of thick, cold continental crust. Examples of both effects can be seen along the eastern margin of the Pacific.

It is concluded that the structure and evolution of young ocean basins is strongly influenced by ancient fracture patterns in the adjacent continental blocks. Although greater freedom for readjustment may develop as an ocean basin matures, the continued need to move, or interact with, major blocks of continental lithosphere may continue to impose severe limitation on directions and rates of spreading. Both oceanic and continental tectonics can be best understood in terms of mutual interactions between plate tectonics, rejuvenation tectonics, and continental remnants of an original ancient global-scale tectonic grid.

In press: Tectonophysics.

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WHOI Contribution No. 6154.

TECTONIC MODEL OF THE MALAWI RIFT, AFRICA

C. J. Ebinger, B. R. Rosendahl
and D. J. Reynolds

In the active Malawi rift, Africa, segments of the border fault system define basins with different acoustic stratigraphies, sediment thicknesses, and variations in the style and amount of faulting. Cross-sectional morphologies and fault patterns within the rift basins depend on the geometrical arrangement of these major boundary fault systems within the Malawi rift, and these patterns are similar to those observed in the Tanganyika rift. Where Proterozoic to Mesozoic structures trend approximately N-S, border fault segments may locally reactivate existing structures or have an orientation subparallel to ancient trends, but the 100 km border fault segmentation generally does not appear to be controlled by pre-existing structure. Structural and stratigraphic patterns within the Malawi and Tanganyika rifts indicate that border fault segments with a zig-zag shape evolve to regionally curvilinear

border fault systems through progressive episodes of extension. The central parts of border fault segments, where maximum vertical displacements have been observed are separated by 50-90 km. The uniform separation of the central parts of border fault segments in both the Malawi and Tanganyika rifts suggest stress concentrations with an average wavelength of 70 km occur along the length of the Tanganyika and Malawi rifts.

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WHOI Contribution No. 6187.

STICK CHARTS OF THE MARSHALL ISLANDS

K. O. Emery

Native Marshall Islanders used charts made from palm ribs lashed together and shells representing atolls and islands tied to the ribs. They served for navigation on sailing canoes in the archipelago until the late nineteenth century, but their use was kept so secret that they were largely mysteries to European and American visitors. Comparison of more than two score of drawings and photographs from publications showed that the charts can be oriented correctly by aligning their longer straight sticks with the crestal azimuth of the dominant swell produced by the northeast trade wind. In this position, atolls have reasonably correct relative positions with respect to true north, considering limitations imposed by gaps between sticks, objectives of navigators, and artistic patterns. Secondary sticks outline areas of refracted swells in the lees of atolls, permitting navigators to determine canoe positions even when atolls were far beyond view.

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WHOI Contribution No. 6232.

CENOZOIC DEVELOPMENT OF THE OUTER CONTINENTAL MARGIN OFF WESTERN NOVA SCOTIA

Stephen A. Swift

The growth pattern for the outer
continental margin of Nova Scotia during

the Late Cretaceous and Cenozoic was studied using seismic stratigraphy and well data. Sediment accumulation was broadly controlled by temporal changes in relative sealevel, but significant spatial and temporal changes in accumulation patterns were caused by changes in sediment supply rate, morphology, erosion by abyssal currents, and salt tectonics. A Jurassic-Lower Cretaceous carbonate platform remained exposed until the Late Cretaceous and controlled the location and steepness of the paleoslope until the late Miocene. Local erosion of the outer shelf and slope in the late Paleocene-early Eocene produced chalky fans on the upper rise. The relationship between erosion of the shelf in the late Eocene and early Oligocene and abyssal current erosion of the upper rise in the Oligocene is unclear. Seaward extensions of Tertiary shelf-edge canyons are poorly defined except for the Eocene fans. In the Miocene, abyssal currents eroded a bench on the upper continental rise. Subsequently, sediments lapped onto and buried the paleoslope. The lower rise above Horizon A⁶ (Oligocene is composed of fans and olistostromes shed from halokinetic uplift of the upper rise. Current eroded unconformities are common in the rise sequence, but the only current deposit is a Pliocene interval (<300 m) restricted to the lowermost rise. Pleistocene turbidity currents eroded the present canyon morphology.

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WHOI Contribution No. 6127.

SUBMARINE GEOLOGY

Brian E. Tucholke

The last significant synthesis of the geology of the continental slope and rise off the eastern United States was published by Emery and Uchupi (1972). In the dozen years since their work, a large amount of geological and geophysical data has been acquired, and there have been many new insights into the geologic structure and history of the margin. Within the limited space available, this chapter is intended to address four points: 1) to summarize the kinds and locations of new geological and geophysical data that have become available, 2) to provide an updated

overview and summary of the general geologic conditions extant in the region, 3) to identify major uncertainties in our knowledge of the geologic structure and processes along the margin, and 4) to summarize the geologic development of the margin from the time of initial sea-floor spreading in the Middle Jurassic. This work is based on an exhaustive survey of unpublished and "gray" literature as well as published reports, only a small fraction of which can be cited here. Specifically excluded are extended reviews of geophysical potential-field data such as gravity and magnetics. The implications of these data for geologic structure, however, are incorporated in the text. The free-air gravity field recently has been reviewed in detail by Grow et al. (1979b), Bowin et al. (1982), and Ewing (1984a-c), and magnetic anomaly patterns have been mapped most recently by Klitgord and Behrendt (1977) and Zeitz and Gilbert (1980a, b).

This summary focuses on the continental slope and the continental rise above 4000 m, generally within the territorial waters of the U.S. Atlantic margin. Although the continental shelf, lowermost continental rise, and abyssal plains are outside this focus, they are discussed where their features have an important bearing on the geologic development of the continental margin.

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WHOI Contribution No. 5975.

TERTIARY PALEOCEANOGRAPHY OF THE WESTERN NORTH ATLANTIC OCEAN

Brian E. Tucholke and Gregory S. Mountain

The Tertiary paleoceanography of the North Atlantic Ocean is known in greater detail than that of earlier periods because this upper part of the geologic record is more accessible to geological and geophysical sampling. The Tertiary record also appears more complex, primarily because of the greater data density. Nonetheless, there are large segments of the Tertiary geologic record about which we know relatively little. For example, the Paleocene and Oligocene sedimentary sections are not well represented on the shallow continental margin because erosion

during sea-level lowstands removed much of the section. The same sections in the deep basin are poorly known because low sediment accumulation rates or erosion by abyssal currents has resulted in preservation of only thin sections. In addition many of these sections are very inadequately sampled in existing Deep Sea Drilling Project (DSDP) drillsites.

Unlike earlier periods, the North Atlantic Ocean basin in the Tertiary was strongly affected by the action of abyssal contour-following currents, particularly following Eocene time. These currents intermittently caused extensive seafloor erosion along the continental margins, decorated the basin with large sediment drifts, and probably influenced productivity patterns by stimulating upwelling. The development and patterns of surface currents, and to some extent deep currents, are dealt with from a paleobiogeographic viewpoint by Berggren and Olsson (this volume). In this paper, we summarize the Tertiary paleoceanography based mainly on other data from the geologic record. The data base consists principally of seismic stratigraphic interpretations that are correlated with rock stratigraphy at DSDP and other boreholes. These data are interpreted within the plate-tectonic evolution of the North Atlantic Ocean basins. Although we concentrate on the paleoceanographic development of the western North Atlantic, it is meaningless to consider this part of the ocean in isolation, so we also discuss "external" factors that affected the geologic record in the western basins. Important aspects of the geologic and oceanographic development are summarized in Figure 1, and Plate 10 shows time-slice snapshots of North Atlantic paleoceanography for the late Maestrichtian, late Paleocene, early middle Eocene, early Oligocene, and late Miocene.

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WHOI Contribution No. 6125.

SUSPECT TERRANES IN THE NORTH AMERICAN
MARGINS AND RELATIVE SEA-LEVELS

Elazar Uchupi and David G. Aubrey

Sea-level trends deduced from tide gauges show considerable variation along strike both on the convergent (western) and divergent (eastern) edges of the North American plate. This variation may reflect the differential reaction to rifting (extension) and sediment loading (in the east) and subduction and translation (in the west) of allochthonous and autochthonous blocks welded onto the North American craton. That these autonomous blocks impart distinct signatures on records of relative sea levels suggests promise in deducing complex terrane topography of other margins using tide-gauge data.

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WHOI Contribution No. 6301.

IMAGING THE OCEAN FLOOR -
HISTORY AND STATE OF THE ART

Peter R. Vogt and Brian E. Tucholke

Bathymetry is the science and technology of ocean depth measurement. In the narrow and traditional sense, the objective of bathymetry is to define the sea floor topographic surface, $h(x,y)$. Most bathymetric studies also interpret the depth data -- usually displayed in contour charts or profiles -- in terms of undersea geomorphology and, in concert with other geophysical data, as a constraint on sub-seafloor geologic structure. In many parts of the ocean, bathymetry is about the only type of geological information available. Thus, compared to land, seafloor topography necessarily plays a larger role in geologic interpretations.

The North Atlantic Ocean covers an enormous area ($4 \times 10^7 \text{ km}^2$) with diverse and numerous geomorphic features at many scales. Bathymetric control is very uneven in distribution and quality. Some areas have been surveyed by overlapping swaths of multibeam bathymetry with reliable mapping of features less than 1 km apart, while other areas of 10^3 or 10^4 km^2 have no soundings, particularly in the equatorial latitudes. Unlike many previous studies, this chapter does not offer a systematic guided tour of the submarine topography. (See Holcombe, 1977 for a glossary of ocean-bottom land forms.) Recent syn-

theses of Atlantic bathymetry include Vogt and Perry (1982) and Emery and Uchupi (1984). Instead, the potential of seafloor "imaging" is evaluated over a large range of spatial scales, approximately ten orders of magnitude from the form of the entire Atlantic basin down to the size of grains in seafloor sediments. Under "submarine imaging" are included 3-D (stereoscopic) descriptions of bottom topography (ordinary bathymetry) as well as 2-D maps recorded by traditional sidescan sonar and photographic systems. "Subaerial imaging" of exposed oceanic crust (e.g., Iceland) includes aircraft and satellite instrumentation that derive images from radar, images illuminated (visual) or energized (near infrared) by solar radiation and images internally energized by geothermal processes (broadband infrared). All these techniques have contributed to one total "image" of the shape, texture, and contrast in basic physical properties across a sharp physical boundary, the outer edge of the solid earth.

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WHOI Contribution No. 6226.

G E O P H Y S I C S

GEOFYSICAL PROFILING, ODP LEG 102

Christian A. Auroux and Ralph A. Stephen

We obtained routine geophysical measurements during ODP Leg 102. On the first part of Leg 102, geophysical data were collected by the R/V FRED H. MOORE during the site survey and by the JOIDES Resolution during the transit from Site 418 to Norfolk, Virginia (Fig. 2A). Underway-geophysics data were also collected on board JOIDES Resolution during the transit to the Azores (second part of Leg 102) from Norfolk to Ponta Delgada (Fig. 2B and 2C).

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WHOI Contribution No. 6284.

HEAT FLOW AND CONTINENTAL BREAKUP:
THE GULF OF ELAT (AQABA)

Zvi Ben-Avraham and Richard P. Von Herzen

Heat flow measurements were made in the major basins of the Gulf of Elat (Aqaba), northern Red Sea. The Gulf is located at the southern portion of the Dead Sea rift which is a transform plate boundary. Vertical temperature gradients were measured with a probe which allows multiple penetration of the bottom during a single deployment, and thermal conductivities were determined by needle probe measurements on sediment cores. A mean heat flux of about 80 mWm^{-2} was found, and the values tend to increase from north to south. This latitudinal gradient corresponds to the general trend of gradual thinning of the continental crust of the Gulf towards the Red Sea where oceanic crust exists. The heat flow data, together with other geophysical data, are consistent with a propagation of rifting from the Red Sea northward along the Dead Sea Rift, where the fractures are primarily shear. The Gulf forms a transition between these two tectonic regimes, extensional Red Sea to the south and transform Dead Sea to the north.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 6299.

TOPOGRAPHY AT THE CORE-MANTLE BOUNDARY

Carl Bowin

Analysis of the Earth's gravity field using ratio of gravity to geoid (g/N) and cumulative degree contribution curve techniques improves resolution of the mass, depth, and dimensions of anomalous mass sources within the planet. The source for four of the ten major geoid anomalies of the Earth have large contributions from harmonic degrees 2 and 3, lie at the core-mantle boundary, and the greatest has a mass anomaly of $4.2 \cdot 10^{22}$ grams. That boundary has a density contrast (4.4 gm/cm^3) which is greater than at any other location, including the contrast at the Earth's surface with space. Thus, relatively small vertical undulations of that boundary produce very large mass anomalies.

Topographic relief of less than 3 km at the core-mantle boundary occurs, and accounts for the existence of the largest geoid anomalies occurring on the Earth.

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WHOI Contribution No. 6330.

TWO-DIMENSIONAL SEISMIC REFLECTION
MODELING OF THE INFERRED FOSSIL OCEANIC
CRUST/MANTLE TRANSITION IN THE BAY OF
ISLANDS OPHIOLITE COMPLEX

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

We investigate the character of Moho reflections from oceanic lithosphere by computing two-dimensional synthetic seismogram models of the inferred fossil crust/mantle transition observed in the Bay of Islands Ophiolite Complex, Western Newfoundland. In an attempt to simulate a seismic reflection experiment on oceanic lithosphere, we calculated normal-incidence seismograms, at a horizontal spacing of 500 m, for three non-contiguous sections of the ophiolite totalling 64 km in horizontal length. In the synthetic models, the Moho reflection event varies from a single phase to two or more phases of up to 1 s (two-way traveltimes total duration). Individual phases show lateral variations in amplitude, and their two-way traveltimes vary by as much as 0.25s over horizontal distances as short as 10km. Lateral discontinuity of the Moho phases results in abrupt variations in the Moho phase. The geological depth to the first-arriving/highest-amplitude Moho structures generating the highest-amplitude Moho reflections range from laterally discontinuous high- and low-velocity lenses of mafic and ultramafic material to inter-layered mafic and ultramafic cumulate lithologies in the Moho Transition Zone. Reflection amplitudes from the top of the residual upper mantle are insignificant, and our modeling suggests that using the highest-amplitude Moho reflector to estimate the thickness of magmatic material can result in errors of up to 1 s two-way traveltime. Multichannel seismic data from both the Western Pacific and Western North Atlantic show traveltime variations similar to those observed in the synthetics. Multiphase Moho reflection events, laterally discontinuous on a scale similar to that observed in the synthetic models, can also be identified in the Western North Atlantic data, suggesting that the structures observed in the inferred crust/mantle transition of the ophiolite

may be characteristic of oceanic lithosphere.

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WHOI Contribution No. 6193.

GEOACOUSTIC SCATTERING FROM SEAFLOOR FEATURES IN THE ROSE AREA

Martin E. Dougherty and Ralph A. Stephen

A strong "refraction branch diffraction," presumably due to scattering from a lateral heterogeneity on or below the sea floor, has been observed on ocean bottom hydrophone data from the Rivera Ocean Seismic Experiment (ROSE). This arrival is unusual because of its coherence and relatively large amplitude. Finite difference modeling of a number of possible seafloor diffractors and associated lateral velocity variations are presented which demonstrate the occurrence and characteristics of "refraction branch diffractions." In general, the half-width of the diffractor must be approximately the same as the seismic wavelength in order to produce a strong diffraction. Velocity gradients present in the models, as well as P-S conversion, complicate the wavelength-halfwidth relationship. Three different models, a hill, a valley, and a subsurface, high-velocity block, all produced diffractions of sufficient amplitude to explain the data. There is a hill along the line with approximately the same dimensions as the model hill and it is the proposed source of the diffracted energy in the data. The large models used also clearly demonstrate the existence of phases which are theoretically possible, but rarely seen in marine seismic (geoacoustic) data such as the pseudo-Rayleigh wave and the P and S interference head waves.

Supported by: ONR Contract N00014-85-C-0001.

WHOI Contribution No. 6370.

SEISMIC AMPLITUDE MODELLING AND THE SHALLOW CRUSTAL STRUCTURE OF THE EAST PACIFIC RISE AT 12°N

K. M. Fischer and G. M. Purdy

Velocity structures of the upper 2 km of the oceanic crust were used to model

seismic refraction data collected on the eastern flank of the East Pacific Rise at 12°N during the Rivera Ocean Seismic Experiment. Data, generated with a Bolt 1500C airgun source, show multiple narrow (<1 km in range) peaks in the amplitude of the first refracted arrival. Record sections separated by as much as 180 km indicate similar amplitude versus range patterns, suggesting that the amplitude peaks are caused by consistent structural features, and not by random crustal inhomogeneities. These amplitude highs do not consistently correlate with seafloor bathymetry, and hence cannot be explained solely by topographic focussing of seismic energy. Through travel-time analysis and ray-tracing we find a crustal model with two vertical zones of concave gradients which focus rays at 6 and 8 km range. Synthetic seismograms and power versus range patterns computed for this model by the reflectivity algorithm are consistent with the two peak amplitude pattern observed on nearly all airgun record sections. These results suggest that the vertical gradient zone structure of the uppermost 2-3 km of ocean crust is fundamentally continuous over the ROSE area.

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WHOI Contribution No. 6333.

THE RELATIONSHIP BETWEEN COASTAL SEICHES AT PALAWAN ISLAND AND TIDE-GENERATED INTERNAL WAVES IN THE SULU SEA

G. S. Giese and R. B. Hollander

A rigorous analysis of tide records from Puerto Princesa on Palawan Island in the Philippines demonstrates that the harbor's fortnightly varying seiche activity is coherent with the cycle of spring-neap tides in the Sulu Sea and lags it by 2.9 days. This delay closely matches the time required for the formation and travel of tide-generated internal solitary waves northwestward across the Sulu Sea and strongly supports the hypothesis that coastal seiches can derive their energy from the tide-producing forces by way of tidal currents and internal waves. However, the analysis also indicates that the quantity of energy transferred from the tide to the seiches has a pronounced seasonal variability which may be related to seasonal variations in wind stress. It is unlikely that accurate predictions of tide-

produced seiches will be possible without a sound theoretical understanding of the mechanisms by which energy is transferred to them by deep-sea internal waves.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 6245.

MEASUREMENT OF IN SITU SEDIMENT THERMAL
CONDUCTIVITY: CONTINUOUS-HEATING METHOD
WITH OUTRIGGED PROBES

J. Jemsek and R. Von Herzen

A multipenetration heat flow instrument featuring outrigged thermal probes has been modified to include in situ thermal conductivity measurement capabilities using a transient heating technique similar to the needle-probe method used on sediment cores. Due to the small radial dimension of the outrigged probes, simple analytical approximations can be used for predicting probe temperatures at relatively short times (2 minutes), which allows accurate equilibrium in situ temperature and thermal conductivity measurements to be made in less than 15 minutes of recording time. The largest instrumental error is incurred in estimating the sediment thermal diffusivity from empirical relationships between conductivity and diffusivity. Although the diffusivity is less certain for sediment of high conductivity, the fractional uncertainty in conductivity is about 2% for nearly all marine sediment. The total instrumental uncertainty for the single probe design is estimated to be 3%. A biaxial probe design, which has the heater and temperature sensor housed in separate steel tubes, has an additional 3% uncertainty due to the imprecise nature of the effective probe radius used in the calculation of the probe time constant. Field calibration of the in situ conductivity measurements was made by comparing the mean conductivity of in situ stations to needle-probe measurements of nearby piston cores. For ten selected sites, in situ and laboratory means show agreement to within 6% with no systematic differences. Significant differences in such field comparisons can be attributed to the discrete sampling of the sediment section. Realistic synthetic conductivity profiles are obtained from gamma ray attenuation (GRAPE) logs of sediment cores in conjunction with water content and needle-probe conductivity measurements. Such profiles illustrate that the potential error in mean conductivity determinations may exceed 10% if large

amplitude vertical variations in conductivity exist at a characteristic wavelength which is small compared to the probe separation.

In press: CRC Handbook of Seafloor Heat Flow.

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WHOI Contribution No. 6300.

HEAT FLOW AND LITHOSPHERIC THINNING IN THE
LIGURIAN BASIN (N. W. MEDITERRANEAN)

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

We present preliminary results of 78 new heat flow measurements collected on a transect across the central Ligurian Basin (South France to Corsica margins). The basin-wide flux has an average of 79 ± 21 mWm⁻² with significant local and regional variability. Correction for the deposition of up to 5 km of post-rift sediment gives a mean value of 102 mWm⁻² which is similar to values for normal oceanic crust of the same age (21 Ma). The total tectonic subsidence (TTS) calculated for the region with probable oceanic crustal structure is comparable to or somewhat greater than 21 Ma crust of the major ocean basins. The heat flow data overall are compatible with the observed TTS in showing substantial lithospheric thinning, but do not tightly constrain thermal models of continental extension and rifting.

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WHOI Contribution No. 5761.

A DEEP TOWED EXPLOSIVE SOURCE FOR
SEISMIC EXPERIMENTS ON THE OCEAN FLOOR

Donald E. Koelsch, Warren E. Witzell, Sr.,
James E. Broda, Frank B. Wooding
and G. M. Purdy

A new seismic source for carrying out high resolution measurements of deep ocean crustal structure has been constructed and successfully used in a number of ocean bottom refraction experiments on the Mid Atlantic Ridge near 23°N. The source is towed within 100m of the ocean floor on a conventional 0.68" coaxial cable and is capable of firing, upon command from the

research vessel, up to 48 individual 2.3 kg explosive charges. The explosive used was commercially available Penta-Erythritol-Tetra Nitrate (PETN) that was activated by 14.9 gm/m Primacord and DuPont E-97 electrical detonators. For safety reasons each detonator was fitted with a pressure switch that maintained a short until the source was at depth in excess of approximately 300 m. In addition, a mechanical protector isolated the detonator from the main charge and was only removed by the physical release of the explosive from the source package. These and other safety precautions resulted in several misfires but three experiments were successfully completed during the summer of 1985 at source depths of 3000-4000m.

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WHOI Contribution No. 6298.

FOCAL DEPTHS AND MECHANISMS OF LARGE EARTHQUAKES ON THE ARCTIC MID-OCEAN RIDGE SYSTEM

John P. Jemsek, Eric A. Bergman, John L. Nabelek and Sean C. Solomon

As part of a global study of the source characteristics and tectonic implications of large earthquakes on mid-ocean ridges, we report on the focal depths and mechanisms of the six largest earthquakes that have occurred in the last 20 years on the Arctic mid-ocean ridge system. For each earthquake we invert the long-period P and SH waveforms to estimate the parameters of the best-fitting point source, including seismic moment, centroid depth, double-couple source orientation, and source time function. Three of the earthquakes occurred on the oceanic spreading center in the Eurasian Basin, along ridge segments spreading at half rates of 4 to 6 mm/yr. These events have mechanisms very similar to those of ridge crest earthquakes on the Mid-Atlantic Ridge: almost pure normal faulting on planes that dip at approximately 45° and strike parallel to the rift axis, moments of 4 to 5 x 10²⁴ dyn cm, centroid depths of 1-2 km beneath the seafloor, and water depths (inferred from the predominant period of water column reverberations) appropriate to epicentral locations within the median valley. The remaining three earthquakes, also characterized by normal faulting, are associated with the continuation of the divergent

plate boundary (2 to 3 mm/yr half rate) onto the continental shelf of the Laptev Sea where the crust becomes transitional in nature. One of the largest known spreading center earthquakes (August 25, 1964, $M_0 = 1 \times 10^{26}$ dyn cm) occurred where the oceanic ridge intersects the outer edge of the continental slope. Wave-form inversion for this event can resolve unilateral rupture from north to south (landward) along a fault at least 30 km in length. The centroid depth is 5 km beneath the seafloor in crustal material with an unusually low shear velocity, but a centroid depth as great as 15 km cannot be ruled out. Two earthquakes beneath the continental shelf have significantly greater centroid depths (10 to 20 km) than mid-ocean ridge earthquakes, indicating a thicker brittle regime and a cooler thermal structure than are typical of oceanic spreading centers. The tectonic environment of these events is more representative of rifted continental lithosphere than of a mid-ocean ridge.

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WHOI Contribution No. 6283.

MEASUREMENTS OF PLUME FLOW FROM A HYDROTHERMAL VENT FIELD

Sarah A. Little, Keith D. Stolzenbach and Richard P. Von Herzen

Simultaneous velocity, temperature, and conductivity data were taken in the convective flow emanating from a hydrothermal vent field located at 10°56'N, 103°41'W on the East Pacific Rise (EPR). The horizontal profiles obtained indicate that the flow field approaches an ideal plume in the temperature and velocity distribution. Such parameters as total heat flux and maximum plume height can be estimated using either the velocity or the temperature information. The results of these independent calculations are in close agreement, yielding a total heat flux from this vent site of 3.7 ± 0.8 MW and a maximum height of 150 ± 10 m. The non-linear effects of large temperature variations on heat capacity and volume changes slightly alter the calculations applied to obtain these values.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 6268.

POST-MIOCENE RIFTING AND DIAPIRISM
IN THE NORTHERN RED SEA

Yossi Mart and David A. Ross

Rifts and diapirs are the dominant structures in the bathyal zone of the northern Red Sea, where commonly the diapirs ascend along normal faults associated with the rifts. The diapirs, in this manner, form elongated features exceeding lengths of 30 km and widths of 4 km. They also penetrate a sedimentary sequence of about 1000 m thickness or less; thicknesses generally considered to be barely adequate for the gravity conversion required to initiate diapiric motion. We suggest that the development of diapirs under these minimal overburden conditions was made possible by the high thermal gradients in the area, resulting from the underlying attenuated continental crust and the ascending mantle that prevail in the rift system of the northern Red Sea. Diapiric evolution was also dependent on the extensional tectonic regime, with its numerous normal faults, forming weaknesses along which the diapirs could move upwards.

In press: Marine Geology.

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WHOI Contribution No. 6189.

A DETERMINATION OF THE SEISMIC
VELOCITY STRUCTURE OF SEDIMENTS
USING BOTH SOURCES AND RECEIVER
NEAR THE OCEAN FLOOR

G. M. Purdy

A trial experiment proves the power and practicality of using both sources and receivers near the ocean floor to make precise measurements of deep (~6000 m) ocean sediment velocity structure. A digitally recording ocean bottom hydrophone receiver operating at a sampling rate of 1800 Hz recorded clear arrivals with bubble pulse frequencies of ~500 Hz from 4 lb explosive charges detonated at depths of 5500 m along a 4 km long wide angle reflection profile. It is shown that corrections for changes in source depth may be computed without approximation and without prior knowledge of the velocity structure. The experiment was located at longitude 56°W in the trough of the Kane Fracture Zone. The velocity structure of the one kilometer thick sedimentary section reveals a 310 m

thickness of 3 km/s material overlying igneous basement.

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Researches, 8, 75-91, 1986.

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WHOI Contribution No. 6131.

NEW OBSERVATIONS OF THE SHALLOW
SEISMIC STRUCTURE OF YOUNG OCEANIC CRUST

G. M. Purdy

The results are presented of three new experiments carried out on the Mid-Atlantic Ridge (MAR) near latitude 23°N using a unique method of studying the seismic structure of the uppermost few hundred meters of the oceanic crust. The data were collected using a fixed ocean floor hydrophone receiver and a controllable explosive source that was towed within a few tens of meters of the rugged bottom topography. These 1-2 km long refraction lines produced for the first time direct observations of the compressional wave velocity structure of the uppermost 200-300 m of the young igneous crust. One experiment was carried out over the site of Hole 648B of the Ocean Drilling Program on a small volcano within the median valley of the MAR. The seafloor velocity was observed to be 2.1 km/s underlain by an approximately linear velocity gradient of 4 s^{-1} . Given that we know the crust at this location consists of fresh basalt lavas with laboratory-measured velocities in excess of 5.8 km/s, porosities at the seafloor of as high as 30-50% are inferred. The two other experiments were located over 7 my old crust near DSDP Site 395 west of the MAR, and were separated by only 14 km laterally, but by over 1400 m in water depth. The experiment positioned in the ~100 m thick sediment pond and that located 14 km to the south atop a prominent topographic high produced results that, within the data resolution, were indistinguishable. The velocity of the uppermost basaltic basement was 4.1 km/s and the velocity gradient was less than 0.5 s^{-1} . This ~2 km/s difference in velocity between the two sites is assumed to be a consequence of age related modifications to the physical properties of the crust. If the primary change is in only the total porosity, then a 15-20% reduction is required to explain these observations. This seems unlikely because any such pervasive process would have been previously observed in geophysical and sampling data (e.g. off-axis volcanism, secondary mineral deposition,

tectonic compression). A combination of many processes acting in unison would be necessary to produce such a decrease in porosity. If the geometry of the cracks and voids were modified in just the right way, then no change in total porosity is required to explain the velocity difference. These on-bottom refraction profiles are proven to be viable and practical experiments that can provide precise information on a scale appropriate to many of the ocean floor's geologic features. They produce results that may be correlated in a meaningful way with results of ocean drilling and downhole measurements.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 6310.

MIGRATION OF MID-OCEAN RIDGE VOLCANISM

Hans Schouten, Henry J. B. Dick
and Kim D. Klitgord

We propose a model linking the propagation of small-offset volcanic spreading centre segments along mid-ocean ridge crests with absolute motion of the plate boundary relative to the underlying mesospheric frame. Such a relationship could be caused by a purely vertical flow of the mantle under spreading centres and would have value in constraining past plate motions from non-transform trends generated during along-ridge propagation and in linking the major-element variability of oceanic crust and upper mantle to the bulk composition and temperatures of mantle ascending under mid-ocean ridges.

In press: Nature.

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WHOI Contribution No. 6157.

A SEISMIC REFLECTION SURVEY OF DSDP SITES 417 AND 418

D. A. Senske and R. A. Stephen

Single channel seismic reflection profiles obtained in the vicinity of DSDP sites 417 and 418 have been studied to determine the relation between reflectors and sediments cored at these sites. Correlation of adjacent profiles has allowed

for the production of maps of depth to basement, depth to sedimentary horizons, bathymetry, and total sediment thickness.

Three reflectors have been observed in the sediment sequence. Two have been correlated to horizons described in the literature elsewhere in the region while the third remains unidentified. An Albian/Genomanian reflector has been identified as B and corresponds closely to the "black clay facies." The second reflector, middle Eocene in age, corresponds to reflector A^c. Elsewhere A^c correlates to a chert layer. However, no cherts were sampled at either site 417 or 418. Due to the variability in intensity of the reflection for A^c it is believed that it is possible to relate reflection intensity with the presence or absence of cherts. The unidentified reflector, Miocene/Oligocene(?) in age, correlates to a turbidite deposit or an erosional surface.

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WHOI Contribution No. 6334.

EXTENDING THE LINEAR REGIME OF THE SEISMIC WAVEFORM INVERSION PROBLEM

Peter R. Shaw

A method is presented for expanding the "locally linear" regime in the iterative seismic waveform inverse problem. This formulation increases the class of starting models that successfully converge on a solution.

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WHOI Contribution No. 6292.

PLATE RECONSTRUCTIONS OF THE SOUTH ATLANTIC USING SEASAT ALTIMETER DATA

Peter R. Shaw

Fossil fracture zones in the world's oceans appear clearly in the Seasat altimeter (geoid) data at wavelengths of about one hundred km and less. In the North and South Atlantic these signatures are stable in form and amplitude from the ridge crest to crust tens of millions of years old and can be mapped across nearly the width of the basin. The signatures diminish in amplitude markedly on crust older than 70 to 80 MYBP, apparently when thickly covered by sediments. Because fossil fracture

zone trajectories closely approximate plate motion flow lines, they may be used to infer the plate kinematic history of the ocean basin. In this paper I describe a new method for estimating the relative poles of opening describing the history of motion between two plates using fracture zone trajectories. The method is an interactive inversion whereby the trajectories of synthetic flow lines are linearized with respect to the pole parameters. When applied to the Seasat altimeter track data, a waveform inversion based upon this method is possible in which the altimeter data are modelled using a synthetic geoid fracture zone signal. This waveform inversion is applied to seventeen prominent fracture zones in the Central and South Atlantic to estimate the poles of opening between the South American and African plates. Altogether, 1,022 Seasat fracture zone crossings are used; for each of these a waveform comparison is made. The new method is found to be robust, and converges to a stable set of pole solutions even if the initial flow lines are small circles about a single pole that poorly approximates the observed trajectories. The solution poles document a Cenozoic plate reorganization similar to that in the North Atlantic.

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WHOI Contribution No. 6347.

FINITE DIFFERENCE METHODS FOR BOTTOM INTERACTION PROBLEMS

Ralph A. Stephen

The finite difference method is a powerful technique for studying seismo-acoustic problems on the ocean bottom. A finite difference method is presented which is stable for sharp, rough liquid-solid interfaces. Arbitrary variations of compressional and shear wave velocities and density in two dimensions (for either a point source with cylindrical symmetry or a line source with Cartesian symmetry) are allowed. The method solves the elastic wave equation (a second-order system of hyperbolic partial differential equations in horizontal and vertical displacement) in the time-space domain using an explicit, centered-difference scheme.

In flat lying media the "snapshot" displays show clearly the partitioning of compressional and shear energy at the sea floor into reflected waves (P), interference head waves (P and S), diving waves (P + S), and the pseudo-Rayleigh wave (Scholte wave). All evanescent wave effects are demonstrated. Scattering from determinis-

tic models of the sea floor including hills, valleys, and strong lateral velocity variations can also be modelled and agree well with observed data from experiments in the Gulf of California and in the 'ROSE' area. In shallow water models the technique shows clearly the evolution of the normal mode pattern and Stoneley waves from a point, impulsive source. The behavior of these waves in range dependent wave guides including into and out of wedges such as the continental margin can also be studied.

In press: Proceedings of the First IMACS Symposium on Computational Ocean Acoustics.

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WHOI Contribution No. 6294.

THE MEASUREMENT OF OCEANIC HEAT FLOW

Richard P. Von Herzen

Among the first investigations to employ electronic instrumentation in the deep sea, the methods of marine geothermal measurements have evolved continuously since their beginnings over 3 decades ago. In most cases, however, the basic method of independently determining the temperature gradient and thermal conductivity to calculate heat flux remains. Techniques of multi-(pogo) probing with in-situ conductivity determinations allow rapid surveys of variability over small regions of the sea floor, and significantly improve the estimates of mean heat flux in such regions compared to single measurements. Measurements in deep sea drill holes to depths of several hundred meters below the sea floor generally confirm the values obtained from the shallower-penetrating (few meters) oceanographic measurements from ships.

In press: Methods of Experimental Physics - Geophysics, Academic Press.

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WHOI Contribution No. 6372.

PALEOGENE GEOCHRONOLOGY:
AN INTEGRATED APPROACH

M. P. Aubry, W. A. Berggren, D. V. Kent,
J. J. Flynn, K. D. Klitgord,
J. D. Obradovich and D. W. Prothero

A geochronologic framework is essential to understanding and estimating rates of geological processes. Various components are fundamental to a truly integrated time scale (e.g., biochronology, radiometric dating, biostratigraphy, magnetostratigraphy). A number of schemes for the Cenozoic incorporating some or all of these components have been developed over the past two decades, spurred to a large degree by the need of the Deep Sea Drilling Project (DSDP) and successors for a reliable chronology for estimating rates of sedimentary processes as well as basement/sediment ages, among other things.

Berggren, Kent & Flynn (1985) recently revised Paleogene geochronology utilizing the integrated methodology described above. Odin & Curry (1985) have presented a detailed critique of their paper and have at the same time raised several questions regarding its validity as a "standard" for Paleogene geochronology. We address their critique here.

The critical comments by Odin & Curry (1985; hereafter referred to as OC85) can be separated into two parts, one dealing with temporal resolution, the other with the overall accuracy of the numerical time-scale for the Paleogene presented by Berggren, Kent & Flynn (1985; hereafter referred to as BKF85). OC85 apparently misinterpreted the role of the geomagnetic polarity sequence in the construction of a numerical time-scale. They incorrectly attribute the source of the large numerical differences between Curry & Odin (1982; hereafter referred to as C082) and BKF85 in the Paleogene to assumptions concerning sea-floor spreading rates. As a result, they overstate the importance of magnetostratigraphy in contributing to the BKF85 determination of ages for major chronostratigraphic subdivisions of the Paleogene. At the same time, however, they underestimate the utility of magnetostratigraphic correlation in resolving small time increments, and make what we regard as untenable numerical assignments on the basis of isotopic ages (primarily glaucony) alone.

We submit that the major differences in the Paleogene time-scales of C082 and BKF85 have little to do with magnetostratigraphy per se; rather the apparent

numerical discordances stem from using different age estimates in constructing a Paleogene chronology. For example, Channell (1982) calibrated virtually the same geomagnetic polarity sequence, with magnetostratigraphic correlations similar to BKF85, using the Paleogene chronology of C082. Channell (1982) estimated that the early/middle Eocene boundary and Anomaly 22 are 45 Ma, about 7 my younger than BKF85's estimate of 52 Ma for both the boundary and the anomaly.

We address the comments of OC85 by first reviewing the role of the geomagnetic polarity sequence in the construction of an integrated numerical geologic time-scale. We next answer the specific points raised by OC85 in their comparative critique of the recently proposed time-scales of C082 and BKF85. We then turn our attention to basic problems we perceive in the methodologic approach used in C082 and OC85 in the formulation of the Paleogene time-scale based on their selective isotope ages. Finally, we present an updated assessment of the biostratigraphic correlations near the Paleocene/Eocene boundary and take this opportunity to revise the Paleogene time scale at this level.

In press: Journal Geological Society.

Supported by: NSF Grant OCE80-17040.

WHOI Contribution No. 6204.

ANTARCTIC BOTTOM WATER CIRCULATION IN THE
SOUTH AUSTRALIAN BASIN DURING THE LAST
3.2 MILLION YEARS

Barbara V. Braatz and Bruce H. Corliss

We analysed deep-sea benthic foraminifera from three Eltanin piston cores (E45-21, E49-53, E50-2) to infer deep-water circulation in the western South Australian Basin during the past 3.2 million years. During the Gauss and early to middle Matuyama chrons, *Epistominella umbonifera* was the dominant species; *Uvigerina* spp. and *Epistominella exigua* increased in abundance during the late Matuyama, and became dominant during the Brunhes chron. The *E. umbonifera* data suggest that these cores were overlain by a cold, more highly carbonate-undersaturated bottom water relative to present day conditions during three periods: 1) early to middle Gauss (3.2 to 2.6 m.y.), 2) early Matuyama (2.3 to 2.0 m.y.), and 3) middle Matuyama (1.9 to 1.1 m.y.). During the Brunhes, cold, carbonate-undersaturated bottom water was replaced by bottom water having properties intermediate between present-day Antarctic

Bottom Water and Circumpolar Deep Water. Comparison of our faunal data with previously published grain-size data (used to infer bottom-water velocities) indicates no direct relationship between bottom-water velocities and variation in cold, carbonate-undersaturated bottom water in the South Australian Basin.

In press: Journal of Foraminiferal Research.

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WHOI Contribution No. 5993.

MICROPALAEONTOLOGICALLY RELEVANT PLANKTON
SPECIES IN MODERN OCEANS COLLECTED BY
SEDIMENT TRAP EXPERIMENTS
Volumes 1 and 2

Sugumu Honjo

Contributions by:

Robert Thunell, Kozo Takahashi,
Barrie Dale, John Steinmetz,
H. Y. Ling and M. Rottman

Living plankton communities are the product of the evolutionary history of their adaption to the oceanic environment. As a result, each plankton community is imprinted by its specific environmental background. In studying the geological development of oceans, paleoceanographers extract past environmental conditions from fossil plankton assemblages under the assumption that a community consisting of dead, sedimented assemblages carries the same information which was included in their living counterpart.

Many thousands of plankton species are produced in the present oceanic environment. Living plankton communities are constructed as a hierarchy of the food chain. Most solar energy is exhausted in the maintenance and reproduction of the entire plankton community of the oceans. Consequently, the majority of plankton is recycled in the upper ocean layers. Their morphology - size and shape - is a transient phase which exists at one point during the material recycling scheme of the ocean. A fossil plankton assemblage is, therefore, usually the very small portion of its living counterpart that survives the biological, chemical recycling of matter in the upper ocean layers, and dissolution and remineralization at the ocean bottom boundary.

In press: American Natural History Museum Press.

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WHOI Contribution No. 6270.

FLYSCH-TYPE AGGLUTINATED FORAMINIFERAL
ASSEMBLAGES FROM TRINIDAD: TAXONOMY,
STRATIGRAPHY AND PALEOBATHYMETRY

M. A. Kaminski, F. M. Gradstein,
W. A. Berggren, S. Geroch
and J. P. Beckman

Diverse flysch-type agglutinated foraminiferal assemblages (105 species belonging to 45 genera) have been identified in Maastrichtian to lower Eocene sediments of the Guayaguayare and Lizard Springs Formations of Trinidad. These assemblages resemble flysch-type assemblages from Labrador, Poland, West Greenland, and the North Sea. Thirteen species documented by Cushman and Renz (1946) are synonymized with species in the Grzybowski collection of flysch-type foraminifera from Poland. The systematics of Cushman and Renz are accordingly revised and supplemented with additional species.

Factor analysis delineated three assemblages in Danian sediments of Well G-287. The first assemblage is dominated by the epibenthic tubular species *Dendrophrya excelsa* and correlates with the relative abundance of *Nuttallides truempyi* and sedimentological criteria suggesting redeposition and sorting from a deep, distal source. A second assemblage consists largely of small, finely agglutinated species and is associated with bioturbated noncalcareous shales interpreted as being in situ. A third assemblage is comprised mainly of ataxophragmiids and lituolids and correlates with the abundance of *Stensioeina beccariiiformis*. This is interpreted as indicating redeposition from a shallower, more proximal source. The distribution of species in the three factor assemblages is used to construct a paleobathymetric model of flysch-type agglutinated foraminifera in southern Trinidad, and this model is compared with the paleobathymetric distribution of flysch-type species in the Polish Carpathians.

Of the 81 common taxa for which stratigraphic ranges are compiled in southern Trinidad, six possess isochronous datum levels in other regions.

In press: Proceedings of the 2nd International Workshop on Agglutinated Foraminifera, Vienna, June 1986.

Supported by: Consortium of Oil Companies and GSA Grant 86-3599.

WHOI Contribution No. 6172.

TWO NEW SPECIES OF Phenacophragma FROM
THE PALEOGENE OF TRINIDAD AND POLAND

Michael A. Kaminski and Stanislaw Geroch

Two new species of the lituolid genus Phenacophragma, characterized by intracamerall hemiseptae, are described from "flysch-type" agglutinated foraminiferal faunas. Phenacophragma beckmanni n.sp. occurs in the Paleocene Lizard Springs Formation of Trinidad and the lower Eocene Hieroglyphic Beds of the Polish Carpathians. Phenacophragma elegans n.sp. has been observed only in Trinidad.

In press: Micropaleontology.

Supported by: Consortium of Oil Companies.

WHOI Contribution No. 6147.

LIFE HISTORY AND RECOLONIZATION AMONG
AGGLUTINATED FORAMINIFERA
IN THE PANAMA BASIN

Michael A. Kaminski,
J. Frederick Grassle and
Robert B. Whitlatch

Benthic foraminifera were examined in spade core samples from a 3912 m deep station in the Panama Basin to determine abundance and microhabitat partitioning among living populations and preservation of dead assemblages. The genera Dendrophrya, Cribrostomoides and Ammodiscus were found to be epifaunal forms, and the genus Reophax predominantly infaunal. Species of Reophax are probably responsible for fine reticulate burrows observed in x-radiographs.

An experiment using recolonization trays was designed to identify opportunistic species of benthic foraminifera, and to assess the rate at which a population can colonize an abiotic substrate. The most successful colonizer at this site is Reophax, while Dendrophrya displays the lowest capability for dispersal. After nine months the abundance of living individuals in sediment trays was one-tenth to one-third that of background abundance, but the faunal diversity did not differ greatly from control samples. Recolonization among benthic foraminifera is more rapid than among macro-faunal invertebrates.

In press: Proceedings of the 2nd
International Workshop on
Agglutinated Foraminifera,
Vienna, June 1986.

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WHOI Contribution No. 6215.

BURIAL OF TREES BY ERUPTIONS OF MOUNT ST.
HELENS, WASHINGTON: IMPLICATIONS FOR
THE INTERPRETATION OF FOSSIL FORESTS

Amy L. Karowe and Timothy H. Jefferson

Lahars and fluvial sediments which buried trees following the May 18, 1980 eruption of Mount St. Helens were investigated during August of 1982. Trees buried in older mudflows, dated at 1885 A.D., 1450-1550 A.D., and 36,000 years B.P., also were examined. Although many logs clearly were transported, large numbers of trees were buried in growth position. Burial by lahars generally resulted in the death of trees, whereas some trees survived burial by fluvial sediments. Scanning electron microscope studies show that trees buried in lahars are well preserved. Pre-1885 buried woods show incipient silicification, and woods buried 36,000 years B.P. show silica impregnation of cell walls.

Features of in situ and allochthonous burial very similar to those seen in southern Washington are found also in Eocene silicified forests in Yellowstone National Park, Wyoming, U.S.A., and in Cretaceous fossil forests in southeastern Alexander Island, Antarctica. Observations of Recent wood from volcaniclastic deposits of Mount St. Helens provide valuable insights into processes of burial and silicification of fossil forests of various ages around the world.

In press: Geological Magazine, 24,
part 4, May issue.

Supported by: Harkness Fellowship of
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WHOI Contribution No. 6312.

NEOGENE CYCLADOPHORID RADIOLARIANS FROM
NORTH ATLANTIC, ANTARCTIC, AND NORTH
PACIFIC DEEP-SEA SEDIMENTS

G. Lombardi and D. B. Lazarus

This paper presents a detailed taxonomic analysis of cycladophorid radiolarians from Neogene high-latitude sediments of the Antarctic, North Pacific, and

North Atlantic. The definition of the genus Cycladophora is emended to include many species previously assigned to Clathrocyclus and Theocalyptra, and Diplocyclus is formally synonymized with Cycladophora. Descriptions, full page plates, and extensive measurements are provided for each species. Eleven new species of Cycladophora are described, including: Cycladophora cosma, C. irregularis, C. robusta, C. conica, C. klingi, C. amphora, C. helios, C. rosetta, C. subhumerus, C. borea, and C. campanula. Cycladophora spongothorax (Chen) is given specific rank, C. regipileus (Chen) is reduced to subspecific rank, and C. pliocenica is introduced as a replacement name for Clathrocyclus bicornis (Hays).

Supported by: NSF Grant DPP83-17087.

WHOI Contribution No. 6266.

EVOLUTIONARY CHANGES IN SOME
LATE NEOGENE PLANKTONIC FORAMINIFERAL
LINEAGES AND THEIR RELATIONSHIPS
TO PALEOCEANOGRAPHIC CHANGES

Bjorn A. Malmgren and W. A. Berggren

Coincidences between evolutionary changes in some late Neogene lineages of planktonic foraminifera and major paleoceanographic events are evaluated to assess possible relationships between paleoclimatic change (in a broad sense) and evolutionary innovations. Previously published data on evolutionary changes in the Globorotalia inflata lineage, the Globorotalia tumida lineage, and the Globorotalia truncatulinoides lineage, and new data on the Sphaeroidinella dehiscentis lineage, are used in the study. Most evolutionary rate changes in these lineages are shown to occur near times of major paleoceanographic events. For example, rapid increase in conicality and weakening of the keel in the G. inflata lineage in the latest Miocene (about 6.0 Ma) began at about the time of global cooling, major sea-level regression, and shift in $\delta^{13}\text{C}/\delta^{12}\text{C}$ ratios in foraminiferal tests. Disappearance of keeled morphotypes (G. conomiozea) within the same lineage, and appearance of nonkeeled forms with rounded periphery (G. puncticulata) coincided with the return of warmer, more stable climatic conditions and higher sea level at about the Miocene-Pliocene boundary (5.3 Ma). The phyletic transformation from G. plesiotumida into G. tumida was initiated about 0.2 myr below this boundary, and was completed about 0.4 myr above it. Supplementary apertures first developed in the S. dehiscentis lineage (the Sphaeroidinella morphotype) about the

Miocene-Pliocene boundary. Frequencies of supplementary apertures were low through the Early Pliocene, but increased rapidly (from about 20 to 90%) between 3.4 and 3.3 Ma, close to the onset of Northern Hemisphere glaciation. Forms without a supplementary aperture (the Sphaeroidinellopsis morphotype) became extinct only 0.3-0.4 myrs later. Although evolutionary change in most variables analyzed exhibits striking relationships to climatic change, some evolutionary time-series do not show any obvious relationship to such change. Chamber numbers in the final whorl in the G. inflata lineage thus decreased gradually over the last 8.3 myrs independently of paleoenvironmental change; gradual decrease in conicality in G. truncatulinoides over the last 0.7 myrs was not related in a simple way to late Quaternary cyclic climatic fluctuations.

In press: *Paleoceanography*.

Supported by: Swedish Natural Science Research Council G-G04076-113 and G-G04076-117; and NSF Grant OCE80-17040.

WHOI Contribution No. 6244.

ANALOG MORPHOCORRELATION:
A NEW TECHNIQUE WITH IMPLICATIONS
FOR HIGH RESOLUTION STRATIGRAPHY

W. C. Parker, Anthony J. Arnold
and W. A. Berggren

The conventional approach to increased biostratigraphic resolution involves identifying additional datum planes defined by discrete events. Sachs and Hasson (1979) demonstrated that the use of multivariate techniques to refine a conventional "datum oriented" taxonomic zonal scheme offers no improvement in precision; however, since the characters upon which the zonal boundaries are based often show continuous stratigraphic variation, they offer an opportunity for continuous stratigraphic correlation based on stage of evolution.

Morphometric analysis was carried out on two lineages: (1) the Globorotalia cibaoensis - G. crassaformis lineage, using a reference section from the early Pliocene of the Rio Grande Rise, spanning approximately 2.6 my, and (2) the G. conoidea - G. inflata lineage, using a reference section from the late Miocene to Recent from the southwest Pacific, spanning approximately 8 my. Stepwise multiple regression of morphological variates generated an equation with an age-prediction confidence limit (95% confidence) of $\pm 165,600$ years in the G. crassaformis

lineage and +402,900 years in the G. conoidea lineage (accuracy is dependent upon calibration of absolute dates in the reference section and our knowledge of sedimentation rates over the measured interval).

Single-equation analog morpho-correlation allows correlation of any sample overlapped by the reference lineage, reducing the need for repeated sampling in a search for discrete events. We demonstrate 1) that analysis of continuous morphologic variation can increase stratigraphic precision with a few carefully chosen variables, and 2) that analog morphocorrelation can yield absolute, rather than relative dates, with quantified error. Any disadvantages inherent in analog morphocorrelation are also found in conventional biostratigraphic techniques, but are usually unquantified and unrecognized.

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WHOI Contribution No. 6126.

ONTOGENY AND HETEROCHRONY IN THE OSTRACODE *Cavellina* CORYELL FROM LOWER PERMIAN ROCKS IN KANSAS

P. N. Schweitzer, R. L. Kaesler
and G. P. Lohmann

Animals evolve by changing their form and by changing the rate at which they develop. Since evolution of development through time may be directly related to the adaptation of their life-histories, study of ontogeny in fossils may yield information about the ecology of extinct animals. We need to know (a) how to measure animals' ontogeny and (b) at what taxonomic level structural differences overshadow differences in development. Two closely related species of the Permian ostracode *Cavellina* were compared to determine how much of the morphological difference between them is due to differences in their ontogenies. Most of the difference is not related to ontogeny. They also differ in a way that could be explained by heterochrony, although this difference is secondary in importance to the structural difference. These findings suggest that ecological adaption might best be studied by examining the changes in development that occur within species through time and space.

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290-301, 1986.

Supported by: NSF Grants OCE82-14930 and OCE84-10221.

WHOI Contribution No. 6128.

STRUCTURE OF THE GLACIAL THERMOCLINE AT LITTLE BAHAMA BANK

Niall C. Slowey and William B. Curry

Though the oxygen-isotope compositions and relative abundances of foraminifera have been used to estimate surface and deep water temperatures during the last glacial maximum [1-4], little is known about the structure of the upper water column at this time. Carbonate bank margins intersect the steep chemical and physical gradients of the thermocline, and the shallow-water benthic foraminifera living on these margins record the gradients in their isotopic chemistry. We have determined the $\delta^{18}O$ compositions of *Globigernoides ruber*, near-surface planktonic foraminifer, and *Cibicidoides floridanus*, a shallow-water benthic foraminifer, in a core recovered from Little Bahama Bank. *Cibicidoides floridanus* exhibits a glacial-interglacial range in $\delta^{18}O$ that is 0.5 ‰ less than *G. ruber*'s, because the benthic foraminifer lived and calcified ~110 meters shallower on the thermocline ~18,000 years ago. After eustatic changes in thermocline position are accommodated, we estimate that temperature at 540 meters paleodepth cooled by ~1.7°C. *Globigernoides ruber* $\delta^{18}O$ values suggest that surface water temperature at this location cooled by ~2.3°C. Thus, while near-surface and mid-thermocline water temperatures during glaciation were slightly colder, the upper water column vertical temperature gradient was not different from today.

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WHOI Contribution No. 6257.

P E T R O L O G Y

PETROLOGIC VARIABILITY OF THE OCEANIC UPPERMOST MANTLE

Henry J. B. Dick

Asthenosphere ascending between diverging lithospheric plates beneath an ocean ridge undergoes decompression

melting. The melt is squeezed to the surface and erupts to form new crust over the ascending mantle. Peridotites dredged from the sea floor are likely to be the most depleted residue of this process. Since the degree of melting is linked to the depth of mantle upwelling, initial temperature, and chemistry, knowledge of the lateral chemical and mineralogic variability of residual mantle peridotites from the ocean ridges provides direct constraints on the generation of the spatially associated basalts.

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and Petrology of the Deep Crust
and mantle: Proceedings of the
USGS/Stanford Workshop.

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WHOI Contribution No. 6164.

LOCAL AND REGIONAL HETEROGENEITY IN MORB
FROM THE MID-ATLANTIC RIDGE BETWEEN
54.5°S and 51°S: EVIDENCE
FOR GEOCHEMICAL ENRICHMENT

Anton P. le Roex, Henry J. B. Dick,
Stan R. Hart and Arch M. Reid

In the late sixties and early seventies Wilson (1965) and Morgan (1972, 1973) introduced the concept of mantle plumes or hotspots as areas of upwelling in the mantle which provide a driving force for plate tectonics; in the oceans the surface expression of such hotspots commonly being manifested as oceanic islands. Work by Schilling and co-workers (e.g. Iceland, Schilling, 1973a; Hart et al., 1973; Azores, Schilling, 1975; Afar, Schilling, 1973b) extended this concept and documented the effect of mantle plumes, located near spreading ridges, on the geochemistry of the spatially associated mid-ocean ridge basalts. Since these early studies the hotspot or mantle plume model in its general form has played an important role in mantle evolutionary models. More recent studies have called into question the physical nature and geometric shape of mantle plumes, their depth and source of origin, and the processes by which their characteristic geochemical signature becomes evident in spatially associated spreading ridge basalts. Relevant references in this regard include Batiza (1984), Allegre et al. (1984), Davies (1984), Sleep (1985), and Schilling et al. (1985).

To investigate these fundamental problems further we have undertaken a detailed sampling of ridge systems in the Southern Ocean in the vicinity of the Bouvet triple junction and the postulated Bouvet mantle

plume. This triple junction marks the bifurcation of the Mid-Atlantic Ridge into the Southwest Indian Ridge, extending towards the east, and the American-Antarctic Ridge extending towards the southwest and terminating at the Scotia arc. Previously we have reported on the geochemical variations and influence of the Bouvet mantle plume on the lavas from the Southwest Indian Ridge (le Roex et al., 1983) and the American-Antarctic Ridge (le Roex et al., 1985). These studies showed that the Bouvet mantle plume has had a significant influence on the composition of lavas erupted along both these ridges, although the influence is considerably more pronounced to the east along the Southwest Indian Ridge. Furthermore, the distribution of plume enriched lavas is unlike that found in the North Atlantic in that great local variability exists in the degree of enrichment shown by the lavas; the full spectrum compositions (depleted to enriched) is at times present within single dredge hauls.

With a view to determining the geographical distribution of the influence of the Bouvet mantle plume in this region, the northern limb of the Bouvet triple junction (i.e. Mid-Atlantic Ridge) was recently dredge sampled. In this article we report on the initial petrographical, mineralogical and geochemical results of our study of dredged basalts from the southern end of the Mid-Atlantic Ridge (between 54.5°S and 51°S) to the north of the triple junction. First we examine the data in terms of local and regional compositional variations with associated implications for underlying mantle heterogeneity. Secondly, we discuss the data within the context of our previous work relating to the influence of the Bouvet mantle plume on spatially associated Southern Ocean spreading ridge basalts.

In press: *Geochemica, Cosmochimica Acta*.

Supported by: NSF Grant DPP83-16490.

WHOI Contribution No. 6293.

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

ALGAL AND BACTERIAL PIGMENT FLUX IN
THE BLACK SEA: IMPLICATIONS FOR THE
ORIGIN OF BLACK SEDIMENT VARVES

Nina Caraco and Susumu Honjo

During the past 7000 years the Black Sea has had anoxic bottom waters containing

hydrogen sulfidel The sediments that have accumulated over this time period are varved. Dark-light pairs of microlaminae are thought to represent seasonal variation in particle flux. Light carbonate-rich layers are formed as a result of spring/summer blooms of the coccolithophorid *Emiliana huxleyi*. The origin of the dark organic layers containing iron sulfides has not been adequately explained. An explanation which attributes dark laminae formation to mass mortality of photosynthetic sulfur bacteria (PSB) was tested using recently conducted seasonal measurements of particle flux in the Black Sea. We found no detectable PSB pigment in sinking particles; we propose an alternate explanation, based on physical mixing, for the formation of the dark varves.

In press: Nature.

Supported by: NSF Grant OCE83-17106.

WHOI Contribution No. 6212.

BENTHIC DECOMPOSITION OF ORGANIC MATTER AT A DEEP-WATER SITE IN THE PANAMA BASIN

Jonathan J. Cole, Susumu Honjo
and Jonathan Erez

Using three independent approaches, we estimated benthic organic carbon remineralization at a 3900-m deep site in the Panama Basin. Estimates from geochemical mass balances ($18 \mu\text{moles C cm}^{-2}\text{y}^{-1}$) agreed reasonably well with estimates based on pore-water oxygen profiles ($14 \mu\text{moles C cm}^{-2}\text{y}^{-1}$). Oxygen was depleted by 1-cm depth in the sediments, indicating that final oxidation occurred within the top 1-cm. Experiments in which ^{14}C -labeled coccolithophorids were placed on the sea floor demonstrated a potential to decompose this material at rates $>0.004 \text{ day}^{-1}$. Freshly derived surface material may have an average residence time on the sea floor of less than one year and the decomposition of this material, as opposed to previously deposited sediment, may account for essentially all of benthic metabolism at this site.

In press: Science.

Supported by: NSF Grant OCE83-09024.

WHOI Contribution No. 6188.

LARGE APERTURE TIME-SERIES OCEANIC SEDIMENT TRAPS: DESIGN OBJECTIVES, CONSTRUCTION AND IN SITU FUNCTION

Susumu Honjo and Kenneth W. Doherty

We have developed sediment traps with 0.5 and 1.5 m^2 apertures which are capable of collecting 12 to 25 samples at programmed intervals, typically weekly or bi-monthly, during one continuous semi- to interannual deployment. We applied a number of new synthetic materials and stable metallic components to ensure reliable, long-lasting performance at any oceanic depth. The key component of the trap is a set of sequentially rotating samplers which is driven by a microprocessor-controlled electronic stepping motor. The electronic power controller controls sampler exchange with a high degree of flexibility and precision, as well as independently recording the executed sampling events. Each sampling bottle is sealed from ambient water during the time samples are stored before recovery. After continuous improvement and modification during 29.5 deployment-years since 1982, we are convinced that these sediment traps can provide a relatively large quantity of oceanic particle fluxes in time series with high experimental reliability.

Supported by: NSF Grants OCE82-08736
and OCE85-17106.

WHOI Contribution No. 6389.

SUBMARINE LIMESTONE IN THE NEARSHORE ENVIRONMENT OFF KUWAIT, NORTHERN ARABIAN GULF

F. Khalaf, J. D. Milliman
and E. M. Druffel

Even with careful petrographic and mineralogic characterization of marine limestones, intertidally and subtidally lithified rocks are often difficult to differentiate, thus hindering an accurate delineation of the diagenetic environment. Limestones from water depths of 6 to 8 m off Kuwait vary in petrographic character from oosparite and biosparite (in which the cement is entirely aragonite) to oomicrite and biomicrite (in which at least some of the cement is microcrystalline magnesian calcite). Carbon-14 dates suggest that the oosparite may have lithified at depths shallower than at present (possibly intertidally) during a lower stand of sea-level. In contrast the biosparite, oomicrite and biomicrite appear to be contemporaneous and to have lithified subtidally.

In press: Sedimentology.

Supported by: ONR Contract N00014-81-C-0009 and NSF Grant OCE81-11954.

WHOI Contribution No. 6271.

BIOLOGICAL PUMPING UPWARDS OF THE COARSE FRACTION OF DEEP-SEA SEDIMENTS

I. N. McCave

In a restricted part of an area intensively sampled by box-core (~50 samples from a 2 x 4 km box), a stiff muddy glacial gravel ("till") is encountered at a depth of 30-40 cm. X-radiographs of the upper 15 to 20 cm of the cores reveal gravel in foraminiferal mud only from the area where there is the deeper "till" layer. The localization strongly suggests that the material in the top of the cores has its source in the deeper layer. Burrowing organisms are postulated to move up this fraction, which is too large to be eaten, by pushing the particles aside. Because the strength of the enclosing mud decreases upwards, the gravel particles move preferentially upwards. That is to say the impulses given by burrowers to stones have a net upward directed component. The upward decrease in shear strength of the sediment is rapid at an interface occurring 4 cm below the surface on average. Thus the hydrostatic pressures of 20 to 200 g exerted by vermiform burrowing animals act within an environment of asymmetrical bulk property permitting an asymmetrical response to the uniformly directed body pressure. This asymmetrical response, a pumping mechanism affecting material which does not pass through the gut, is contrasted with the mixing of finer sediments that are eaten and excreted, documented by many other workers. Dimensional arguments suggest the flux of material is related to $G = D_b/SL_m$ and sparse data suggest a critical value of G above one. The mechanism is also applicable to maintenance of Mn nodules and their nuclei at the surface. If macrofossils have behaved like gravel, some shellbeds may have been generated and some stratigraphic anomalies caused by this means.

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

WHOI Contribution No. 6267.

IN SITU MEASUREMENTS OF PARTICLE SETTLING VELOCITY IN THE DEEP SEA

I. N. McCave and T. F. Gross

Two instruments, the remote optical settling tube and the benthic autonomous settling tube, have been deployed on the Nova Scotian continental rise at 4820 m depth. The few results obtained suggest that optical and gravimetric methods give comparable results. The settling velocity

distribution is relatively insensitive to assumptions about particle density, but even using declining density with increasing size indicating increasing water content, the total concentration inferred using Mie theory is rather higher than the level of light attenuation indicates through correlations with gravimetric data. The coarser end of the size distribution changes more with overall change in concentration than the fine end and the settling velocity distribution shows the presence of several modes. The two principal ones can be matched with modal sizes of ~3.3 μm and ~60 μm in Coulter Counter data, allowing inference of Stokes density contrasts of 1.5 and 0.061 g cm^{-3} , respectively. At concentrations of about 200 mg m^{-3} , more than 50% of the material has a settling velocity less than $2 \times 10^{-4} \text{ cm s}^{-1}$ (probably <3 μm in size). But this percentage appears to decrease with an increase in total concentration.

Supported by: ONR Contracts N00014-82-C-0019 and N00014-85-C-0001.

WHOI Contribution No. 6311.

SUSPENDED MATTER REGIME IN THE YELLOW SEA

John D. Milliman, Li Fan, Zhao Yiyang, Zheng Tiemin and Richard Limeburner

Winter and summer oceanographic conditions in the Yellow Sea produce distinctly different distributions and compositions of suspended particles within the water column. During the winter strong northwest winds cool and mix the local water column and generate energetic surface waves which resuspend bottom sediment in the north Yellow Sea and in the shoal regions of the western Yellow Sea near Jiangsu Province. Excess/deficient suspended matter distributions show that resuspended sediment from the north Yellow Sea is transported southwards along the eastern tip of the Shandong Peninsula; resuspended sediment off the Jiangsu coast is transported offshore. Wintertime suspended particle concentrations in near-bottom waters can exceed 500 mg/l in near-shore areas and shore areas and 20 mg/l in offshore waters.

During the summer, light southerly winds and a strongly stratified water column localize the distribution of resuspended sediments. Nearbottom concentrations of suspended particulates are generally less than 10 mg/l . Surface concentrations are not dissimilar to those seen during the winter, but the particles are primarily biogenic rather than resuspended mineral grains.

In press: Deep-Sea Research.

Supported by: ONR Contract N00014-81-C-0009 and NSF Grant INT85-01366.

WHOI Contribution No. 6171.

SEASONAL FLUXES OF SILICOFAGELLATES
AND Actiniscus IN THE SUBARCTIC
PACIFIC DURING 1982-1984.

Kozo Takahashi

A seasonal flux study of silicoflagellates and Actiniscus was conducted at subarctic Pacific Station PAPA (50°N, 145°W; water depth 4200 m) during September 1982 through August 1984 using PARFLUX high resolution time series sediment traps deployed at 1000 m and 3800 m depths. The time series sediment trap samples were collected for 4 to 16-day periods depending on the samples; most of the samples were collected for 14 to 16-day periods. A total of 47 samples represents nearly a two-year continuous record of the fluxes of silicoflagellate and Actiniscus taxa at 3800 m depth. An additional 12 samples from 1000 m represent a 6-month period, providing a pair of samples from two depths of each synchronized time series which is essential to understand particle sinking processes.

Seven silicoflagellate taxa, several additional variants of silicoflagellates, and Actiniscus pentasterias group were enumerated. A total of more than 32×10^3 specimens were identified to species level and counted in this study. Distephanus speculum and Dictyocha mandrai are the dominant taxa, generally contributing > 75% of the flux assemblages. Considerable intra-annual and interannual flux variability was observed with the range of total silicoflagellate flux varying from 5×10^3 to 700×10^3 skeletons $m^{-2}day^{-1}$. Seasonal flux patterns of D. speculum and its closely related taxa are internally consistent and they conform with the productivity signals shown by diatom, mass, or opal fluxes. The seasonal flux pattern of D. mandrai exhibits its own unique late fall/early winter production signals with most of the cumulative flux concentrated during this season in year 1.

The sinking mechanism of silicoflagellates is large aggregates which sink faster than discrete specimens. Data suggest that silicoflagellates generally sink faster than marine snow mediated diatom assemblages. The larger influence of fecal material may be responsible for the observed faster sinking speeds than diatoms. No significant dissolution of silicoflagellate assemblages occurs in the water column

due to innate protection and to accelerated sinking. Most of the silicoflagellates supplied to the sea floor are subsequently dissolved and only 1% of the total supply is preserved in the surface sediments, with considerably altered assemblages.

In press: Journal of Marine Research.

Supported by: NSF Grant OCE85-02472.

WHOI Contribution No. 6200.

ECOTYPIC SIZE CHANGES OF Coscinodiscus marginatus (DIATOM)

Kozo Takahashi

The valve diameters of a diatom taxon, Coscinodiscus marginatus, were measured using year-long, 1982-1983, time-series sediment trap samples recovered from subarctic Pacific Ocean Station PAPA. A cyclic trend in size changes of valves was observed in seasonal flux samples collected at 3800 m depth. Results of actual valve size measurements and percentages of valve counts in fine and coarse size fractions show a parallel trend, suggesting the significance of valve counts for implying size distribution. Similar valve measurements were conducted on fossil specimens taken from samples of a gravity core recovered at the same Station PAPA. The size distributions of the valves of C. marginatus from the past several thousand years are similar to that of the present day. The valve size from each time slice is comparable to that of our time-series samples. On the other hand, the size of the C. marginatus valves from the last glacial maximum (-18,000 yrs. B.P.) was markedly different from that of present day counterparts. They were relatively large and the size distribution was strongly, negatively skewed.

Supported by: NSF Grant OCE85-02472.

WHOI Contribution No. 6106.

TECHNICAL REPORTS

DESCRIPTION OF WHOI ROCK DREDGE
SAMPLES, VOLUME II

J. E. Broda and P. J. Andrew

This report is Volume II in the series of reports entitled "Descriptions of WHOI Rock Dredge Samples." This volume repre-

sents the final step in the major effort to catalog and prepare initial descriptions for all rock dredge samples in the WHOI Sea Floor Samples Collection, and to distribute this information throughout the scientific community. The distribution of this report completes the initial description of the backlog of WHOI Dredge Samples. The data contained in this volume is an accumulation and transcription of initial descriptions made at sea, along with post-cruise descriptions performed at the lab by the curatorial staff.

Volume II contains individual stations executed during the period 1963 through 1986. It also presents a digitized listing of all dredge station data for the entire WHOI Dredge Collection through 1986. The data are sorted by Marsden Squares and can serve as a regional index for all rock descriptions included in Volumes I-III.

Supported by: NSF Grant OCE85-19889.

WHOI Technical Report 86-44.

DESCRIPTIONS OF WHOI SEDIMENT CORES VOLUME 7

J. E. Broda and P. J. Andrew

This report supplements Volumes 1-6 of the core descriptions published previously in this sequence (Johnson and Driscoll, 1975; 1977; Broda, Franks, and Keith, 1981). It contains visual descriptions and smear slide analyses for all cores received in the geological samples collection of the Woods Hole Oceanographic Institution between mid-1980 and mid-1984. Approximately 240 sample localities from the North Atlantic, South Atlantic, Mediterranean and Pacific Oceans are represented. Charts of ships' tracks and updated computer listings of all cores in the WHOI collection are also included.

Supported by: NSF Grant OCE82-00119.

WHOI Technical Report No. 85-8.

IN SITU MEASUREMENT OF THERMAL CONDUCTIVITY USING THE CONTINUOUS-HEATING LINE SOURCE METHOD AND WHOI OUTRIGGED PROBE

J. Jemsek, R. Von Herzen
and P. Andrew

The outrigged thermal probes of a "pogo" marine geothermal probe have been adapted to measure thermal conductivity in situ by the continuous-heating line source technique. The instrumental uncertainty in

applying the analytical theory to a single probe and double probe configuration is found to be 3 and 6 percent, respectively. The in situ outrigged single probe (0.32 cm dia.) is essentially a scaled-up version of the needle probe (0.08 cm dia.). The main advantage of the outrigged probe over a larger radius probe (e.g., violin-bow probe) is that for short-time temperatures (<2 min.) simple approximations to the exact solution for a perfectly conducting cylindrical probe are achieved. The continuous-heating compares favorably with the pulse-heating technique, the latter being more energy efficient.

The continuous-heating method applied to the thin outrigged probe allows for accurate equilibrium in situ temperature and thermal conductivity estimates in less than 15 minutes of recording time. The technique has been applied to several hundred marine heat flow stations. Comparison of in situ measurements to needle probe measurements made on nearby piston cores indicate agreement to within 5%. The conductivity profiles of the in situ data and core data show that the piston coring process frequently does not retrieve the upper meter of surficial sediment.

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WHOI Technical Report No. 85-28.

KING'S BAY/CUMBERLAND SOUND, GEORGIA PART I: EXPERIMENT REPORT JUNE-JULY 1985

David G. Aubrey

A month-long field experiment was conducted during June and July 1985 at King's Bay/Cumberland Sound, Georgia, under the combined auspices of the Naval Civil Engineering Laboratory and the Woods Hole Oceanographic Institution. Nine estuarine stations were occupied over the duration of the experiment measuring velocity, sea surface elevation, and water quality (salinity, temperature and transmissivity) as well as wind waves. The data document the amplification of the tide from St. Mary's Inlet north into King's Bay (an increase in the dominant M_2 tidal range from 0.90 m offshore of St. Mary's Inlet to a high of 0.99 m at King's Bay). The M_2 tide dominates records of velocity, sea surface, temperature, and salinity throughout the estuary. Half way through the experiment, the bay became warmer and less saline, reflecting increased freshwater flow into the estuary through the Crooked River, St. Mary's River, and other smaller rivers. All velocity gauges measured a net down-

estuary mean flow over the duration of the experiment. Net volume discharge of water from the inlet averaged 300-350 m³/second over the month of measurement. Net discharge of fine sediment is at least 2600 tonnes per day, and perhaps as high as 26,000 tonnes per day. Data from this field experiment provide the only useful basis for verification and evaluation of various numerical models applied to King's Bay/Cumberland Sound.

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DEPARTMENT OF OCEAN ENGINEERING

Robert C. Spindel, Department Chairman

OCEAN ENGINEERING

University of North Carolina
at Chapel Hill, Research Triangle Park

SOME RELATIONS BETWEEN THE VARIOUS CRITERIA
FOR AUTOREGRESSIVE MODEL ORDER
DETERMINATION

D. Burshtein and E. Weinstein

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.

Published in: IEEE Transactions on
Acoustics, Speech, and Signal
Processing, ASSP-33, August 1985.

Supported by: ONR Contracts N00014-
80-C-0381 and N00014-85-K-0272.

MAXIMUM ENTROPY AS A SPECIAL CASE OF THE
MINIMUM DESCRIPTION LENGTH CRITERION

M. Feder

The Maximum Entropy (ME) and Maximum Likelihood (ML) criteria are the bases for two approaches to statistical inference problems. A new criterion, called the Minimum Description Length (MDL), has been recently introduced. This criterion generalizes the ML method so it can be applied to more general situations, e.g., when the number of parameters is unknown. In this paper we will show that ME is also a special case of the MDL criterion; maximizing the entropy subject to some constraints on the underlying probability function is identical to minimizing the code length required to represent all possible i.i.d. realizations of the random variable such that the sample frequencies (or histogram) satisfy those given constraints.

Published in: IEEE Transactions of
Information Theory.

Supported by: ONR Contract N00014-

MULTIPATH TIME-DELAY ESTIMATION VIA THE EM
ALGORITHM

M. Feder and E. Weinstein

We consider the application of the EM algorithm to the multipath time delay estimation problem. The algorithm is developed for the case of deterministic (known) signals, as well as for the case of wide-sense stationary Gaussian signals.

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80-C-0381.

WHOI Technical Report No. 87-3.

OPTIMAL MULTIPLE SOURCE LOCATION
ESTIMATION VIA THE EM ALGORITHM

M. Feder and E. Weinstein

We developed an algorithm for multiple source localization based on the Estimate-Maximize (EM) method. The EM method is an iterative algorithm that converges to the Maximum Likelihood (ML) estimate of the unknown parameters by exploiting the stochastic system under consideration. In our case the algorithm will converge to the exact ML estimates of the various source location parameters, where each iteration increases the likelihood of those parameters.

Published in: IEEE International
Conference on Acoustics, Speech
and Signal Processing, ICASSP
1985, March 1985.

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80-C-0381 and N00014-85-K-0272.

CONVERGENCE ANALYSIS OF LMS FILTERS WITH
UNCORRELATED GAUSSIAN DATA

A. Feuer and E. Weinstein

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 (mse) 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 mse performance and rate of convergence of the LMS adaptive scheme.

Published in: IEEE Transactions on Acoustics, Speech and Signal Processing, ASSP-33, February 1985.

Supported by: ONR Contracts N00014-80-C-0381 and N00014-85-K-0272.

RELATIONS BETWEEN BELINI-TARTARA, CHAZAN-ZAKAI-ZIV, AND WAX-ZIV LOWER BOUNDS

E. Weinstein

A class of lower bounds on the mean square error in parameter estimation is presented, based on the Belini-Tartara lower bound. The Wax-Ziv lower bound is shown to be a special case in the class. These bounds tend to be significantly tighter than the Chazan-Zakai-Ziv lower bound when the parameter to be estimated is subject to ambiguity and threshold effects.

Supported by: ONR Contracts N00014-80-C-0381 and N00014-85-K-0272.

LOWER BOUNDS ON THE MEAN SQUARE ESTIMATION ERROR

E. Weinstein and A. J. Weiss

A general class of lower bounds on the mean square error (mse) in random parameter estimation is formulated. These bounds are generated using functions of the parameter and the data that are orthogonal to the data. A particular choice in the class yields a new lower bound which is superior to both the Cramer-Rao and Bobrovsky-Zakai lower bounds.

Published in: Proceedings of the IEEE, 73, 9, September 1985.

Supported by: ONR Contracts N00014-80-C-0381 and N00014-85-K-0272.

MULTIPLE SOURCE LOCATION ESTIMATION USING THE EM ALGORITHM

E. Weinstein and M. Feder

We present a computationally efficient scheme for multiple source location estimation based on the EM Algorithm. The proposed scheme is optimal in the sense that it converges iteratively to the exact Maximum Likelihood estimate of all the unknown parameters simultaneously. The method can be applied to a wide range of problems arising in signal and array processing.

Supported by: ONR Contract N00014-85-K-0272 and prepared for the Naval Air Systems Command.

WHOI Technical Report No. 86-26.

A LOWER BOUND ON THE MEAN-SQUARE ERROR IN RANDOM PARAMETER ESTIMATION

A.J. Weiss and E. Weinstein

A new lower bound on mean-square error in parameter estimation is presented. The bound is tighter than the Cramer-Rao and Bobrovsky-Zakai lower bounds. It requires no bias or regularity assumptions, it is computationally simple, and it can be applied to estimates of vector parameters or functions of the parameters.

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Supported by: ONR Contracts N00014-80-C-0381 and N00014-85-K-0272.

FLUID DYNAMICS

NEAR-SURFACE TURBULENCE IN A GRID-STIRRED TANK

B. H. Brumley and G. H. Jirka

In order to elucidate the turbulent structure below a shear-free gas-liquid interface, turbulence measurements were made in a 50 cm-square by 40 cm-deep tank stirred by a vertically oscillating grid well below the surface, using a split-film anemometer probe rotating in a horizontal circle. This instrument is able to measure both vertical and horizontal velocity fluctuations to within 0.4 mm of the surface, from which spatial spectra and profiles of rms velocity fluctuations

and integral length scales can be calculated. The turbulent structure is affected by the presence of the surface within a "surface-influenced layer" roughly one integral scale, or ten percent of the distance from the surface to the center of the grid stroke, in thickness. The shapes of the spectra and profiles within the surface-influenced layer are predicted to a good first approximation by the source theory of Hunt and Graham (1978), which treats the turbulent structure as the superposition of homogeneous turbulence with an irrotational velocity field driven by a source distribution at the surface which cancels the vertical velocity fluctuations there. The magnitudes (as opposed to the shapes) of the profiles scale according to the values that would otherwise occur in the vicinity of the surface-influenced layer were the surface not present. These magnitudes are adequately predicted by the bulk relations determined by Hopfinger and Toly (1976) and Thompson and Turner (1975), with no apparent dependence on turbulent Reynolds number. There are some minor discrepancies between the measured profiles and those of Hunt and Graham. A thin layer of reduced velocity fluctuations below what would be expected from the theory was observed near the surface. Also, anisotropy in the velocity spectra at depths within the surface-influenced layer extended well into the inertial subrange, whereas the Hunt and Graham theory predicts no anisotropy at high wavenumbers.

In press: Journal of Fluid Mechanics.

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WHOI Contribution No. 6174.

HORIZONTAL SWIMMING AND GRAVITATIONAL SINKING OF *Capitella* SP.1 LARVAE: IMPLICATIONS FOR SETTLEMENT

C. A. Butman, J. P. Grassle
and E. J. Buskey

Horizontal swimming and gravitational sinking of the lecithotrophic larvae of *Capitella* sp.1 were measured on laboratory-reared organisms during their planktonic life. Swimming was quantified using a video-computer system for motion analysis under both infrared and directed white light conditions. Gravitational fall velocities were measured on anesthetized larvae in a temperature-controlled particle settling chamber. Swimming and sinking measurements were made on larvae within approximately 12 hours of hatching and at about 24-hour intervals for the following two days. Mean swim speeds were be-

tween 2.5 and 3.3 mm/sec on the first day and decreased to 1.6 to 2.3 mm/sec on day three. Mean fall velocities ranged between 0.8 and 1.0 mm/sec and did not change significantly over the pelagic period. The larvae displayed both photokinetic and phototactic behaviors, swimming slower and toward the white lights, especially early in their development. The capability of these organisms to select settlement sites by horizontal swimming among available habitats is limited to essentially still water, since water velocities occurring within millimeters of the seabed exceed these measured swim speeds for most realistic field flows. Vertical swimming up and down, coupled with passive transport and deposition, are more likely involved in the habitat selection process.

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WHOI Contribution No. 6264.

LARVAL SETTLEMENT OF SOFT-SEDIMENT INVERTEBRATES: THE SPATIAL SCALES OF PATTERN EXPLAINED BY ACTIVE HABITAT SELECTION AND THE EMERGING ROLE OF HYDRODYNAMICAL PROCESSES

C. A. Butman

Literature on factors controlling larval settlement of soft-sediment invertebrate larvae is reviewed to determine the spatial scales of species distribution that can be explained by active habitat selection. Studies of hydrodynamical processes which may determine or affect settlement or recruitment also are reviewed, again with a major focus on the scales of pattern explained by a given process. Active habitat selection has been demonstrated conclusively in still-water laboratory studies for spatial scales of centimeters to tens of centimeters. This is one to six orders-of-magnitude smaller than the spatial scales of pattern observed in the field; correlations between species and sediment composition have been documented for spatial scales of tens of meters to tens of kilometers. Field tests of the active habitat selection hypothesis suggest that larvae may choose preferred habitats over scales of tens of centimeters to tens of meters, but the results are inconclusive because hydrodynamical alternative hypotheses were not considered or tested. Tests of the hypothesis that

larvae, postlarvae or meiofauna sink, accumulate or are resuspended and transported like passive particles indicate that considerations of hydrodynamical processes must be included in studies of larval settlement phenomena. A brief discussion of the flow and sediment transport environment in the bottom boundary layer is provided for perspective on the physical processes that larvae encounter as they get closer to the seabed. Flow velocities within larval body lengths of the seabed generally exceed larval swim speeds, even in relatively weak forcing flows. Because the transport and deposition of passive particles results in pattern of sediment heterogeneity at the same spatial scales that patterns of species heterogeneity have been documented, it is suggested that some larvae may be deposited, accumulate and exist in dynamic equilibrium with the flow environment, as are the surficial sediments at these large scales. Once deposited over a broad region of the seafloor, the larvae or postlarvae may actively select preferred habitats at smaller spatial scales. Further discussion of the compatibility of the alternative hypotheses of active habitat selection and passive deposition is provided; the relative importance of the two processes in creating observed patterns of infaunal distribution likely depends on the species, flow regime, and time and space scales involved.

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WHOI Contribution No. 6303.

STORM-DOMINATED BOTTOM BOUNDARY LAYER DYNAMICS ON THE NORTHERN CALIFORNIA CONTINENTAL SHELF: MEASUREMENTS AND PREDICTIONS

D. A. Cacchione, W. D. Grant, D. E. Drake and S. M. Glenn

Measurements of near-bottom velocity profiles in 85 m water depth during a storm on the continental shelf off northern California using the GEOPROBE tripod

in December 1979 provided estimates of shear velocities, u_* , and roughness lengths, z_0 , when the near-bottom velocity profiles were logarithmic. These estimates agree within 90 percent confidence intervals with values computed from a simple near-bottom combined wave-current model that includes moveable bed effects. The reasonably good comparison between model and profile estimates of u_* suggests that such models can be used to predict bed shear stresses (or shear velocities) under combined flows of waves and currents typical of stormy conditions on continental shelves if corrections to the velocity profile resulting from suspended sediment are small. The repeated occurrences of storms of similar intensities and wind velocities during the winter months off northern California suggest that the resultant high bottom stresses due to the combined effects of waves and currents are major factors in controlling the distribution of surficial sediment on the central portion of the northern California shelf.

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WHOI Contribution No. 6235.

PERIODICITY IN FECAL PELLET PRODUCTION BY THE CAPITELLID POLYCHAETE, Mediomastus ambiesta THROUGHOUT THE DAY

C. M. Fuller, C. A. Butman and N. Conway

Rates of fecal pellet production in Mediomastus ambiesta, a capitellid polychaete, were determined by collecting and counting at three censusing intervals (6, 12 and 24 hours). The field-collected worms were maintained in culture in a dark incubator at near-ambient water temperature (20° C) for at least a month prior to the study. Rates of pellet production exhibit a dramatic and repeatable cycle over the course of the day. Pellet production by worms censused at 6-hour intervals was highest from 2400 to 0600 (Daylight Savings Time) and decreased by about a factor of four from 0600 to 1800; almost no pellets were produced between 1800 and 2400. From these experiments it is not possible to determine if the cycle is an innate, programmed behavior (e.g., a circadian rhythm) or a response to some cyclically occurring external stimulus. Whether genetically or externally controlled, the cycle may be for avoiding predation by a twilight or night-active predator

or it may be due to metabolic constraints of the organisms.

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Supported by: NSF Grant OCE85-000875.

WHOI Contribution No. 6265.

SHEAR INSTABILITY IN A HIGHLY STRATIFIED ESTUARY

W. R. Geyer and J. D. Smith

Shear instability is found to be the principal mechanism of vertical exchange within the pycnocline of a salt wedge estuary. A field program involving high resolution velocity and density measurements, as well as high frequency acoustic imagery, allowed direct comparison of instantaneous Richardson number distributions to the occurrence of shear instability. The theoretical stability threshold of 0.25 is consistent with the measurements, based on estimates of gradients that contain the mean as well as fluctuations due to internal waves. An effective stability threshold based on mean gradients is found to be $Ri \approx 0.33$, reflecting a significant contribution of internal wave shear. The integral effect of the mixing process is to homogenize the gradients of velocity and density, producing linear profiles of these quantities across the pycnocline. A turbulent Prandtl number of unity is suggested by the vertical distributions of velocity and density during periods of active vertical mixing.

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WHOI Contribution No. 6142.

LONG TERM IN SITU CALCULATIONS OF KINETIC ENERGY AND REYNOLDS STRESS IN A DEEP SEA BOUNDARY LAYER

T. F. Gross, A. J. Williams III
and W. D. Grant

Long term measurements of Reynolds stress and kinetic energy are necessary to characterize the bottom boundary layer during storms which transport sediment in the HEBBLE area on the Nova Scotian Rise. The BASS current meter system employed an on-board microcomputer to process 2 Hz velocity vector data into 20-minute averages of velocity vectors and the turbulent Reynolds stress tensor. The data indicate

a bottom boundary layer, which is usually transitional, with bottom roughness scaling between viscous, $z_0 = \nu/9u^*$, and rough, $z_0 = k_s/30$. During the periods of transitional flow, the logarithmic layer was not a useful indicator of boundary stress. Direct stress and energy measurements showed that the stress was much less than that indicated by the slope of the transitional mean logarithmic velocity profile. Several westward high velocity events, which were modulated by a significant tidal component were recorded. It appears, from this data set, that the mean westward flow must be accompanied by a train of internal tidal waves to achieve the velocities necessary to be the sediment transport events identified as "benthic storms."

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Supported by: ONR Contract N00014-85-0001.

WHOI Contribution No. 6155.

A SUSPENDED SEDIMENT STRATIFICATION CORRECTION FOR COMBINED WAVE AND CURRENT FLOWS

S. M. Glenn and W. D. Grant

A simple model for the near bottom, combined wave and current flow over a moveable sediment bed is presented. The model is an extension of the Grant and Madsen (1979) combined wave and current model, with moveable bed effects on the physical bottom roughness included as in Grant and Madsen (1982). The unsteady conservation of fluid momentum and sediment mass equations, which are coupled through an eddy diffusivity closure scheme, are solved for the wave and current velocity profiles, along with the suspended sediment concentration and transport profiles. Sample runs are presented to illustrate the effect of varying wave conditions on the current, the mean sediment concentration, and the mean sediment transport. Results show that for fine to medium sands, self stratification of the flow can be important during storms due to the large amount of sediment suspended by the waves and the enhanced turbulent mixing associated with the wave-current interaction. The theory easily can be generalized for inclusion in a full Ekman layer model.

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WHOI Contribution No. 6291.

HYDRODYNAMIC FORCE ON CIRCULAR CYLINDERS

O. S. Madsen

The determination of the hydrodynamic force per unit length of a circular cylinder moving in a plane perpendicular to its axis in a nonuniform unsteady flow of an ideal fluid of infinite extent is formulated as a series expansion in the small parameter ka , where a is the cylinder radius and k^{-1} the length scale of the nonuniformity of the flow. Neglecting terms of order $(ka)^2$ and higher, the force per unit length is found to be in agreement with Taylor's (1928) result for a strictly two-dimensional flow in which the cylinder axis is perpendicular to the plane of flow. For the general three-dimensional case the present result is, however, at variance with the customary Morison formulation of the inertia force associated with nonuniformity of the flow. The nature of these differences and their significance are discussed in the context of the prediction of inertia forces on piles in non-linear waves.

Published in: Applied Ocean Research, 8, 3.

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WHOI Contribution No. 6023.

DISSIPATION OF INTERNAL WAVE ENERGY IN THE BOTTOM BOUNDARY LAYER ON THE CONTINENTAL SHELF

L. P. Sanford and W. D. Grant

A theoretical model is developed considering a linear mode 1 internal wave train propagating into a shallow wedge subject only to energy dissipation in the turbulent bottom boundary layer. The model incorporates variable vertical and cross shelf distributions of density. Internal wave energy dissipation is calculated by extending recently developed wave-current interaction boundary layer theories, allowing for the nonlinear interaction of surface waves, internal waves, and a steady current in a rough turbulent boundary layer. Enhanced dissipation estimates using the wave-current interaction drag formulation are contrasted to dissipation estimates using common linear and quadratic drag formulations. Differences between the formulations are substantial; use of a constant drag coefficient in the quadratic formulation under-

estimates dissipation, while use of a constant eddy viscosity (linear drag) overestimates dissipation. Dissipation of internal wave energy in the bottom boundary layer on the continental shelf is found to be of potential first order importance to the internal wave energy balance on the shelf, depending in a predictable way on shelf slope, density distribution, total flow environment, and bottom roughness.

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WHOI Contribution No. 6240.

IMAGE PROCESSING

THE DOMAINS OF UNDERWATER VISIBILITY

J. S. Jaffe

Several domains of underwater visibility are illustrated using a computer program to simulate underwater image formation. The basic limitations of conventional underwater optical imaging are described. In addition, several image processing techniques have been applied to underwater video images. The results of applying grey level enhancement and spatial filtering are illustrated.

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Supported by: PEW Memorial Trust.

WHOI Contribution No. 6166.

MULTIBEAM IMAGING USING SPATIALLY VARIANT INSONIFICATION

J. S. Jaffe and P. M. Cassereau

The simultaneous transmission of a number of specially coded waveforms can provide a number of substantial advantages for active sonar imaging. Two of the possible advantages are increased imaging speed and better sidelobe rejection. In order to maintain the integrity of the individual but simultaneously transmitted beams, the signals must possess specific mathematical properties. A narrow autocorrelation function and a small cross correlation function are desirable in

order to insure both accurate range resolution and rejection of neighboring beams. It is demonstrated that this design criterion is identical to that encountered in multi-access, spread spectrum, communication systems. The time-bandwidth properties of the system therefore limit the simultaneous requirement of decorrelatable beams and good range resolution. As specific implementation of the technique, a frequency hopping code is presented. The performance of this code is examined and it is demonstrated that this code is nearly optimal with respect to the above criterion. Various configurations of transducers are considered that specifically exploit the properties of spatially variant insonification. The principles of multibeam sonar imaging systems using spatially variant insonification are illustrated by constructing several examples of active sonar systems whose performance is superior over traditional designs.

Supported by: PEW Memorial Trust.

WHOI Contribution No. 6379.

CONSTRAINED RECONSTRUCTION OF COMPLEX WAVEFORMS

J. S. Jaffe and R. Fricke

We consider the reconstruction of the complex transmission coefficients of screens from their projected wavefields. The technique that we use in order to recover the screen's complex transmission coefficient is to iteratively solve a system of linear equations that relate the screen to the observed data. We are interested in the special case when we have detailed a-priori knowledge about the distance of the object. In this instance we constrain the solution such that the reconstructed screen conforms to a real positive function. We explicitly formulate the wave equation and demonstrate that a substantial increase in noise immunity and/or resolution enhancement of the recovered function is possible using this method.

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WHOI Contribution No. 6328.

DIFFERENCE FOURIER ANALYSIS OF "SURFACE FEATURES" OF BACTERIORHODOPSIN USING GLUCOSE EMBEDDED AND FROZEN HYDRATED PURPLE MEMBRANE

J. S. Jaffe and R. M. Glaeser

A difference Fourier map of the projected structure of bacteriorhodopsin has been synthesized from electron diffraction amplitudes collected from membranes prepared in the glucose embedded state and the frozen hydrated state. Phases of a recently published data set for glucose embedded specimens [Henderson; in press] were used for the difference Fourier map.

A moderate resolution (9Å) and high resolution (4.25Å) map both indicate that glucose is exchangeable for water in the region of the map corresponding to the lipid regions. We interpret this as indicating that there is a small surface depression in this region of the structure. The depth of this feature is estimated to be 1/8 the thickness of the protein region in the membrane. The data obtained in this study rules out the existence of an aqueous transmembrane channel, the dimensions of which are large enough to allow free exchange of glucose for water. Several new features are also observed in the protein region of the membrane. These features are probably due to segments of the polypeptide at the aqueous interface that are well ordered in frozen hydrated specimens but not in glucose embedded specimens. Candidate structures for the origin of these features are extensions of the helices or linker regions connecting the helices.

In press: Journal of Molecular Biology.

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WHOI Contribution No. 6272.

INSTRUMENTATION

LASER IMAGING VELOCIMETRY: DIRECTIONAL, PEDESTAL-FREE VELOCIMETRY WITHOUT BEAM SPLITTING OR FREQUENCY OFFSET

Y. C. Agrawal

This paper represents a synthesis of work presented in fragments elsewhere. A number of new concepts make a uniquely

simple velocimeter, doing away with beam-splitting optics, frequency offset devices, and yet yielding a measurement of the velocity vector from the complex signal obtained from an array of photodiodes used as the detector.

The operating principle is as follows: A single beam from a TEM laser illuminates the probe volume. The scattered light is collected and forms a Fourier Transform image on a pinhole. A microscope objective is subsequently used to match the structure in the scattered field as seen at the pinhole, to the spacing of line array photodiodes. The line array is configured electronically to appear like two periodic arrays, displaced by a quarter period. Thus, two signals are obtained per velocity channel. These form the real and imaginary parts of a complex signal which can be demodulated in a number of ways using algorithms developed in the radar/sonar contexts which provide excellent estimates of the photocurrent center frequency. For example, the pulse pair covariance algorithm estimates the mean frequency as a first moment from the value at zero lag of the gradient of the autocorrelation function to the function itself.

The advantages of this method are obvious in the simplification achieved. There are disadvantages to consider. The chief disadvantage being that in backscatter geometries, where the signals are typically much weaker, the array noise can be overwhelming, which can to some extent be overcome by image intensifiers such as the microchannel plate. A second disadvantage is one of the unavailability of pre-wired diode arrays, which has required the use of self scanning arrays with the consequent loss of speed, hence range of velocities. However, this is merely a question of developing custom arrays. The elimination of beamsplitting and frequency offset devices makes possible very much more compact 'flashlight' velocimeters.

In press: Proc. of Applications of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, July 7-9, 1986.

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WHOI Contribution No. 6161.

OBSERVATIONS OF THE DEEP-SEA BOTTOM BOUNDARY LAYER WITH A PROFILING BACKSCATTER LDV

Y. C. Agrawal

Towards the quantitative understanding

and prediction of deep-sea sediment transport under applied fluid stresses, a large experiment has been underway on the bottom of the continental rise off Nova Scotia in water depths of 4800 m. This High Energy Bottom Boundary Layer Experiment (HEBBLE) incorporates a suite of instruments for velocity, optical transmission and acoustic determination of the sediment concentration profile in the bottom few meters. A backscatter laser Doppler velocimeter is used to study the bottom 25 cm of the boundary layer, which is of order 10 m thick. This instrument is a two-axis (u,v), internally-recording type and is mounted on an untethered vehicle for launch and recovery.

In this presentation, we describe the instrument and the methods of deep-sea LDV research. Also, the instrument was successfully deployed in September of 1985 in a test launch prior to a long term 'event triggered' deployment. During this deployment, the bottom currents were weak, of order 2 cm/s and the suspended sediment concentration was correspondingly low. In the data to be presented, we view the statistics of the velocity field at a number of heights above the seafloor. Although the currents were weak, the velocity field appears to follow the expectations of a classic one-dimensional Ekman boundary layer. We shall discuss the importance of this measurement in light of the distributed bottom roughness environment of the experiment and stress the value of the measurement towards estimating the local bottom friction. Finally, we shall describe the long term event triggered experiment and present preliminary analysis of the data obtained from it in the April '86 cruise.

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WHOI Contribution No. 6162.

TIME RESOLVED DISSIPATION ESTIMATES FROM A TWIN VELOCITY ESTIMATE LASER DOPPLER VELOCIMETER

Y. C. Agrawal and E. A. Terray

In a number of geophysical flows, for example under waves, the determination of turbulent energy dissipation over time scales small compared to wave periods (or group periods) is of great significance. It has been known to workers in the field

of laser velocimetry that direct estimates of dissipation from a computation of the variance of the acceleration can be severely biased due to all the sources of spectral broadening, viz transit time, sub sample volume velocity gradients and turbulence. Thus, considering the advantages of linearity and drift free operation of the Doppler velocimetry method, new approaches are required. We present here the analysis of a method based on obtaining two estimates of the same velocity component at points separated by less than an inverse Kolmogoroff wavenumber. Although two point velocimeters have been developed in the past by van Maanen and Veth, their object has been to extend the observation of the velocity spectrum into the dissipation region ($kn=1$). To our knowledge, the analysis and trade-offs for short term estimation of dissipation has not been reported.

Clearly, when two such independent estimates of the velocity are obtained, the dissipation as estimated from the cross-correlation of the two derived accelerations is unbiased. However, in order to obtain short time estimates, one must examine the statistics of the dissipation estimate itself. Examining the variance of the dissipation estimate in terms of the two accelerations yields the simple result that the error in the estimate is dependent upon the fourth order moments of the underlying fluid acceleration itself and on the factor as follows:

$$\sigma_{\epsilon}/\epsilon = \{k_4 - 1 + 2\delta + \delta^2\}^{1/2}$$

where δ is the quantity $\dot{n}^2/\dot{u}^2$ and K_4 is the kurtosis of the fluid acceleration. In order to minimize the errors of estimating the dissipation above, the variance of $(\dot{u}_1\dot{u}_2)$ is computed over a bandwidth corresponding to $kn=1$ only.

In this paper, we shall present the analysis for estimating the quantities of interest and preliminary data from laboratory flows.

In press: Proc. of Applications of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, July 7-9, 1986.

Supported by: ONR Contract N00014-C-85-0001.

WHOI Contribution No. 6160.

ONE TURN OF THE SCREW: DESCRIPTION, CALIBRATION AND APPLICATION OF A SIMPLE TECHNIQUE FOR FINE SCALE, VERTICAL SECTIONING OF FRESH MARINE SEDIMENTS

C. M. Fuller and C. A. Butman

The expectation that the depth of the bed which is eroded during resuspension events is on the order of millimeters in coastal embayments and that benthic biota may periodically determine the surface sediments available for transport prompted the design of a technique for fine-scale vertical sectioning of fresh sediment cores from the field. An upward-displaced piston, core-extruding device was developed that enables sectioning of cores at ≥ 1 -mm increments with no loss of sample and no smearing along the core wall. Calibration experiments to define the precision of the technique for sectioning at 2-mm increments indicate that deviation of extruded grain-size distributions from those initially layered in the cores are within the measurement and technician error for the experiments; vertical sectioning of sediments is precise at least to within $\pm$ the largest grain size in the sediment horizons. The technique was tested on field cores collected from a muddy habitat at 10-m depth in Buzzards Bay, Massachusetts (USA). The preliminary results indicate that the microstratigraphy (2-mm sections) of the sediments varies significantly between the spring and fall; the microstratigraphy of the macrofauna provides one explanation for these results. The maximum depth of the bed resuspended by the flow could be defined only for the physically graded sediments observed in the spring. More measurements and experiments are required to define this depth for the fall samples. These results strongly support the routine application of this technique to define sediment transport parameters in potentially bioturbated environments.

Supported by: NOAA, National Sea Grant College Program under Grant No. NA84AA-D-00033 (R/P-21); and PEW Memorial Trust.

WHOI Contribution No. 6192.

VAXCLUSTER MANAGEMENT AND USER EXPERIENCE

R.C. Groman

This paper reviews Woods Hole Oceanographic Institution's experiences in implementing a VAXcluster during the summer and fall of 1985. These experiences may

help you prepare for, and avoid, the hurdles and problems that we encountered.

Published in: USA 1985 Fall Proceedings of the Digital Equipment Computer Users Society, December 9-13, 1985.

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WHOI Contribution No. 6111.

ARGO: CAPABILITIES FOR DEEP OCEAN EXPLORATION

S. E. Harris and R. D. Ballard

Developed by the Deep Submergence Laboratory of the Woods Hole Oceanographic Institution, ARGO is an unmanned instrument platform designed for deep ocean search and survey. Integrating both visual and acoustic imaging techniques for real-time viewing, ARGO is a system which provides continuous, around-the-clock operation for seafloor exploration. With a design depth of 6,000 meters, it is towed on a steel-armored coaxial cable which supports several channels of frequency-multiplexed signals. In addition, surface support is highly integrated, bringing together ship control, navigation, and vehicle operation into a transportable control center.

In our expedition that found the TITANIC, this system was tested for the first time and proved itself by delivering the exciting pictures of the famous shipwreck lying on the bottom of the ocean. This paper will briefly describe ARGO and the reasons for its development. Examples of ARGO imaging from our first year of operation will demonstrate how modern oceanographers remotely sense the ocean floor.

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WHOI Contribution No. 6217.

THE FAST PROFILER

J. K. Hoyt and A. M. Bradley

The Fast Profiler is an autonomous, streamlined, gravity driven vehicle cap-

able of high speed (15 knots) vertical excursions to depths of 6000 meters. This axially symmetric torpedo shaped vehicle can guide itself to an acoustic beacon at the surface. Phase difference measurements made at four hydrophones mounted in the nose of the body are used to actuate control surfaces to correct vehicle attitude. The oceanographic sensor package is initially intended to measure conductivity and temperature as a function of depth. These variables are used in the equation of state of seawater to calculate the total transport of large-scale circulation patterns. This paper outlines the mechanical and electronic design of the fish.

Published in: Proceedings of the Fourth International Symposium of Unmanned, Untethered Submersible Technology, June 24-27, 1985, Marine Systems Engineering Laboratory (MSEL), University of New Hampshire.

Supported by: NSF Grant OCE83-10168.

WHOI Contribution No. 6169.

THE FLYING FISH: AN UNTETHERED SENSOR PLATFORM WITH ACOUSTIC HOMING CAPABILITY, ITS ROLE IN GLOBAL SCALE HYDROGRAPHIC SURVEYS

J. K. Hoyt and A. M. Bradley

A free-fall vehicle developed as a platform for a suite of oceanographic sensors is described. The vehicle's principal attributes are portability, speed, and acoustic homing. The vehicle architecture promotes the use of automated diagnostics and data collection. Concurrent with the vehicle development program at Woods Hole, several manufacturers are designing sensors which can be interfaced both mechanically and electronically with the fish. Intercomparison tests with the conventional CTD sensors are planned for late 1985 and early 1986. This paper presents the basic specifications of the Flying Fish to assist in the planning of experiments based on this instrument system. We also present some suggestions for the infrastructure required to support global scale hydrographic surveys.

Published in: Proceedings of the IEEE OCEANS '85 Conference, San Diego, CA, November 12-14, 1985.

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WHOI Contribution No. 6168.

GENERAL PURPOSE RACK, BACKPLANE,
AND BOARD SET FOR IN-SITU OCEANOGRAPHIC
INSTRUMENTATION

E. Mellinger, K. Prada, R. Koehler
and K. Doherty

The need for a configurable, high-performance family of computer "building blocks" led to the design of a general purpose backplane architecture for the construction of processor systems to be used in oceanographic instrumentation. The architecture, called the "Instrument Bus," includes a CMOS backplane based on the IEEE 796 (Multibus 1) standard, along with a card rack structure and mechanical specification to fit the standard 6" I.D. pressure case. A card set based on the 80C86 CPU was designed and implemented using this architecture. The set includes the CPU, 64k memory module, serial and parallel I/O, clock/timebase, counter/timer, and 16-bit A/D converter. The flexibility of the backplane specification accommodates a wide variety of CPU and I/O devices and a wide range of resulting computer processing power. Designs scheduled for the near future include high speed (1 Mbit/sec) serial I/O, 68HC11 CPU, and a TMS 320-based numeric processing slave. Applications to a number of instrument design situations are discussed.

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083-004.

WHOI Contribution No. 6263.

HIGH DENSITY STATIC RAM FOR IN-SITU
BULK DATA STORAGE

E. Mellinger

Static CMOS Random Access Memory (RAM) can be packaged to achieve a density of 1 MByte per running inch of 6" I.D. pressure case, using 64 kbit memory devices. A bulk data storage subsystem using this technique, including 1 MByte/sec CPU interface, backup power system, and memory array of up to 16 MBytes, was constructed and tested in an operational microstructure profiler. Results are discussed, and the general advantages and disadvantages of this data storage method are considered.

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083-004.

WHOI Contribution No. 6262.

OPTICAL PARTICLE SIZING FROM SMALL
ANGLE SCATTERING -- FURTHER RESULTS

J. B. Riley and Y. C. Agrawal

An optical method for instantaneous measurement of suspended particle size distribution shows promise for the study of boundary layer dynamics in the ocean where suspended particles affect boundary layer flow through stratification. The method is based on observing the angular distribution of scattered light, $I(\theta)$, from a sample, and inverting to produce the suspended particle size distribution, $n(r)$. In a previous paper, an analytic inversion based on the Fraunhofer approximation was examined. The function $\theta^3 I(\theta)$ was found approximately to be related by a Fourier transform to $n(r)$, with the result that elementary signal processing concepts apply. In this work, the use of the Fraunhofer approximation is explored by comparison with results from "exact" Mie theory. Matrix inversion algorithms, including Singular Value Decomposition, are employed for the inversion with promising results. That the matrix relating $n(r)$ to $\theta^3 I(\theta)$ approximately performs a discrete Fourier transform is noted and exploited to improve the construction of the matrix. This construction reduces the singularity and size of the matrix, and results in efficient, less noise sensitive algorithms for finding $n(r)$ from $I(\theta)$, and vice versa.

Experimental results in light of the theoretical background and analysis of synthetic data will be presented.

Published in: Ocean Optics VIII,
Soc. Photo Opt. Instr. Engrs.,
Orlando, FL, April 3-5, 1986.

Supported by: WHOI Coastal Research
Center.

WHOI Contribution No. 6163.

STANDARDS - WHY BOTHER?

W. E. Terry

Increased acceptance of several new oceanographic flow sensors such as Coastal Ocean Dynamics Applications Radar (CODAR), Doppler backscatter profilers, the Inter-Ocean S-4, the Smart ACM and others have

renewed our interest in flow measurement techniques and methods of data interpretation.

Several areas exist in which the oceanographic current meter community might begin to establish guidelines or "standards." Specific problem areas are discussed, and some specific solutions are recommended.

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WHOI Contribution No. 6138.

NEW DEVELOPMENTS IN THE MOCNESS, AN APPARATUS FOR SAMPLING ZOOPLANKTON AND MICRONEKTON

P. H. Wiebe, A. W. Morton, A. M. Bradley,
R. H. Backus, J. E. Craddock, V. Barber,
T. J. Cowles and G. R. Flierl

Four variants of the Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS) have been constructed to sample a broad size spectrum of oceanic animals from microzooplankton to micronekton. The systems differ in mouth opening dimensions (ranging from 1/4 to 20 m²), the number of nets carried (from 5 to 20), and the mesh size of the netting (from 64 μ m to 3.0 mm). A new electronics package enables an operator to send commands down a single conductor, armored cable to open/close the nets and provides 12-bit resolution for the environmental (temperature, depth, conductivity) and net operation data (flow, net-frame angle, net-bar release), which are transmitted up the cable to the deck unit at 2-s intervals. A microcomputer system, interfaced to the deck unit, calculates salinity, volume filtered by a net, net trajectory velocity, and vertical velocity. The data are printed out and stored on disc, and profiles of temperature and salinity versus depth are plotted during the course of the tow. Analysis of the relationship between the geometry of the MOCNESS under tow and the past and present methods used to estimate the water filtered by a net revealed that significant bias is introduced when the ascent or descent angle of a net is disregarded. The bias is a function of the ratio of vertical velocity to net trajectory velocity and results in an underestimate of volume filtered while shooting a net and an overestimate while hauling.

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313-323, 1985.

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WHOI Contribution No. 5856.

MEASUREMENT OF TURBULENCE WITH AN ACOUSTIC CURRENT METER ARRAY IN THE OCEANIC BOTTOM BOUNDARY LAYER

A. J. Williams III, J. Tochko, R. Koehler
and W. D. Grant

A vertical array of acoustic current meters measures the vector flow field in the lowest 5 meters of the oceanic boundary layer. By resolving the velocity to 0.03 cm/s over 15 cm paths, it samples the dominant turbulent eddies responsible for Reynolds stress to within 50 cm of the bottom. Profiles through the inner boundary layer, from six sensor pods, of velocity, turbulent kinetic energy, and Reynolds stress can be recorded for up to four months with a 2 Hz sample rate and 20 minute averaging interval. We can study flow structure and spectra from as many as 4 event triggered recordings of unaveraged samples, each lasting one hour, during periods of intense sediment transport. Acoustic transducer multiplexing permits 24 axes to be interfaced to a single receiving circuit. Electrical reversal of transducers in each axis eliminates zero drift. A deep sea tripod supports the sensor array rigidly with minimum flow disturbance yet releases on command for free vehicle recovery.

In press: Journal of Atmospheric
and Oceanic Technology.

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WHOI Contribution No. 6369.

RICHARDSON NUMBER FLOAT

A. J. Williams III, C. H. Converse
and J. W. Nicholson

A neutrally-buoyant free vehicle, ballasted to float 200 meters below the sea surface and carrying an array of velocity sensors, thermistors and a self recording CTD, has monitored velocity shear and stratification in a fluid parcel for one day. Turbulence, one candidate for interior ocean mixing, may occur when the Richardson number drops to 1/4 from its

more commonly observed rms value of 1. Based on a series of shear profiles, it has been hypothesized that patches of turbulence persist for many days, providing a location where internal wave shear causes mixing. The instrument designed to test this hypothesis is a 5 meter vertical array of acoustic current meters and thermistors on a platform with acoustically controlled buoyancy adjustment and depth telemetry. The instrument measures velocity, temperature, and tilt, and forms and records 2-minute averages of velocity, temperature, and the correlation of the vector components of velocity. Coupled with a time series of conductivity, temperature, and depth, the Richardson number of a parcel of water can be followed for weeks.

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WHOI Contribution No. 6279.

M O O R I N G S

WAVE TANK STUDY OF MOORED BUOY HULLS FOR AIR-SEA INTERACTION APPLICATIONS

H. O. Berteaux and Lt. R. L. Boy

Measurements of atmospheric and oceanic parameters for Air-Sea interaction studies are made from deep sea moored surface buoys. The buoys support a set of meteorological sensors. Self recording instruments inserted in the mooring line monitor water temperature and oceanic currents. Because of constant wave action, the instruments on the buoy and in the line undergo repeated motions which introduce large noise levels and sometimes shake the instruments close to destruction.

Tests have been recently conducted at the Wave Research Facility of the Oregon State University to observe the response of moored buoys and assess the impact of buoy shape and mooring attachment on the motion of the sensors. This paper presents the rationales for the selection of the hull shapes, and the considerations for scaling and modeling the buoys. A novel approach for modeling the mooring line is explained. A review is made of the data acquisition and processing techniques. A summary of the test results

concludes the paper.

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WHOI Contribution No. 6211.

O C E A N A C O U S T I C S

A PLANETARY WAVE ANALYSIS USING THE ACOUSTIC AND CONVENTIONAL ARRAYS IN THE 1981 OCEAN TOMOGRAPHY EXPERIMENT

C. S. Chiu and Y. Desaubies

Using the maximum-likelihood estimation method, quasi-geostrophic wave solutions are fitted to the observations of the 1981 Ocean Acoustic Tomography Experiment. The experiment occupied a 300 km square area centered at 26°N, 70°W, and had a duration of approximately 80 days. The data set consists of acoustic travel-time records, moored temperature records and CTD profiles. The acoustic data correspond to integral measurements of the temperature (or sound-speed) field.

The optimal fit to the data corresponds to three waves in the first baroclinic mode, evolving under the presence of a westward mean flow with vertical shear. The mean flow is found to be weak (approximately 2 cm/s) but changes the wave periods significantly by producing large Doppler shifts. The waves are dynamically stable to the mean flow, have weak, nonlinear interactions with each other and do not form a resonant triad; thus, they constitute a fully linear solution.

Evidence for the existence of the waves is strongly supported by the high correlation (approximately 0.9) between the data and the fit, the large amount of signal energy resolved (approximately 80%), the excellent quality of the wave-parameter estimate (only about 10% in error), and the general agreement between the observations and quasi-geostrophic linear dynamics.

In press: Journal of Physical Oceanography.

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WHOI Contribution No. 6254.

TOMOGRAPHIC RESOLUTION OF MESOSCALE EDDIES

IN THE MIZ-A PRELIMINARY STUDY

C. S. Chiu, J. F. Lynch and
O. M. Johannessen

The system performance of acoustic travel-time tomography to resolve mesoscale eddies in the Marginal Ice Zones (MIZ) is evaluated. Acoustic ray arrivals are found to be separable with signal bandwidths larger than 25 Hz. The adequacy of resolution of mesoscale perturbations in the vertical plane containing the acoustic multipaths connecting a pair of transceivers is studied. Resolution in this plane is seen to be strongly dependent upon the characteristics of the sound channel. For optimal, minimum mean-square-error estimators, resolution is directly related to accuracy, with better resolution implying higher accuracy.

Horizontal and vertical resolution lengths of orders 40 km and 200 m, respectively, are found in the upper water column for a transmission range of 150 km. The implication is that horizontal resolution is adequate to resolve MIZ eddies but vertical resolution is not, since the horizontal scale of the eddies is of the same order whereas the vertical scale is much shorter. The incorporation of bottom-reflected arrivals is found to improve resolution significantly. However, the improvement only occurs in the horizontal direction and saturates when more than 14 of these arrivals are included. Beyond this point, additional travel-time observations give mostly redundant information. On the other hand, the disappearance of less stable non-bottom-interacting ray paths can result in a significant loss of resolution, but only vertically. The deficiency in vertical resolution is a result of the upward refracting nature of the MIZ sound channel. Simulation inversions based on realistic eddy profiles are performed to further reflect system performance. It is demonstrated that, with the deployment of only a few additional vertical arrays of point sensors, adequate vertical resolution is achievable.

In press: Journal of Geophysical Research, Special MIZ Issue.

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WHOI Contribution No. 6253.

MAPPING SEAFLOOR GEOACOUSTIC PROPERTIES IN SHALLOW WATER FROM MONOCHROMATIC PRESSURE FIELD DATA: TWO METHODS BASED ON HANKEL TRANSFORM INVERSION

G. V. Frisk, J. F. Lynch and
G. J. Tango

A survey is presented of recent related work (comprising numerical modeling and field experiments) on the determination of seafloor geoacoustic properties in shallow water from monochromatic pressure field measurements obtained using synthetic aperture and towed arrays. Two related techniques are discussed, their common foundation lying in the Hankel transform inversion of the pressure versus range data to obtain a depth-dependent Green's function versus horizontal wave-number. Characteristic features of the Green's function, such as the peaks associated with normal mode propagation in the shallow water waveguide, are used to extract the geoacoustic properties (compressional and shear) as a function of depth in the bottom.

In press: Proceedings of the 18th Annual Offshore Technology Conference, Houston, Texas, May 5-8, 1986.

Supported by: ONR Contracts N00014-85-K-0062 and N00014-82-C-0152.

WHOI Contribution No. 6136.

OCEAN ACOUSTIC TOMOGRAPHY: MESOSCALE VELOCITY

B. M. Howe, P. Worcester and R. C. Spindel

The travel times of acoustic pulses transmitted in opposite directions over a 300 km distance in mid-ocean have been used to measure the fields of sound speed and absolute water velocity with mesoscale resolution. The experiment, which took place west of Bermuda during August and September 1983, consisted of transceivers on two moorings that sent and received signals every two hours for 21 days. Ray paths in opposite directions were found to be very nearly reciprocal; effects due to internal waves and mean currents were small. Sum travel times were inverted to obtain sound speed at two day intervals, and differential travel times were inverted to obtain absolute current velocity u . The principal results are: (i) Range-averaged sound speed perturbation $\delta C(z)$ decreased over the 21 days by $5 \pm 0.2 \text{ m s}^{-1}$ at 1000 m depth, corresponding to a temperature decrease of approximately 1° C ;

similar (but lesser) changes are measured at other depths. The changes are associated with the first baroclinic mode. (ii) The field $\delta C(x,z)$ determined from XBT measurements at the start of the experiment agrees with the field determined using the acoustic data within estimated errors of $\pm 1.6 \text{ m s}^{-1}$. It is thus possible to obtain range-dependent δC information from acoustic measurements made in a single vertical slice. (iii) During the 21 days, the range-averaged barotropic velocity mode increased by a factor of 3 while the baroclinic mode decreased by a factor of 2. The estimated error in range-averaged $u(z)$ is $\pm 2 \text{ cm s}^{-1}$ above the main thermocline and $\pm 1 \text{ cm s}^{-1}$ below, while for range-dependent $u(x,z)$ the errors are 5 cm s^{-1} and 3 cm s^{-1} , respectively. No significant range-dependence in $u(x,z)$ was found. The baroclinic velocity agrees with geostrophic velocities inferred from the XBT measurements at deployment and AXBT measurements 11 days after the end of the reciprocal transmissions.

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WHOI Contribution No. 6408.

THREE RELATED RESONANCE METHODS FOR THE DETERMINATION OF SEAFLOOR GEOACOUSTIC PROPERTIES

J. F. Lynch, G. V. Frisk, S. D. Rajan, J. Tango, M. F. Werby, A. Nagl and H. Uberall

A survey is presented of recent related work on the determination of seafloor geoaoustic properties using resonance methods. Three related techniques are discussed. The first two techniques have their common foundation in the Hankel transform inversion of complex pressure field versus range data to obtain a depth-dependent Green's function versus horizontal wavenumber. In shallow water, the Green's function shows resonances associated with the normal modes of the waveguide which are used to extract the geoaoustic properties (compressional and shear) as a function of depth into the bottom. The third technique has its basis in the fact that the plane-wave reflection coefficient of the ocean bottom shows resonances both as a function of frequency and angle of incidence. As in the Green's function techniques, the resonances depend on the properties of the ocean bottom.

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WHOI Contribution No. 6220.

MULTIPLE SCATTERING OF NORMAL MODES FROM ROUGH SURFACES WITH APPLICATIONS TO SHALLOW WATER ACOUSTICS, ARCTIC ACOUSTICS, AND OCEAN ACOUSTIC TOMOGRAPHY Part I - Theory

J. F. Lynch, J. H. Miller, C. S. Chiu and G. V. Frisk

Modal eigenvalues and times of flight are important data for shallow water acoustics and acoustic tomography. Scattering of modes by surface roughness causes these quantities to change and fluctuate (viz. bias, wander, and spreading occur) and so they must be accounted for in inversions for bottom and/or water column properties. In order to account for such surface scattering, a simple multiple scattering formula based on the coupled radial equations of range-dependent normal mode theory is presented. Moments of the leading terms of this series are discussed and approximate analytical results for both a simple hard bottom waveguide and an Arctic channel (without ice cover) are presented. Numerical calculations of modal rough surface scattering will appear in a future companion manuscript to this one. Directions for future research are also discussed.

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WHOI Contribution No. 6344.

A PERTURBATIVE INVERSE METHOD FOR THE DETERMINATION OF GEOACOUSTIC PARAMETERS IN SHALLOW WATER

J. F. Lynch, S. D. Rajan and G. V. Frisk

An inverse method is described for obtaining the acoustic properties of a horizontally stratified bottom in shallow water from measurements of the magnitude and phase versus range of the pressure field due to a CW point source. These data are numerically Hankel transformed to obtain the depth-dependent Green's function versus horizontal wavenumber. The Green's function contains prominent peaks at horizontal wavenumbers corresponding to the eigenvalues for any trapped and vir-

tual modes excited in the waveguide. The eigenvalues are then used as input data to a perturbative inverse scheme. The method is applied to the problem of determining the compressional wave speed as a function of depth and is demonstrated for experimental data. The results are compared with those obtained using an iteration of forward models method.

In Press: Proceedings of the I.C.A. Congress Symposium on Underwater Acoustics, July 1986.

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WHOI Contribution No. 6230.

RESULTS FROM THE MIZEX '84
PRELIMINARY TOMOGRAPHY EXPERIMENT:
IMPLICATIONS FOR MIZ, ARCTIC AND SURFACE
WAVE TOMOGRAPHY

J. F. Lynch, R. C. Spindel, C. S. Chiu,
J. H. Miller and T. G. Birdsall

During MIZEX '84, a 224 Hz center frequency acoustic tomography sound source was deployed off Spitzbergen, Norway, in 1200 m of water. Over the course of ten days it transmitted hourly signals that were recorded by receivers at two locations, one moving with the ice pack and the other stationary. The main purpose of the transmissions was to answer the following questions: 1) can the signals be coherently averaged to improve the signal-to-noise ratio of the multipath arrival peaks; 2) are the surface scattering and bottom reflection losses acceptably low, 3) are the arrivals identifiable; 4) are the arrivals stable; and 5) are the arrivals resolvable? Our data analysis provides positive answers, indicating that ocean acoustic tomography is feasible in MIZ regions. However, the shallow bathymetry in the MIZEX '84 area increases the difficulty of the problem, consistent with the observations of Palmer (1985) and Deferrari and Nguyen (1985) in the shallow water of the Straits of Florida.

In analyzing the data, it was noticed that the phase (or travel time) fluctuation spectra of surface interacting rays exhibited a shape similar to that of the surface wave frequency spectrum. This suggested that tomography could also measure the surface wavefield, a previously unexplored possibility. Theoretical expressions are derived in this paper which relate the acoustic fluctuations to standard surface wave descriptors, e.g. the frequency-directional spectrum. These expressions are then used to compute the

surface wave frequency spectra for two days of data. Though these spectra are uncorroborated by other wave spectrum measurements (e.g. waverider buoys), the RMS waveheights predicted by the acoustics agree well with RMS waveheights estimated by windforce data.

In Press: Journal of Geophysical Research, Special MIZ Issue.

Supported by: ONR Contracts N00014-86-C-0127, N00014-85-C-0001 and N00014-82-C-0152.

WHOI Contribution No. 6219.

AN INVERSE METHOD FOR OBTAINING THE
ATTENUATION PROFILE AND SMALL VARIATIONS
IN THE SOUND SPEED AND DENSITY PROFILES OF
THE OCEAN

S. D. Rajan and G. V. Frisk

An inverse method is presented for the determination of the compressional wave speed, compressional wave attenuation, and density as a function of depth for a horizontally stratified ocean bottom. It is based on a perturbation technique for which the required input information is the plane-wave reflection coefficient of the bottom as a function of incident angle at a fixed frequency. The reflection coefficient is related to variations of the acoustic properties about known reference values through a nonlinear integral equation which is then linearized using the Born approximation. An acceptable stable solution of the integral equation is obtained using a priori constraints on the solution. Resolution of the solution obtained is studied using the resolving power theory of Backus and Gilbert¹. Examples of inversions using synthetic data are presented using noise-free and noisy data. Results obtained with noise-free data show good agreement between true and reconstructed profiles. Inversions performed with noisy data yield stable, acceptable results.

In press: Proceedings of the I.C.A. Congress Symposium on Underwater Acoustics, July 1986.

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

WHOI Contribution No. 6397.

PERTURBATIVE INVERSION METHODS
FOR OBTAINING BOTTOM GEOACOUSTIC
PARAMETERS IN SHALLOW WATER

S. D. Rajan, J. F. Lynch and G. V. Frisk

Three perturbative inverse methods for obtaining bottom geoaoustic parameters as a function of depth in shallow water are described. The required input data are the trapped mode eigenvalues for one or more frequencies, the group velocity dispersion curves for one or more modes, or the CW pressure field versus range. In each case, a Fredholm integral equation arises which can be solved using linear inverse theory, and for which resolution and variance estimates of the solution can be readily made. Attention is focused primarily on the modal eigenvalue inverse problem for which the theory for determining the compressional wave speed, compressional wave attenuation, and density is developed in detail. Properties of this technique are studied using synthetic data and include investigations of the dependence of the results on acoustic frequency, number of modes excited, and partial a priori knowledge of the bottom. The method is demonstrated on experimental data obtained in Nantucket Sound at 140 Hz and 220 Hz. Directions of future research on these techniques are indicated.

In press: Journal of the Acoustic Society of America.

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WHOI Contribution No. 6259.

OCEAN ACOUSTIC TOMOGRAPHY:
A REVIEW

R.C. Spindel

Ocean acoustic tomography is a technique for observing the dynamic behavior of ocean processes by measuring the changes in travel time of acoustic signals transmitted over a number of ocean paths. The travel time varies in proportion to the magnitude of the sound speed and current inhomogeneities along each path. The latter quantities can be estimated using mathematical inverse methods. A group of researchers have been developing this idea into a practical measurement tool. In this paper we review the basis for tomography, its implementation in several pilot experiments, and some current programs. We point out the limitations of present equipment and techniques and suggest areas for further development.

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WHOI Contribution No. 6057.

RECONSTRUCTION OF A COMPLEX-VALUED FIELD
USING THE HILBERT-HANKEL TRANSFORM

M. S. Wengrovitz, A. V. Oppenheim
and G. V. Frisk

An exact real-part sufficiency condition does not apply to a one-dimensional even signal or to a two-dimensional circularly symmetric signal. In this paper, an approximate real-part sufficiency condition is developed and the two-dimensional result is used in a reconstruction algorithm. The algorithm is applied to synthetic and experimental underwater acoustic fields.

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WHOI Contribution No. 6175.

UNDERWATER ROBOTICS

THE APPLICATION OF DIFFERENTIAL GPS TO
MARINE VESSEL DYNAMIC POSITIONING

R. P. Denaro, P. V. W. Loomis
and D. Yoerger

Dynamic Positioning of marine vessels is conducted to support at-sea drilling operations, survey, diver and submersible vehicle support. Current sensors used for position reference experience a variety of error characteristics and reliability problems, and often require extensive installation effort. As an alternative, differential GPS, used in conjunction with other low-cost sensors, may eliminate many of these problems. This paper discusses the dynamic positioning application of differential GPS in terms of error sources and design concepts.

Supported by: NSF Grant OCE85-11431.

JASON: AN INTEGRATED APPROACH TO ROV
AND CONTROL SYSTEM DESIGN

D. R. Yoerger and J. B. Newman

ROVs can be made more capable and easier to operate through the use of supervisory control techniques. Supervisory control systems combine precision navigation, closed-loop control, and a well-designed man-machine interface. They can improve ROV performance and decrease operator workload. Survey and inspection tasks can be performed and repeated more precisely and efficiently. Performance can be maintained in poor visibility and high currents. Vehicle motions can complement manipulator movements, so that more difficult manipulative tasks can be completed with simple arms.

While closed-loop control can be added to existing platforms, performance may be limited by several factors. First, high quality navigation data is required. Also, the vehicle dynamics must be well behaved. Finally, performance is limited by disturbances and by uncertainty in the vehicle dynamic model. In this paper, the interactions of these factors is discussed focussing on JASON, a new ROV under development that will perform scientific tasks on the sea floor to depths of 6000 meters.

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SUPERVISORY CONTROL SYSTEM
FOR THE JASON ROV

D. R. Yoerger, J. B. Newman
and J. J. E. Slotine

A prototype supervisory control system for a remotely operated vehicle (ROV) is described and several key elements demonstrated in simulation and in-water tests. This system is specifically designed to fill the needs of JASON, a new ROV under development that will perform scientific tasks on the seafloor to depths of 6000 m. JASON will operate from the ARGO towed imaging platform, which is currently operational.

Supervisory control is a paradigm for combined human and computer control. Several key elements of the supervisory control system are presented. These include the closed-loop positioning system based on a high-resolution acoustic navigation system, a monitoring capability for

assessing performance and detecting undesirable changes, and an interface that allows the human operator and the computer system to specify the desired vehicle trajectory jointly.

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Applied Sonics, Inc.

WHOI Contribution No. 6183.

DESIGN OF UNDERWATER VEHICLES FOR
HIGH PERFORMANCE CONTROL

D. R. Yoerger, C. J. von Alt, A. D. Bowen
and J. B. Newman

Design considerations for high performance control of remotely operated underwater vehicles are presented, focussing on the performance limits imposed by navigation, actuators, dynamic uncertainty, control strategies, and the dynamics of the vehicle. As coupling between translation and attitude present a major impediment to high bandwidth control, techniques for reducing this coupling are presented. In-water test data is presented for the new JASON Junior vehicle currently being designed and built at the Deep Submergence Laboratory.

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PHYSICAL OCEANOGRAPHY

DEPARTMENT OF PHYSICAL OCEANOGRAPHY

Robert C. Beardsley, Department Chairman

PO-1

COASTAL CIRCULATION
AND DYNAMICS

SHIPBOARD ACOUSTIC DOPPLER PROFILER
VELOCITY OBSERVATIONS
NEAR POINT CONCEPTION: SPRING 1983

J. A. Barth and K. H. Brink

During April 1983, shipboard Doppler acoustic log current profiles were collected in an effort to characterize the flow field near Points Conception and Arguello, California. Subsurface velocity maps derived from these profiles have been used to describe spatial flow structures both on and off the shelf and to investigate flow variability as a function of time and of wind stress. Persistent westward flow out of the northern half of the Santa Barbara Channel and eastward flow into its southern half were observed regardless of the direction of the local wind stress. During one well-documented upwelling-favorable wind event, currents responded in the form of an energetic (maximum 21 m speeds $> 60 \text{ cm s}^{-1}$) off-shore squirt of cold water. During weak or downwelling-favorable winds, currents continuous with the Santa Barbara Channel outflow were observed flowing to the northwest following the local isobaths before turning offshore west of Point Arguello. Evidence for wind forcing of current fluctuations nearshore between the Points and north of Point Arguello was found. Lack of a thermal wind balance between directly measured velocity shear and horizontal density gradient was explained by the presence of large accelerations in the momentum equations. Lack of a consistent relation between velocity and temperature gradient illustrates the difficulty in estimating velocity from temperature information alone in this area.

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WHOI Contribution No. 6239.

LOCAL ATMOSPHERIC FORCING DURING CODE
PART 1: A DESCRIPTION OF THE MARINE
BOUNDARY LAYER AND ATMOSPHERIC
CONDITIONS OVER A NORTHERN CALIFORNIA
UPWELLING REGION

R. C. Beardsley, C. E. Dorman, C. A. Friehe, L. K. Rosenfeld and C. D. Winant

As part of the Coastal Ocean Dynamics Experiment (CODE), meteorological instruments were deployed on buoys and at coastal stations, and instrumented aircraft flights and coastal soundings were made to study the three-dimensional structure of the marine boundary layer over the continental shelf off northern California during the 1981 and 1982 upwelling seasons. These measurements show that after the atmospheric spring-transition, the airflow in the marine layer is dominated by the North Pacific High, and the surface wind field over the shelf is characterized by periods of strong (7-15 m/s), upwelling-favorable alongshelf winds lasting for up to 30 days, interrupted by shorter periods of much weaker winds directed either equatorward or poleward. These periods of weak or reversed winds typically last several days and are called wind relaxations even though they are primarily associated with coastally trapped perturbations of the marine layer along the central and northern California coast and not with a large-scale weakening of the North Pacific High.

The atmospheric boundary layer measurements made in CODE suggest a simple conceptual model which can explain much of the physiology or structure of the marine layer and associated surface wind field during periods of persistent upwelling-favorable winds. During these periods, which represent the quasi-steady state regime during the upwelling season, the inversion base of the marine layer drops eastward towards the coast until it intersects the coastal mountain range at a height of several hundred meters, and the associated thermal wind produces an along-shelf wind jet which has a maximum speed just below the inversion base. Turbulent mixing tends to homogenize any stratification in the marine layer beneath the jet and couple the jet to the ocean surface producing strong upwelling-favorable winds over the shelf. Day/night heating/cooling over the narrow coastal strip beneath the marine layer generates a weak cross-coast secondary circulation which causes the core of the alongshelf jet to drop in elevation and shift onshore. This diurnal change in the marine layer structure explains both the daytime acceleration of the surface winds observed over and near the coast and its offshore decay, and the associated offshore increase in the subdiurnal along-shelf wind. Thus the quasi-steady component of the wind stress has a significant curl over the inner shelf during periods of active upwelling.

This mean summer atmospheric boundary layer regime is occasionally interrupted by synoptic and/or mesoscale events or anomalous conditions. Analysis of the CODE observations suggests five types of

events, two primarily synoptic-scale conditions which lead to stronger-than-normal upwelling favorable winds over the shelf, and three primarily mesoscale events which lead to wind relaxation. About half of the wind relaxation events observed in 1981 and 1982 are believed to be associated with either coastal-trapped gravity currents or internal Kelvin waves which propagate northward in the marine layer along the central and northern California coastal mountain range.

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WHOI Contribution No. 6313.

A STOCHASTIC MODEL FOR WIND-DRIVEN CURRENTS OVER THE CONTINENTAL SHELF

K. H. Brink, D. C. Chapman
and G. R. Halliwell, Jr.

A stochastic model for current, pressure and density fluctuations over the continental shelf and slope is solved for coherence, phase and gain between the oceanographic variables and wind stress. Comparison of wind stress spectra and transfer functions show that free coastal-trapped wave physics tends to exist in a frequency band bounded at the low end because of frictional predominance, and at the high end because of the absence of wind energy at appropriate alongshore length scales. The transfer functions for density and especially cross-shelf velocity show that these variables are sensitive to short length scales in the forcing, and are thus difficult to predict in general.

Model results are compared to observations of bottom pressure and alongshore velocity from the 1982 Coastal Ocean Dynamics Experiment (CODE) off northern California. The results agree with observations, at least qualitatively, with regard to spatial and frequency patterns in coherence and gain. The poorest point of agreement is in the amplitude of wind stress-current gains, which the model systematically underpredicts. The comparisons do demonstrate the importance of including accurate representations of bottom friction and of both cross-shelf and alongshore gradients of wind stress amplitude.

In press: Journal of Geophysical Research

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WHOI Contribution No. 6275.

APPLICATION OF WIND-FORCED, LONG COASTAL-TRAPPED WAVE THEORY ALONG THE CALIFORNIA COAST

David C. Chapman

The theory of wind-forced, frictional, long, coastal-trapped waves is applied along the California coast (i) to examine the sensitivity of the model to the numerous arbitrary and subjective choices which must be made during the application procedure, and (ii) to hindcast observable quantities in the region of the Coastal Ocean Dynamics Experiment (CODE) in an attempt to understand the dynamics of the region.

Results of the model sensitivity study show that the model predictions are highly sensitive to the choice of wind stress used to force the model. Along the California coast, measured coastal and buoy winds are far superior to the calculated (Bakun) winds. The model predictions are relatively insensitive to uncertainties in the other model inputs.

Hindcast results show that bottom pressure and alongshelf currents over the shelf are primarily wind forced throughout the year with most of the forcing located between Pigeon Pt. (~ 200 km south of CODE) and the CODE site. While the time variability is hindcast quite well, the model systematically underpredicts the bottom pressure and alongshelf currents by a factor of 1.2-2.5 and fails to predict the observed mid-shelf vertical structure of the alongshelf currents. Cross-shelf velocities and temperatures are poorly hindcast throughout.

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WHOI Contribution No. 6356.

THE CHARACTER AND MOTION OF SUSPENDED SEDIMENT OVER THE SHELF-EDGE AND UPPER SLOPE OFF CAPE COD

James H. Churchill, Pierre E. Biscaye
and Frank Aikman

Time series of suspended particulate matter concentration made by transmissometers deployed on the shelf-edge and upper slope off New England are examined together with data from companion sensors. At the shelf-edge instrument cluster (on the 125m isobath) the highest SPM concentrations were apparently due to sediment resuspended further onshore and advected to the transmissometer by offshore motion

of the shelf-edge density front. This was likely due to a tendency for more frequent episodes of high bottom stress, and thus more sediment resuspension, progressing on-shore from the outer shelf. The decrease of surface wave current amplitude with depth was primarily responsible for this cross-shelf gradient in bottom stress. On one occasion very turbid water was observed at the shelf-edge when the bottom stress was very low and the frontal motion was small. Data obtained from the U.S. National Marine Fisheries Service showed unusually intensive bottom trawling activity in the vicinity of the transmissometer during this time. This data further indicates that resuspension by trawlers may be an important source of suspended material on the shelf-edge. The record of the transmissometer deployed over the upper slope indicates that transport of particulate material in suspension from near the bottom on the shelf into the slope region occurred primarily along density surfaces, and was not continuous but intermittent.

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WHOI Contribution No. 6276.

NEAR-BOTTOM CURRENTS OVER THE CONTINENTAL SLOPE IN THE MID-ATLANTIC BIGHT

G. T. Csanady, J. H. Churchill
and B. Butman

Near-bottom currents faster than 0.2 m s^{-1} , the approximate threshold for resuspension of unconsolidated fine-grain sediment, occur frequently over the upper continental slope (depth $> 500 \text{ m}$) but their probability is low ($< 1\%$) over the mid-slope belt of $1 - 2 \text{ km}$ depth. Their presence is invariably tied to topographic wave activity, although it is often superimposed inertial oscillations which kick the current speed over the threshold. Episodes of intense inertial oscillation apparently occur randomly and last typically for $10 - 20$ days. Their energy source is unknown. Topographic waves appear irregularly, vary from one mooring line to the next and from one mooring deployment to another; their energy has a slight minimum over mid-slope. Their irregularity is apparently a reflection of their random generation associated with Gulf Stream instability.

In press: Continental Shelf Research.

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WHOI Contribution No. 6316.

A DESCRIPTION OF THE 1981 AND 1982 SPRING TRANSITIONS OVER THE NORTHERN CALIFORNIA SHELF

Steven J. Lentz

The spring transition between winter and summer conditions on the northern California continental shelf occurred suddenly, over a period of days, in late March in 1981 and in mid-April in 1982. The spring transition marks the onset of the upwelling season over the continental shelf and is a response to an atmospheric spring transition associated with a sudden seasonal change in the large scale atmospheric pressure field over the North Pacific. The 1981 and 1982 spring transitions over the northern California shelf are characterized by a drop in the water temperature over the shelf of $2-4^\circ\text{C}$ and a reduction of the temperature difference across the water column at mid-shelf from 2°C to 0.5°C . Isotherms and isopycnals, level prior to the spring transition, slope upward toward the coast after the spring transition. The mass balance for the 1982 spring transition event is roughly two dimensional, with offshore flow near the surface balanced by weaker subsurface onshore flow. The alongshore momentum balance during the 1982 spring transition is not two dimensional and includes the establishment of an alongshore pressure gradient which opposes the wind and apparently drives a poleward flow observed during a period of weak wind following the spring transition. The cross-shelf momentum balance is geostrophic, with density fluctuations contributing to the cross-shelf pressure gradient. The heat budget for the spring transition event is roughly two dimensional, with the drop in temperature due primarily to a cross-shelf exchange of heat associated with the cross-shelf circulation.

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WHOI Contribution No. 6199.

SEDIMENT MOVEMENT ALONG THE U.S. EAST
COAST CONTINENTAL SHELF, PART 1:
ESTIMATES OF BOTTOM STRESS USING THE
GRANT-MADSEN MODEL AND NEAR-BOTTOM
WAVE AND CURRENT MEASUREMENTS

Vincent D. Lyne, Bradford Butman
and William D. Grant

Bottom stress is calculated using the wave-current interaction model of Grant and Madsen (1979, J. Geophys. Res., 84, 1797-1808) for several long-term time series observations made on the U.S. east coast continental shelf. The sensitivity of the calculations to uncertainties in the input current and wave observations is examined, and changes in bottom stress caused by a moveable bed is estimated using the parameterizations of Grant and Madsen (1982, J. Geophys. Res., 87, 469-482).

The time series of wave and current measurements input to the Grant-Madsen model were obtained by means of a bottom tripod system which measured current at a fixed distance above the seafloor using a Savonius rotor and vane, and waves by means of a pressure sensor. To provide long-term observations, the variables were burst sampled about 10% of the time. Wave energy is reasonably resolved by the bottom pressure measurements; wave period is only good during large storms when it is accurate to 1-2 seconds. The time-series of wave speeds is aliased by wave groupiness. Errors in current speed and direction depend on the speed of the mean current relative to the wave. For weak bottom currents, errors in computed bottom stress may be as much as 100%. In general, errors in bottom stress caused by uncertainties in current speed and wave characteristics measured by the tripod are about 10 percent.

During storms, the bottom stress calculated using the Grant-Madsen models exceeded stress computed from conventional drag laws by a factor of 1.5 at these mid-shelf sites. Thus oscillatory currents associated with surface waves contribute substantially to bottom stress on the shelf, even in water as deep as 80 m. Given that the Grant-Madsen model is correct, constant drag law parameterizations of bottom stress will substantially underestimate stress and sediment transport.

On the south flank of Georges Bank, bottom roughness associated with megaripples may be responsible for enhanced measured stresses. Moveable bed effects due to sand ripple formation are reasonably well modelled but the photographic observations are not adequate to confirm the large ripples predicted to form during storms because the bottom is obscured by suspended sediment. Bed armoring, bioturbation and extensive shell hash may affect

ripple formation.

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WHOI Contribution No. 6332.

SEDIMENT MOVEMENT ALONG THE U.S. EAST
COAST CONTINENTAL SHELF, PART 2:
MODELLING SUSPENDED SEDIMENT CONCENTRATION
AND TRANSPORT RATE DURING STORMS

Vincent D. Lyne, Bradford Butman
and William D. Grant

Long-term near-bottom wave and current observations and a one-dimensional sediment transport model are used to calculate the concentration and transport of sediment during winter storms at 60-80 m water depth along the southern flank of Georges Bank and in the Mid-Atlantic Bight. Calculations are presented for five stations, separated by more than 600 km alongshelf, that have different bottom sediment texture, bedforms, and current conditions. A modified version of the sediment transport model presented by Grant and Glenn (1983, Tech. Rep. Am. Gas Assoc., 1, 167 pp.) and Glenn (1983, D. Sc. Thesis, M.I.T., Cambridge, 237 pp.) is used to examine the influence of wave-current interaction, sediment stratification and limitations on the erodability of the bottom sediments on the concentration of sediment in the water column and on transport. Predicted suspended sediment concentrations are much higher than observed unless an erosion limit of order a few millimeters for sediments finer than 94 μ is imposed. The agreement between predicted and measured beam attenuation is better at the stations that have significant amounts of silt plus clay in the surficial sediments than for areas with coarse grained sediments. Sediment concentrations during storms estimated by Moody et al. (1986, Cont. Shelf. Res.) are within 50% of the model predictions. Sediment transport rates for sediments 94 μ m and finer are determined largely by the concentrations in the surficial sediment and the erosion depth limit. Large alongshelf transports in the direction of storm-driven currents are inferred for the Mid-Atlantic Bight stations.

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WHOI Contribution No. 6210.

OBSERVATIONS OF SUBTIDAL CURRENTS OVER
THE NORTHERN CALIFORNIA CONTINENTAL SLOPE
AND ADJACENT BASIN: SOME EVIDENCE
FOR LOCAL WIND FORCING

Marlene Noble, Robert C. Beardsley,
James V. Gardner and Robert L. Smith

Currents at several depths were monitored on the upper slope, the mid-slope and over an adjacent deep-sea basin off northern California for nearly simultaneous periods from 4 to 14 months. In 1980 and 1981, subtidal current fluctuations with periods shorter than 32 days were oriented parallel to the topography over the slope, but had no consistent orientation over the basin. Mean currents flowed northwestward over the slope and southward in the basin. The subtidal current fluctuations in the three regions were generally incoherent with each other and were weakly coherent with wind stress and coastal sea level. Observations of wind-driven flow over the slope are consistent with a non-resonant model for wind-forced shelf and slope currents, but the observations are too limited to define specific model parameters. Over the basin, the wind-forced currents have characteristics similar to those predicted by stochastic models for wind-forced flow in the open ocean.

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WHOI Contribution No. 6290.

BAROTROPIC SEMIDIURNAL TIDAL CURRENTS
OFF NORTHERN CALIFORNIA DURING THE
COASTAL OCEAN DYNAMICS EXPERIMENT (CODE)

L. K. Rosenfeld and R. C. Beardsley

Barotropic semidiurnal tidal currents measured off the coast of northern California during the Coastal Ocean Dynamics Experiment (CODE) are examined. While the pressure field is consistent with the idea that the semidiurnal surface tide is dominated by a Kelvin wave, a high degree of variability over alongshore distances of order 25 km is observed in the velocity field. Comparison with existing models used to predict tidal velocities from sea level measurements cannot account for this spatial structure. Perturbation analysis of a Kelvin wave propagating along a coastal boundary with bumps characterized by an alongshore length scale much less than the Rossby radius of deformation shows effects

on the velocity and pressure field which decay offshore with the alongshore scale of the bumps. The effect on the velocity field exceeds that on the pressure field by a factor equal to the ratio of the Rossby radius to the alongshore scale of the bumps. We conclude that the along-shore structure observed in the measured barotropic semidiurnal tidal currents may be due in part to the local variations in the coastline geometry in the CODE region.

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Research.

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WHOI Contribution No. 6177.

SCATTERING OF CONTINENTAL SHELF WAVES AT
A DISCONTINUITY IN SHELF WIDTH

John L. Wilkin and David C. Chapman

An analytical solution is presented for the scattering of a free shelf wave incident upon a discontinuity in shelf width in a barotropic ocean. The discussion of solutions relying on backscattered free-waves with large wavenumbers which may not exist in a realistically stratified ocean is avoided by considering only the range of parameters over which energy transmission is nearly 100 percent. There is a substantial transfer of energy to modes other than that of the incident wave. The mode most readily excited is that which has the cross-shelf structure most closely coinciding with that of the incident wave. The resultant presence of multiple modes produces a strong along-shelf modulation in flow intensity and phase progression downstream of the scattering region which may affect the interpretation of shelf wave observations. A non-dispersive long shelf wave pulse is shown to scatter into a train of pulses of differing mode numbers, each propagating at its own free wave speed.

In press: Journal of Physical
Oceanography

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WHOI Contribution No. 6137.

A NOTE ON THE BAROTROPIC DISCHARGE
OF A HOMOGENEOUS FLUID
ONTO A CONTINENTAL SHELF

A. W. Woods and R. C. Beardsley

Strong flow from a river or estuary onto a gently sloping continental shelf is a commonly-occurring geophysical phenomenon. As a very simple model for this phenomenon, we consider the steady discharge of a homogeneous fluid onto a rotating, two-dimensional continental shelf with constant bottom slope (and a rigid top surface). The flow is barotropic and bottom friction is the principle dissipation mechanism. Both steady state and time-dependent numerical models were developed to examine the dependence of the structure of the flow over the shelf on the strength of the river discharge. The numerical results indicate that for weakly nonlinear flow, vortex stretching due to the offshore motion of the river discharge is balanced by bottom friction and the jet turns sharply to the right (facing offshore at the river mouth in the northern hemisphere), in agreement with the arrested topographic wave solutions given by Csanady (1979, J. Phys. Oceanogr., 8, 47-62) and Beardsley and Hart (1978, J. Geophys. Res., 83, 873-883). As the river discharge is increased, advection tends to conserve the cyclonic vorticity induced by topographic stretching, so the jet is advected offshore to the left, slowing down and turning to the right. The results of several simple laboratory experiments indicate that for even stronger discharge, the jet separates into a cyclonic and an anticyclonic eddy, on the left and the right of the jet, respectively, before being entrained into a sequence of rightward moving eddies. When considered together, the numerical and laboratory experiments suggest that an increasing discharge causes a transition from a weakly nonlinear steady flow regime, to a highly structured, strongly nonlinear flow field with time-dependent eddy formation.

In press: Continental Shelf Research.

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WHOI Contribution No. 6237.

INSTRUMENTATION
AND EXPERIMENTAL
METHODOLOGY

THE MR, A METEOROLOGICAL DATA SENSING,
RECORDING AND TELEMETERING PACKAGE
FOR USE ON MOORED BUOYS

Richard E. Payne

A new meteorological sensing, recording, and telemetering package based on digital data processing techniques has been developed for long term (6 month) deployments on surface buoys moored in the ocean. Data are recorded on magnetic cassette tapes and telemetered via satellite and Service Argos. Sensors for measuring vector averaged wind speed and direction, air and water temperatures, relative humidity, solar radiation, and barometric pressure were selected for accuracy and reliability. Except for relative humidity, performance of the sensors has been excellent. Results of ship to buoy comparisons of wind speed and air temperature sensors show agreement within the basic ship sensor accuracies, i.e., 0.1 ms^{-1} and 0.4 C , respectively.

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WHOI Contribution No. 6186.

LABORATORY MODELS

ROTATING SHOCKS IN A SEPARATED
LABORATORY CHANNEL FLOW

L. J. Pratt

Laboratory studies of the qualitative effects of wall separation on a hydraulic jump in a rotating channel are described. Separation is induced by increasing the rotation rate while maintaining a constant flow rate through the channel. It is found that separation can occur in the (super-critical) flow upstream of the jump but not in the (subcritical) downstream. Separation also suppresses the abrupt depth changes and associated vertical-plane turbulence that characterize nonrotating jumps and gives rise to a train of wall-trapped

cross waves.

A potential vorticity-conserving shock-joining theory indicates that stationary shocks with separated upstream flow and attached downstream flow are possible within a certain range of upstream Froude and Burger numbers. This result may be contrasted with the theory due to Nof (1984, J. Phys. Oceanogr., 14, 1683-1702) which indicates that stationary shocks are not possible when both upstream and downstream flows are separated. Although the present theory predicts fairly well the conditions under which stationary shocks form, detailed comparisons between predicted and observed end states are not as successful.

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WHOI Contribution No. 6343.

SOLITARY WAVES IN A VERTICAL WATERY CONDUIT IN SYRUP: THE POSSIBILITY OF LABORATORY SOLITONS

John A. Whitehead

Conduits of a water-syrup mixture are produced in syrup by buoyant upwelling. These have been shown to be models of many geological systems, such as hot spots, melt rising through a viscous crystalline matrix of mantle material, or conduits of melt rising through ambient magma in magma chambers. Solitary waves in these conduits have collision properties that resemble those of the Korteweg-deVries class of solitons. Laboratory experiments with video images of 18 collisions in corn syrup are reported. These show that solitary waves in the conduits do not completely act like solitons. Amplitude is conserved upon collision to better than $\pm 10\%$ for most of the data. There is a slight enlargement of the large wave at the expense of the small wave, as revealed by a best fit line with a slope of 0.802 with a correlation coefficient of 0.945. The collisions produced clear phase changes which had large scatter when plotted against the expected KDV formula. The origin of the scatter, whether it comes from errors in the analysis technique or whether the scatter is real is beyond the resolution of the present experiment and hence must remain unclear.

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WHOI Contribution No. 6185.

OCEAN CIRCULATION

GIBRALTAR EXPERIMENT A PLAN FOR DYNAMIC AND KINEMATIC INVESTIGATIONS OF STRAIT MIXING, EXCHANGE AND TURBULENCE

Harry L. Bryden and Thomas H. Kinder

The flow through the Strait of Gibraltar has always held a special fascination for oceanographers. Attempts to understand and measure the strong currents in the Strait stimulated many of the early advances in oceanography (Deacon, 1971, Scientists and the Sea, 1650-1990: A Study of Marine Science). Over the centuries, the focus of scientific investigations has shifted from understanding how the mass budget of the Mediterranean is maintained in the presence of the strong inflow of Atlantic water through the Strait of Gibraltar, to observing the outflow of Mediterranean water over the Gibraltar sill, to measuring the two-layer exchange of Atlantic inflow and Mediterranean outflow through the Strait. In the past few years the focus has again shifted to the study of how the dynamical constraints for flow through a narrow and shallow strait act to control the amount of exchange between the Atlantic and Mediterranean basins. To investigate the dynamics of flow through a strait, a year-long field experiment has been designed to measure the flows through the Strait of Gibraltar, including their time variability over tidal to seasonal time scales, and to assess the importance of friction, mixing, rotation, and nonlinear processes in controlling the exchange through the Strait. This field program, called the Gibraltar Experiment, will be carried out by a group of American, Spanish, Moroccan, Canadian and French scientists during the period from Fall 1985 to Fall 1986.

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WHOI Contribution No. 6124.

ASSESSING THE ENERGETICS AND DYNAMICS OF THE GULF SYSTEM AT 68°W FROM MOORED CURRENT MEASUREMENTS

Melinda M. Hall

The energetics and dynamics of the Gulf Stream at 68°W have been investigated using year-long time series of velocity and temperature throughout the water column.

The major results that have emerged are as follows. (1) There is a net conversion of mean to eddy kinetic and potential energies, the barotropic mechanism being more than twice as strong as the baroclinic. These energy exchanges are dominated by what is happening in the upper 1000 m of the water column. (2) Comparison with other studies suggests that the mooring site may be characterized as a region of downstream spatial growth in eddy energy, with a growth rate of $3-4 \times 10^{-3} \text{ km}^{-1}$. (3) Curvature changes due to the changing Stream path are sufficient to balance stretching of the water column below the thermocline, the dominant measurable effect in the vorticity equation. (4) A kinematic scheme including and relating barotropic cross-stream velocities, local temperature changes, stretching, and curvature changes is shown to be generally consistent with the observed data. (5) The vertical mass divergence $\partial w / \partial z$ affects continuity at lowest order, and may be associated with along-stream changes in transport, a vertical redistribution of the alongstream momentum flux, or changing Stream width.

In press: Journal of Marine Research.

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WHOI Contribution No. 6252.

A LEAST-SQUARES FIT OF THE ADVECTIVE-DIFFUSIVE EQUATIONS TO LEVITUS ATLAS DATA

Nelson G. Hogg

The distributions of temperature, oxygen and potential vorticity on two isopycnals and the geostrophic shear between them are used to obtain the underlying flow fields and the diffusivities through a least-squares inversion of the steady state, advective-diffusive equations. The source of the data is the Levitus Atlas, and the two isopycnals are located in a 24° square centered on the Mediterranean Water tongue in the eastern North Atlantic. One isopycnal is in the thermocline and the other beneath so chosen to be near the level of maximum salinity and temperature anomaly.

Although tracer distributions on the two levels are similar, the inversion suggests that they result from quite different processes. In the thermocline a warm, salty tongue protrudes into the subtropical gyre and results from downward diffusion of heat and salt in the north and lateral

exchange with Antarctic Intermediate Water in the south. At the true Mediterranean Water level the flow is down the direction of the tongue and the advective flux is balanced by a lateral diffusive flux.

The least squares technique gives estimates for the streamfunction which are quite insensitive to some of the subjective choices that must be made while the diffusion coefficients are relatively more sensitive. In particular, in order to overdetermine the problem the cross isopycnal variation of the cross isopycnal diffusivity must be constrained. A method based on the difference in values between the two levels reduces the residual variance substantially more than one based on Gargett's (1984, J. Mar. Res., 42, 359-393) Brunt-Väisälä frequency dependence.

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WHOI Contribution No. 6255.

THE NORTHERN RECIRCULATION GYRE OF THE GULF STREAM

Nelson G. Hogg, Robert S. Pickart, Ross M. Hendry and William J. Smethie, Jr.

Results from two recent field programs in the western North Atlantic are presented with particular emphasis on the deep circulation. New long-term moored current measurements show that the flow north of the Gulf Stream and east of the New England Seamount Chain is toward the west from 500 m to the bottom with very little depth dependence. Nearly $40 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ is transported to the west near 63°W , and half of this recirculates back to the east over the Seamount Chain to add a strong component to the deep Gulf Stream between the Chain and the Grand Banks. We call this current the "Northern Recirculation Gyre" in contrast with a similar feature to the south of the Stream popularly known as the "Worthington Gyre" (Worthington, 1976, The Johns Hopkins Oceanographic Studies, 6, 110 pp.). The new gyre is similar to that proposed by Hogg (1983, Deep-Sea Res., 30, 945-961) but somewhat smaller in scale. Its relationship to the Gulf Stream and the Deep Western Boundary Current is made explicit by the new measurements.

Tracer measurements show that the Northern Recirculation Gyre exchanges water properties with the Deep Western Boundary Current where the two are in close proximity along the northern boundary. The relatively high values of oxygen and freon, so imparted, are then advected

to the interior where the gyre carries water eastward under the Gulf Stream. Beneath the thermocline these tracer fields are practically homogeneous within the gyre, perhaps a reflection of the expulsion process described by Rhines and Young (1983, J. Fluid Mech., 133, 133-145). An advective-diffusive model is used to interpret some slight differences between the various tracer distributions.

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WHOI Contribution No. 6190.

THE SEASONAL VARIATIONS OF SURFACE CURRENTS IN THE TROPICAL ATLANTIC OCEAN: A COMPARISON OF SHIP DRIFT DATA WITH RESULTS FROM A GENERAL CIRCULATION MODEL

P. L. Richardson and S. G. H. Philander

Historical ship-drifts from the tropical Atlantic Ocean and surface currents from a general circulation model forced with monthly mean climatological winds are compared. The model accurately reproduces the spatial structure of the currents and its time-dependence, which varies considerably from the eastern side of the basin where a semi-annual harmonic is prominent to the western side where an annual harmonic is dominant. However, the amplitude of the simulated surface currents in the western side of the basin is too large. Mixing processes in the model appear to be too weak, especially when the winds are weak in regions where the thermocline is deep. High frequency fluctuations of the winds need to be taken into account, and parameterization of the mixing needs to be improved, especially when the Richardson number is small.

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WHOI Contribution No. 6222.

SEASONAL CYCLE OF VELOCITY IN THE ATLANTIC NORTH EQUATORIAL COUNTERCURRENT AS MEASURED BY SURFACE DRIFTERS, CURRENT METERS, AND SHIPDRIFTS

P. L. Richardson and G. Reverdin

This report describes the general circulation and seasonal variation of currents in the equatorial Atlantic concentrating on the North Equatorial Countercurrent (NECC) using data collected as part of the SEQUAL and FOCAL experiments plus historical ship-drifts. During 1983-1985, the Lagrangian circulation was studied by launching and tracking 30 freely drifting drogued buoys in the North Equatorial Countercurrent and 23 in the South Equatorial Current (SEC). In addition, continuously recording current meters were moored for 20 months at depths from 20 to 300 m near the center of the NECC at 6N, 28W. These measurements are the longest series ever obtained in this current and provide information about its seasonal and interannual variations, and zonal, meridional, and vertical structure.

The seasonal cycle of the NECC is very regular from year to year. Each year the NECC starts up in May-June, it flows eastward across the Atlantic with surface speeds up to 143 cm/sec in the west, it extends down to 350 m at 28W, it flows into both the Guinea Current and North Equatorial Current, it disappears or reverses from about January-June west of 18W. Some near-surface water of the NECC is inferred to downwell and flow equatorward toward the Equatorial Undercurrent. The South Equatorial Current flows into the North Brazil Current which, during spring, continues up the coast into the Caribbean. During fall, the North Brazil Current retroflects or turns back on itself between 45-50W forming the western NECC. Some South Equatorial Current water also enters the NECC along its southern edge. The retroflexion establishes a meander pattern in the NECC that slowly propagates westward during fall at a speed of 4 cm/sec. The meanders have a displacement of about 300 km in latitude, a wavelength of 900 km, and meridional velocity fluctuations up to 100 cm/sec. The swift currents and time dependent meanders in the western NECC cause a high eddy kinetic energy $\sim 2400 \text{ cm}^2/\text{sec}^2$ equivalent to that of the energetic part of the Gulf Stream.

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WHOI Contribution No. 6297.

OBSERVATIONS OF NEW, LARGE, AND STABLE
ABYSSAL CURRENTS AT MID-LATITUDES
ALONG 165E

William J. Schmitz, Jr.

Unexpectedly large and stable abyssal mean flows have recently been observed along 165E, between 31 and 41N. These results are based on two deployments of a moored array for roughly a year each. Time-averaged currents at 4000 m are about $5 \pm .5 \text{ cm s}^{-1}$ to the southwest near 41N and $6 \pm .9 \text{ cm s}^{-1}$ to the northwest near 33N, on opposite sides of the Kuroshio Extension. These mean flows were reproduced between array deployments to within a fraction of a cm s^{-1} and a few degrees True. At 41N the abyssal mean kinetic energy is several times larger than eddy kinetic energy so that the flow visually does not reverse. At 33N, near the southern edge of the Kuroshio Extension, the abyssal mean and eddy fields are of roughly the same amplitude. These results along 165E are in contrast to similar observations along 152E, where the abyssal zonal mean flows are notably less stable than at 165E. However, estimates of the latitudinal and two-year averaged zonal flow components are approximately the same at both longitudes, typically in the range of 1.4 to 1.9 cm s^{-1} to the west.

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WHOI Contribution No. 6341.

TWO-YEAR MOORED INSTRUMENT RESULTS
ALONG 152E

William J. Schmitz, Jr., Pearn P. Niiler
and Chester J. Koblinsky

Results from a two-year (nominal) deployment of a moored array along 152E from 28N to 41N are presented, with emphasis on similarities and differences between settings (approximately year-to-year). Ten moorings and 38 instruments were involved, from the fall of 1980-1982. Current-temperature meters spanned the water column from 500 to 4000 m depths with occasional instruments in the vicinity of 300 m depth and near the bottom ($\sim 6000 \text{ m}$). Many of the variations from deployment to deployment are connected with meandering of the Kuroshio Extension, located in the middle of the array near 35 - 36N, that is, upper level features near the center of the array were generally stable in some sense relative to the current axis. Some properties of the abyssal ($\sim 4000 \text{ m}$) cur-

rents were comparatively more variable, with these changes not connected to meandering of the Kuroshio Extension in an obvious way. The vertical structure and frequency distributions of eddy kinetic energy were generally similar in shape and to some extent in amplitude from deployment to deployment, especially when translated relative to meanders in the Kuroshio Extension, but in the opposite direction.

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WHOI Contribution No. 6342.

UPPER OCEAN SHEAR AND DENSITY VARIABILITY
AT THE EQUATOR DURING TROPIC HEAT

John M. Toole, Hartmut Peters
and Michael C. Gregg

A four and one-half day time series of upper ocean shear and density observations was collected in the tropical Pacific Ocean in November 1984. The measurements were made on the equator at $139^{\circ}50'W$ during a period when the equatorial undercurrent was well developed and 20-30 day period velocity fluctuations were prominent. Shear observations were collected with a ship-mounted acoustic-Doppler velocity profiler; density data were obtained from a loosely tethered microstructure instrument. The mean shear profile during the series strongly reflected the structure of the undercurrent, however, the meridional component contributed significantly to the magnitude of the total shear. The mean Richardson number was large near the undercurrent core but fell to values less than 0.5 25 meters above and below the core and was below 0.25 in the upper 40 m for most of the sample period. Buoyancy frequency varied on a diurnal time scale in the upper 50 m owing to the solar heating cycle, but a compensating diurnal shear cycle was found only above 24 m. Consequently, the Richardson number varied diurnally in the depth range 25-50 m. The shear and density fluctuations at depths greater than 50 m were not clearly connected to the diurnal near surface features and exhibited no dominant periodicity. As has been seen in previous internal wave studies, the data below the diurnal surface layer exhibited a cutoff at $Ri \sim 0.25$, perhaps indicative of shear mixing control of the Richardson number distribution.

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WHOI Contribution No. 6141.

SPATIAL DISTRIBUTIONS AND VARIABILITY
OF SUSPENDED PARTICULATE MATTER IN
WARM CORE RING 82B

James K. B. Bishop and Terrence M. Joyce

Spatial distributions and variability of suspended particulate matter (SPM) were determined optically during CTD/transmissometer surveys of Warm Core Ring (WCR) 82B and surrounding waters in June 1982. SPM distributions within 30 km of ring center from the surface to the depth of the 27.6 kg m^{-3} potential density surface at 800 m were different from surrounding waters. Waters within this core region of the ring had higher SPM concentrations between potential densities of 26.0 and 26.75 kg m^{-3} and had lower concentrations between 26.8 to 27.5 kg m^{-3} when compared to surrounding waters. These results suggest that processes with WCR 82B (as opposed to lateral exchange processes with surrounding waters) were most important in governing particle distributions near ring center.

Such isolation was not true for entrainment zone waters 70 - 80 km from ring center. In this region, waters shallower than 100 m showed a strong influence of waters from the continental shelf. In the entrainment zone, SPM concentrations between the 26.8 to 27.5 kg m^{-3} potential density surfaces (between 100 and 380 m) were higher compared with waters of similar density both within the ring and in the surrounding Slope Water. In addition, higher SPM concentrations were found in the region of offshore flow behind the ring than in the onshore flow ahead of the ring. This produces a net offshore transport of SPM by WCR 82B for entrainment zone waters of this potential density interval of between $2,900$ and $15,800 \text{ g SPM sec}^{-1}$. These results suggest that WCR's may be very important in the dispersal of resuspended continental slope sediments 100-200 km away from the continental margin.

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WHOI Contribution No. 6238.

David M. Nelson, James J. McCarthy,
Terrence M. Joyce and Hugh W. Ducklow

As anticyclonic (warm-core) ocean eddies lose kinetic energy and rotational velocity by frictional decay, the initial central depression in the thermocline forming the lower boundary of the eddy becomes less pronounced. This relaxation of the thermocline results in upwelling in the interior of the ring. We estimate that the upwelling velocity at the center of the Gulf Stream warm-core ring 82-B between April and June of 1982 was between 0.5 and 1.5 m/day , which was sufficient to supply 40-100% of the nitrate and 20-50% of silicate taken up by the phytoplankton in the core region of the ring. This enhanced nutrient transport may explain the fact that warm-core eddies are often local maxima in phytoplankton biomass and primary productivity, have intensified vertical nutrient gradients within the seasonal thermocline and can show increases in primary production following intense storms. Warm-core rings may consequently be important oceanic features for the downward flux of biogenic particles.

Supported by: NSF Grant OCE85-01176.

WHOI Contribution No. 6195.

THEORETICAL MODELS

ON CROSS-GYRE TRANSPORTS

G. T. Csanady

What is the fate of surface Ekman transport entering a subtropical gyre through its zonal boundaries? This question is investigated by resolving interior transport of a deep surface layer into non-vortical (potential flow) and non-divergent (solenoidal) components. For an idealized 1-1/2 layer model driven by zonal wind, explicit analytical solutions are readily found separately for the transport potential and the streamfunction of the solenoidal transport component. These, together with classical results on Sverdrup transport and the pressure field, reveal transport balances that the classical solutions tend to conceal. Application to the North Atlantic shows the necessity of massive cross-gyre transport by the western boundary current, from the tropical region into the subtrop-

ical gyre, as well as from the latter to the subpolar gyre. These cross-gyre transports constitute a major conduit for the poleward flow of warm (25°C) surface water.

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WHOI Contribution No. 6139.

RADIATION OF TOPOGRAPHIC WAVES FROM GULF STREAM MEANDERS

G. T. Csanady

In a two-layer model of the Gulf Stream and underlying cold water mass, meander formation and pinch-off generates substantial pressure torque on the interface. This transfers vorticity to the lower layer and acts, over a sloping sea floor, as a source term for topographic waves. The source intensity is proportional to the Jacobian of surface pressure and interface elevation. Other possible source terms (interfacial or bottom shear stress curl or horizontal momentum flux divergence) are dwarfed by the pressure torque.

Model calculations show that individual meander pinch-off events radiate topographic waves with characteristics very much as observed. The radiation field is quite unlike a plain monochromatic wave: the perceived frequency of oscillation varies in proportion to distance from the source.

In press: Continental Shelf Research.

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WHOI Contribution No. 6228.

INTERACTION OF TWO INITIALLY UNTILTED DISCRETE VERTICAL VORTEX DOUBLETS IN A GEOSTROPHIC TWO-LAYER FLUID

Nelson G. Hogg and Henry M. Stommel

The interaction between four point vortices in a two layer fluid is studied. Initially, these are taken as pairs, one directly above the other, separated by unit distance. Their subsequent history is studied as a function of the Rossby deformation radius and their relative strengths. Particular emphasis is placed upon cases in which it is possible for two or more

vortices to escape through mutual interaction and self propulsion. This is an extension of our previous study of "hetons."

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WHOI Contribution No. 6135.

MODELING THE LARGE-SCALE INFLUENCE OF GEOTHERMAL SOURCES ON ABYSSAL FLOW

Terrence M. Joyce and Kevin G. Speer

An approximate temperature perturbation equation for a continuously stratified deep ocean layer on an equatorial β plane is presented. A vertically integrated flow is allowed, which in the present study is forced by uniform upwelling. Solutions with truncated vertical structure are presented which are forced by a representation of localized geothermal heat sources. Solutions exhibit a range of behavior from passive advection to β plume, depending on the ratio of barotropic flow speed to long Rossby wave phase speed. Owing to the different phase speeds of the vertical modes, the forced vertical structure is dispersed, which can result in positive and negative temperature anomalies both upstream and downstream of the source. Furthermore, it is clear that the ability of localized sources to influence "upstream" conditions is enhanced in equatorial regions compared with higher latitudes, where the background flow is better able to advect the temperature perturbations downstream. Depending on the strength of the imposed temperature anomaly at the source, there may or may not be a large-scale reversal of the total flow field. Thus the correlations between temperature, geostrophic shear, and a passive tracer such as ^3He can be positive, negative, or zero away from the geothermal source.

In press: Journal of Geophysical Research

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WHOI Contribution No. 6288.

ON CLOSING THE OCEANIC CIRCULATION

James R. Luyten, Nelson G. Hogg
and Henry M. Stommel

Two examples of circulation in a homogeneous ocean driven by balanced evaporation-precipitation and closed by a Fofonoff-type inertial current on the western

side are given. The balances that obtain in the vorticity equation in different regions are discussed.

In press: Deep-Sea Research.

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WHOI Contribution No. 6140.

ON PARSONS' MODEL OF THE OCEAN CIRCULATION

Joseph Pedlosky

A model is constructed for the circulation of a combined subtropical and sub-polar ocean. The model is similar to that first proposed by Parsons (1969, J. Fluid Mech., 39, 511-528) with the important difference that where the isopycnal separating the upper and lower layer outcrops, the Ekman flux is allowed to freely cross the outcrop line instead of being blocked by the isopycnal.

It is shown that this completely alters the global circulation pattern. Outcropping of the cold layer still occurs but along the path described by Luyten, Pedlosky and Stommel (1983, J. Phys. Oceanog., 13, 292-309), i.e., without an associated separated "Gulf Stream" current.

The Ekman flux across the outcrop line implies a water mass conversion which can be calculated directly from the wind stress distribution and is of the order of 5 Sverdrups. This water is allowed to return to the cold water domain along the northern rim and forms a novel branch to the classical Stommel-Arons circulation picture.

A free parameter in this model is the depth of the warm water layer on the eastern boundary. However, it is shown that the requirement of continuous solutions requires H to be greater than a critical minimum value which depends only on the reduced gravity, γ , the maximum windstress, τ_M , and the ocean width, x_e , according to the relation

$$\gamma H^2/2 = \tau_M x_e.$$

The nature of the model is then reviewed when a deep upwelling from lower to upper layer is allowed.

Supported by: NSF Grant ATM84-13515.

WHOI Contribution No. 6366.

WAVE-WAVE INTERACTION OF UNSTABLE BAROCLINIC WAVES

Joseph Pedlosky and Lorenzo M. Polvani

Two slightly unstable baroclinic waves in the two-layer Phillips model are allowed to interact with each other as well as the mean flow. A theory for small dissipation rates is developed to examine the role of wave-wave interaction in the dynamics of vacillation and aperiodicity in unstable systems.

It is shown that the form of the dissipation mechanism as well as the overall dissipation timescale determines the nature of the dynamics. In particular, dissipation proportional to potential vorticity is shown to expunge amplitude vacillation due to wave-mean flow interaction.

Wave-wave interaction, however, can yield amplitude vacillation. As the dissipation is decreased, the solutions evolve from steady waves (although propagating) to periodic vacillation until finally at small dissipation rates, chaotic behavior is obtained.

This occurs in a range of relative growth rates of the two waves which depends on the strength of the wave-wave and wave-mean flow interactions.

For some parameter values, a relaxation oscillation occurs in which a burst of wave activity is followed by a nearly wave-free state. The stabilized mean flow relaxes back to its unstable state and the process is then renewed.

In press: Journal of the Atmospheric Sciences.

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WHOI Contribution No. 6304.

HYDRAULIC CONTROL OF SILL FLOW WITH FRICTION

L. J. Pratt

The hydraulics of strait and sill flow with friction is examined using a reduced gravity model. It is shown that friction moves the critical (or control) point from the sill to a location downstream. If the strait has constant width, the control point lies where the bottom slope is the negative of the drag coefficient C_d . If $-C_d$ exceeds the bottom slope everywhere, the flow cannot be controlled (in the classical sense that energy and flow force are minimized). Friction also decreases the minimum obstacle height which is required to establish hydraulically controlled flow in the classical laboratory towing experiment. Also, friction greatly encourages the establishment of stationary hydraulic jumps in the lee of the sill and may give

rise to multiple equilibrium states due to upstream jumps. Some consequences of these results for deep ocean overflows are given using the Iceland-Faroe overflow as an example.

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WHOI Contribution No. 6198.

INSTABILITY OF BAROCLINIC WAVES WITH BOTTOM SLOPE

David Steinsaltz

Pedlosky's theory explaining the behavior of unstable baroclinic waves in the β -plane (Pedlosky, 1970, J. Atmos. Sci., 27, 15-30) is modified to include a sloped bottom (although the β effect is ignored). The result found is the same sort of non-linear oscillatory behavior described by Pedlosky, except in the case of short wavelengths for negative shears. In that case, the theory predicts an initial explosive growth of the wave amplitude, so that it will reach amplitudes which are very large compared with its initial scale. This suggests a possible mechanism for small-scale current fluctuations in the oceans.

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WHOI Contribution No. 6365.

THE KORTEWEG-deVRIES EQUATION FROM LABORATORY CONDUIT AND MAGMA MIGRATION EQUATIONS

John A. Whitehead and Karl R. Helfrich

Wave equations that govern porous flow in a matrix and analogous equations for fluid conduits can be reduced to the Korteweg-deVries equation in the limit of small perturbations.

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WHOI Contribution No. 6191.

TURBULENCE AND MIXING, FINE- AND MICRO-SCALE PROCESSES

THE INFLUENCE OF PLANETARY ROTATION ON OCEANIC DOUBLE-DIFFUSIVE FLUXES

Dan Kelley

Does planetary rotation inhibit double-diffusive fluxes in oceanic thermohaline staircases? The Taylor number (Ta), a traditional measure of the effect of planetary rotation in convecting fluids, is $O(1)$ for laboratory diffusive staircases and $O(10^4)$ for oceanic diffusive staircases. Given this large difference in Ta , can laboratory-based flux laws be applied to the ocean? Lacking measurements of rotating double-diffusive fluxes, these questions are answered using an analogy between diffusive convection and thermal convection, so that empirical data for thermal convection can be used. It is first shown that flux measurements in rotating thermal convection are collapsed onto a simple curve when a newly-formulated boundary-layer Taylor number (Ta_{bl}) is used in place of Ta . The fluxes are strongly inhibited when Ta_{bl} exceeds a critical value of about 10^3 , as expected from theory. Applying this inhibition criterion to diffusive convection shows that planetary rotation is not important in either the laboratory or the ocean. This verifies the hitherto untested assumption that laboratory-based flux laws can be applied directly to the ocean without correction for the effects of planetary rotation.

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WHOI Contribution No. 6364.

INTERFACE MIGRATION IN THERMOHALINE STAIRCASES

Dan Kelley

A theory for the vertical migration speed (e) of interfaces within thermohaline staircases is developed and illustrated with several oceanic examples. It expresses e in terms of layer-to-layer variations in the vertical buoyancy flux (J). Three mechanisms which can induce migration are considered: (1) the non-linearity of the equation of state; (2) layer-merging (the coalescence of adjacent layers); and (3) interface-splitting (the

creation of new layers at the interfaces between existing layers). The migration speeds associated with nonlinearity are predicted to be much smaller than those associated with layer-merging and interface-splitting. This is because layer-merging and interface-splitting lead to $O(1)$ variations in J , while nonlinearity leads to much smaller $O(10^{-2})$ variations. Even layer-merging and interface-splitting are small effects, in the sense that interfaces will not have time to migrate far before the staircase re-adjusts to a new equilibrium state with no migration. Interface migration caused by the mechanisms considered here is not likely to be easily observable: for example, it is predicted that e is less than 10^{-8} m.s^{-1} in the thermohaline staircases in the Arctic halocline. Furthermore, the vertical fluxes of heat and salt associated with interface migration are predicted to be small, typically less than about 10 percent of the total fluxes. The apparent migration speeds ($e \sim 10^{-4}$ to 10^{-3} m.s^{-1}) inferred by tracking interfaces in Arctic profiles are much too large to result from the mechanisms investigated here. These measurements probably indicate either (a) migration associated with other mechanisms (e.g. asymmetric entrainment during interface-splitting) or (b) horizontal variability in the drifting staircase.

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WHOI Contribution No. 6289.

MODELS FOR FINITE AMPLITUDE SALT FINGERS IN AN INTERFACE PART II: FASTEST GROWING FINGERS

Eric Kunze

A model for fastest-growing fingers is developed in which the fingers have finite length and lengthen in time. A finger Richardson number constraint is used to limit the length and fluxes of the fingers. This constraint is equivalent to the collective instability criterion. It is able to reproduce the traditional $\Delta S^{4/3}$ flux law and the laboratory-measured dependence on density ratio, but only if the interface is thin enough (~ 30 cm) that individual fingers extend through it. For the 2-5 m thick interfaces that seem to be typical of ocean thermohaline staircases, the model's fluxes depend on interface thickness (unlike the $\Delta S^{4/3}$ flux law) and are over an order of magnitude smaller than $\Delta S^{4/3}$ flux law predictions. This may explain why dissipation rates measured in the thermohaline staircase east of Barbados are

thirty times smaller ($\sim 3 \times 10^{-10}$ W/kg) than $\Delta S^{4/3}$ law predictions ($\sim 80 \times 10^{-10}$ W/kg).

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WHOI Contribution No. 6315.

FINE- AND MICROSTRUCTURE AT THE EDGE OF A WARM CORE RING

Raymond W. Schmitt, Rolf G. Lueck
and Terrence M. Joyce

As part of the Warm Core Rings Experiment, a set of intensive observations of thermohaline intrusions at the outer edge of a warm ring were obtained. The observations included a CTD tow-yo, repeated microstructure profiles and continuous acoustic Doppler velocity measurements. The survey was performed relative to the drift of a drogued surface buoy. The CTD data allowed us to map the three dimensional structure of the intrusive features. The data indicate that the core of a cold, fresh intrusion became lighter as it extended across the front. This is contrary to the usual expectation that such intrusions should get denser under the influence of salt fingers. An explanation for this apparent behavior can be found in the microstructure profiles, which suggest that the diffusive interfaces associated with the intrusion are the dominant mixing process, since they are more strongly unstable and reveal higher turbulence levels than nearby fingering regions. Clear signatures of double diffusive mixing are seen in the fine- and microstructure data; however, the turbulent dissipation in the diffusive layers was not as high as the laboratory flux laws predict and shear-driven turbulence may be the stronger mixing mechanism. Double diffusion clearly plays some role in mixing the intrusive features but its role in actually generating the intrusions remains ambiguous, given the tendency of Warm Core Rings to wrap "streamers" of shelf, slope and Gulf Stream Waters around themselves.

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WHOI Contribution No. 6216.

FINE- AND MICROSCALE STRUCTURES IN THE
NW ATLANTIC SUBTROPICAL FRONT

John M. Toole and Raymond W. Schmitt

Observations of fine- and microscale structures within an upper ocean front in the subtropical Atlantic have revealed direct evidence for vertical shear mixing. Relatively intense patches of temperature and velocity microstructure were found at depths where the Richardson Number, the stability parameter for stratified shear flow, was near 0.3 or smaller. The low Richardson Number values were associated with packets of short vertical wavelength internal waves which may have been affected by the larger scale velocity and density structure of the front.

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WHOI Contribution No. 6319.

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

OCEAN RESPONSE TO HURRICANE GLORIA:
SATELLITE-DERIVED SEA SURFACE COOLING

Peter Cornillon, Lothar Stramma
and James F. Price

Satellite-derived infrared images of the western North Atlantic are used to investigate SST cooling over the western North Atlantic caused by Hurricane Gloria (1985). Relatively cloud-free skies before and after Gloria allow a nearly unobstructed view of the track from 26°N to New England, 41°N, and the data show considerable detail of the horizontal structure and the regional variability of SST cooling. All along the track there is a pronounced asymmetry of SST cooling with much stronger and more extensive cooling found on the right side of the track. Significant regional variations in SST cooling appear to be well correlated with hydrographic conditions. The greatest cooling (up to 5°C) occurred in slope waters north of the Gulf Stream where the seasonal thermocline is shallowest and most compressed; moderate cooling (up to 3°C) occurred in the open Sargasso Sea where the thermocline is deeper and more diffused; little or no cooling occurred in

shallow coastal waters (bottom depth less than 20 m) where the water column was probably isothermal before Gloria's passage. These qualitative results are consistent with the notion that vertical mixing within the upper ocean, rather than air/sea heat exchange, is the dominant SST cooling mechanism of hurricanes.

Supported by: ONR Contract
N00014-81-C-0062.

WHOI Contribution No. 6287.

DIURNAL RESPONSE OF SEA SURFACE
TEMPERATURE OBSERVED AT LOTUS

James F. Price, Robert A. Weller
and Clarke M. Bowers

Air-sea observations made by the Long Term Upper Ocean Study (LOTUS) in the Sargasso Sea are used to determine the dependence of the diurnal response of sea surface temperature, ΔT_s , upon surface heating, H , and wind stress, S . The available data set is extensive, including two summers and 361 days in total. It samples virtually the full range of possible H, S conditions, and the range of ΔT_s is from zero up to about 3°C.

Analyzed data show a clear trend of increasing ΔT_s with increasing H and with decreasing S (the qualitative result expected). A fairly smooth, local average function calculated from the data itself can account for about 90 percent of the variance of ΔT_s , showing that there is a direct, and significant, dependence of ΔT_s upon the meteorological forcing.

The analyzed data are compared to a theoretical model function developed under the assumption that wind stress causes vertical mixing via shear flow instability of the wind-driven current. This model accounts for about 80 percent of the observed variance, and shows an H, S dependence consistent with the data.

In press: Journal of Geophysical
Research.

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WHOI Contribution No. 6318.

DOPPLER VELOCITIES IN THE MIXED LAYER DURING MILDEX

Jerome Smith, Robert Pinkel and
Robert A. Weller

During MILDEX, a number of sensors were deployed from FLIP in an effort to monitor the small scale structure in upper mixed layer currents. Fixed depth VMCMs at 2 m and 6 m depth monitored the near surface shear, while slowly profiling VMCMs were used to sense the velocity profile down to 150 m on an hourly basis. Depths of specific interest were examined with a package which measured vertical as well as horizontal currents, and displayed the readings in FLIP's lab in real time.

Vertical profiles of horizontal velocity frequently indicated the presence of strong downwind jets. These had maximum velocities in excess of 25 cm/sec at depths of 10 to 35 m below the surface. Significant surface convergences are associated with these jets and can be easily visualized by scattering tracers (computer cards) on the sea surface. The vertical motions associated with these Langmuir-like cells is frequently sufficient to overcome the stratification in the top 10 m due to afternoon solar heating.

One of the Doppler sonars on FLIP was directed such that the beam grazed the sea surface. Surface returns were received over ranges 600 to 1400 m from FLIP. While the sonar lacks the resolution to see the small scale structure measured by the direct sensors, large scale cell like structures were seen in both the scattering intensity and Doppler velocity. The cells appear to move with the bulk flow of the mixed layer, to be oriented approximately downwind, and to have maximum cross-wind spacings of about three times the mixed layer depth. Peak convergences are of order $\pm .003 \text{ sec}^{-1}$ at these largest scales.

In press: Journal of Physical
Oceanography.

Supported by: ONR Contract N00014-84-
C-0134, NR 083-400.

WHOI Contribution No. 6209.

TECHNICAL REPORTS

DATA TABULATIONS AND ANALYSIS OF DIURNAL SEA SURFACE TEMPERATURE VARIABILITY OBSERVED AT LOTUS

Clarke M. Bowers, James F. Price, Robert
A. Weller and Melbourne G. Briscoe

Air/sea measurements from the Long-Term Upper Ocean Study (LOTUS) buoy in the Sargasso Sea are analyzed to learn how the diurnal response of sea surface temperature, ΔT_s , is related to the surface heating, H , and the wind stress, S . Data are taken from the LOTUS-3 and LOTUS-5 records which span the summers of 1982 and 1983. The basic data are shown in monthly plots, and the analyzed daily values of ΔT_s , H , and S are given in tables and in figures.

Analyzed data show a clear trend of ΔT_s increasing with H and decreasing with S . A best-fit, three-parameter, empirical function can account for 90 percent of the variance in a screened subset of the LOTUS data (172 days) and 81 percent of the variance of the full data set (361 days).

The analyzed data are also compared with a theoretical model function now used for ocean predictions in the Diurnal Ocean Surface Layer model (DOSL) of Fleet Numerical Oceanography Center. The DOSL model function was derived from the assumption that wind-mixing occurs by a mechanism of shear flow instability. It is fully predictive and shows a parameter dependence consistent with the LOTUS data over a wide range of H and S . The DOSL model function can account for almost as much variance as the best-fit empirical function.

Prepared for: ONR under Contracts
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N00014-84-C-0134, NR 083-400.

WHOI Technical Report 86-5.

STATUS REPORT ON OCEAN DATA TELEMETRY

Melbourne G. Briscoe

This document contains two workshop reports and several brief technical reports, all on aspects of ocean data telemetry and platform positioning. The principal topic is a Summary of an Ocean Telemetry Workshop held at the AGU/ASLO Ocean Sciences Meeting in New Orleans, Louisiana, on 15 January 1986. A brief version of this summary appeared in EOS, Transactions of the American Geophysical

Union, 4 March 1986. Both the full summary presented here and the brief form in EOS were coauthored by D. Brooks of Texas A&M University.

Included here is a list of the attendees at that workshop (Appendix A) and a description of the goals and membership of the AGU Ocean Sciences Section Technical Committee on Ocean Data Telemetry and Platform Positioning, which was formed at that meeting (Appendix B).

An earlier, informal, local workshop on telemetry was held at Woods Hole in March 1985; a report on that meeting is in Appendix C.

Technical summaries are given on Meteor-Burst Telemetry (Appendix D), the GEOSTAR positioning system (Appendix E), tradeoffs for various telemetry systems (Appendix F), proposed communications network [authored by M. Comberiate from NASA Goddard] (Appendix G), and the possibilities of a new kind of HF telemetry system (Appendix H).

A small discussion at Woods Hole prior to the January Telemetry Workshop is reported in Appendix I.

Prepared for: ONR under Contracts
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N00014-85-C-0001, NR 083-004.

WHOI Technical Report 86-17.

GIBRALTAR EXPERIMENT A PLAN FOR DYNAMIC AND KINEMATIC INVESTIGATIONS OF STRAIT MIXING, EXCHANGE AND TURBULENCE

Harry L. Bryden and Thomas H. Kinder

The flow through the Strait of Gibraltar has always held a special fascination for oceanographers. Attempts to understand and measure the strong currents in the Strait stimulated many of the early advances in oceanography (Deacon, 1971, *Scientists and the Sea, 1650-1990: A Study of Marine Science*). Over the centuries, the focus of scientific investigations has shifted from understanding how the mass budget of the Mediterranean is maintained in the presence of the strong inflow of Atlantic water through the Strait of Gibraltar, to observing the outflow of Mediterranean water over the Gibraltar sill, to measuring the two-layer exchange of Atlantic inflow and Mediterranean outflow through the Strait. In the past few years the focus has again shifted to the study of how the dynamical constraints for flow through a narrow and shallow strait act to control the amount of exchange between the Atlantic and Mediterranean basins. To investigate the dynamics

of flow through a strait, a year-long field experiment has been designed to measure the flows through the Strait of Gibraltar, including their time variability over tidal to seasonal time scales, and to assess the importance of friction, mixing, rotation, and nonlinear processes in controlling the exchange through the Strait. This field program, called the Gibraltar Experiment, will be carried out by a group of American, Spanish, Moroccan, Canadian and French scientists during the period from Fall 1985 to Fall 1986.

Prepared for: ONR under Contract
N00014-85-C-0001, NR 083-004

WHOI Technical Report 86-29.

HYDROGRAPHIC DATA FROM R/V OCEANUS CRUISE 133, LEG VII

George P. Knapp and Henry M. Stommel

Hydrographic data collected during R/V OCEANUS cruise 133, leg VII are presented. These data include temperature, salinity and dissolved oxygen observed at standard levels by a Neil Brown Instrument Systems' CTD-02 profiler and salinity, dissolved oxygen, silicate, phosphate and nitrate values at the observed depths of the collected water samples. Ninety-four stations were occupied on a meridional section at (nominally) 52° West from Brazil to Greenland. Also presented are a series of sectional profiles of the six observed parameters as a function of depth.

Prepared for: NSF under Grant
OCE80-15789.

WHOI Technical Report 86-38.

MOORED CURRENT METER AND TEMPERATURE- PRESSURE RECORDER MEASUREMENTS FROM THE WESTERN NORTH ATLANTIC (HIGH ENERGY BENTHIC BOUNDARY LAYER AND ABYSSAL CIRCULATION EXPERIMENTS 1983-1984)

Ellen Levy and Susan A. Tarbell

Summaries of long-term current, temperature and pressure measurements from moored instruments in the western North Atlantic are presented. The moorings were set in March 1983 and retrieved seventeen months later. Composite plots of filtered time series are presented on the printed pages of the report and the basic data series are displayed in the microfiche. These displays include statistics, histograms, spectral plots, variables versus time, progressive vector diagrams (provecs) and

scatter plots.

Prepared for: ONR under Contracts
N00014-82-C-0019, NR 083-004 and
N00014-76-C-0197, NR 083-400; and
NSF under Grant OCE82-14925.

WHOI Technical Report 86-14.

A SUMMARY OF HISTORICAL SOFAR FLOAT DATA IN THE WESTERN NORTH ATLANTIC 1972-81

Theresa K. McKee

SOFAR float observations from the years 1972 to 1979 have been edited and analyzed to produce a uniform and error-free data set suitable for archiving. These data were collected from the western North Atlantic during three major experiments directed by H. T. Rossby of the University of Rhode Island. The data are shown here in plots of the composite and individual trajectories, as time series plots of velocity components, and for the LDE floats, as time series plots of temperature, pressure, vertical velocity, and vertical displacement. These data comprise about 72 years of SOFAR float observations, and are a unique resource for Lagrangian studies of the North Atlantic circulation.

Prepared for: NSF under Grants
OCE82-14066, OCE86-00055,
OCE81-17467 and OCE81-09145.

WHOI Technical Report 86-24.

DYNAMIC PRESENTATION OF LONG TERM UPPER OCEAN STUDY (LOTUS) DATA USING VIDEOTAPE

Ellyn T. Montgomery

In order to show efficiently the large amount of data obtained during the Long Term Upper Ocean Study (LOTUS), a new method of data presentation was developed. Three data variables can be included in a simple color contour plot, but if successive color contour plots are recorded on videotape, a fourth variable, time, can also be shown.

This report documents the process of making a videotape presenting scientific data, from raw data to finished videotape. The videotape shows internal wave kinetic energy versus frequency and depth; the time variation of the videotape displays real time variation in the ratio of 14/30 second to one week, or about 1 month of data every 2 seconds.

Prepared for: ONR under Contracts
N00014-76-C-0197, NR 083-400 and
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 86-33.

FASINEX (FRONTAL AIR-SEA INTERACTION EXPERIMENT) (JANUARY-JUNE 1986): SUMMARIES FOR FASINEX MOORING CRUISES PHASE ONE: R/V KNORR CRUISE 119 PHASE THREE: R/V KNORR CRUISE 123

Nancy J. Pennington and
Robert A. Weller

The Frontal Air-Sea Interaction Experiment (FASINEX) was a study of the response of the upper ocean to atmospheric forcing in the vicinity of an oceanic front in the subtropical convergence zone southwest of Bermuda, the response of the lower atmosphere in that vicinity to the oceanic front, and the associated two-way interaction between ocean and atmosphere. FASINEX began in the winter (January 1986), concluded in the early summer (June 1986) and included an intensive period in February and March. The experiment took place in the vicinity of 27°N, 70°W where sea-surface-temperature fronts are climatologically common.

Measurements were made from buoys, ships, aircraft and spacecraft. This report summarizes the mooring deployment and recovery cruises. FASINEX Phase One, the deployment cruise, located a frontal feature, mapped it and set an array of surface and Profiling Current Meters across the front. Phase Three, the recovery cruise returned to the FASINEX area to retrieve the instrumentation that had been on station for six months. Additional measurements were made in the frontal region during these cruises. The activities carried out and the underway data collected on these two cruises, details of the moored array and a preliminary statement of the data return from the array, and the data telemetered from the moored array via ARGOS are summarized in this report.

Prepared for: ONR under Contract
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 86-35.

FASINEX (FRONTAL AIR-SEA INTERACTION
EXPERIMENT) (JANUARY-JUNE 1986):
CRUISE SUMMARIES FOR FASINEX PHASE TWO
R/V OCEANUS CRUISE 175
R/V ENDEAVOR CRUISE 141

Nancy J. Pennington and
Robert A. Weller

The Frontal Air-Sea Interaction Experiment (FASINEX) was a study of the response of the upper ocean to atmospheric forcing in the vicinity of an oceanic front in the subtropical convergence zone southwest of Bermuda, the response of the lower atmosphere in that vicinity to the oceanic front, and the associated two-way interaction between ocean and atmosphere. FASINEX began in the winter (January 1986), concluded in the early summer (June 1986) and included an intensive period in February and March. The experiment took place in the vicinity of 27°N, 70°W where sea-surface-temperature fronts are climatologically common.

Measurements were made from buoys, ships, aircraft and spacecraft. This report summarizes the shipboard work done on R/V OCEANUS and R/V ENDEAVOR during Phase Two, the dual ship/multi-aircraft measurement period. The two ships worked individually, jointly and as ground truth for the aircraft during the month. Each ship carried specialized instrumentation for measuring oceanographic and meteorological parameters. Information describing the sampling strategy, station positions and times are included. This report contains summaries of the data collected and some preliminary results.

Prepared for: ONR under Contract
N00014-84-C-0134, NR 083-400.

WHOI Technical Report 86-36.

GULF STREAM VELOCITY STRUCTURE
THROUGH COMBINED INVERSION OF
HYDROGRAPHIC AND ACOUSTIC DOPPLER DATA

Stephen D. Pierce

Near-surface velocities from an acoustic doppler instrument are used in conjunction with CTD/O₂ data to produce estimates of the absolute flow field off of Cape Hatteras. The data set consists of two transects across the Gulf Stream made by the R/V Endeavor cruise EN88 in August 1982. An inverse procedure is applied which makes use of both the acoustic doppler data and property conservation constraints. Velocity sections at approximately 73°W and 71°W are presented with formal errors of 1-2 cm/s. The net Gulf

Stream transports are estimated to be 116 ± 2 Sv across the 'south' leg and 161 ± 4 Sv across the 'north.' A Deep Western Boundary Current transport of 4 ± 1 Sv is also estimated. While these values do not necessarily represent the mean, they are accurate estimates of the synoptic flow field in the region.

Prepared for: NSF under Grant
OCE85-01176 and NASA under Grant
NAG 5-534.

WHOI Technical Report 86-41.

SOFAR FLOAT MEDITERRANEAN OUTFLOW
EXPERIMENT: DATA FROM THE FIRST YEAR,
1984-1985

James F. Price, Theresa K. McKee,
James R. Valdes, Philip L. Richardson
and Laurence Armi

In October, 1984, the Woods Hole Oceanographic Institution SOFAR float group began a three-year long field program to observe the low frequency currents in the Canary Basin. The principal scientific goal was to learn how advection and diffusion by these currents determine the shape and amplitude of the Mediterranean salt tongue. Fourteen floats were launched at a depth of 1100 m in a cluster centered on 32N, 24W, and seven other floats were launched incoherently along a north/south line from 24N to 37N. At the same time investigators from Scripps Institution and the University of Rhode Island used four other SOFAR floats to tag a sub-mesoscale lens of Mediterranean water. Slightly over twenty years of float trajectories were produced during the first year of the experiment.

In this report we briefly describe the 1984 field operations and show the first year's SOFAR float data. Perhaps the most striking result is that westward flow within the Mediterranean salt tongue was found to be confined to a rather narrow jet (roughly 150 km in meridional extent) which had a mean speed of roughly 2 cm/s^{-1} . To the north or south of this jet the mean flow was much weaker and eastward. This suggests that currents associated with the salt tongue itself (rather than the gyre scale circulation) may be most important for determining the salt distribution.

Prepared for: NSF under Grants
OCE82-14066 and OCE86-00055.

WHOI Technical Report 86-31.

HYDROGRAPHIC DATA FROM R/V ENDEAVOR
CRUISE #90

M. C. Stalcup, T. M. Joyce,
R. L. Barbour and J. A. Dunworth

The final cruise of the NSF-sponsored Warm Core Rings Program studied a Warm Core Ring (WCR) in the Fall of 1982 as it formed from a large northward meander of the Gulf Stream. This ring, known as 82-H or the eighth ring identified in 1982, formed over the New England Seamounts near 39.5°N, 65°W. Surveys using Expendable Bathythermographs, Conductivity-Temperature-Depth-Oxygen stations and Doppler Current Profiling provide a look at the genesis of a WCR. These measurements reveal that WCR 82-H separated from the Gulf Stream sometime between October 2-5. This ring was a typical WCR with a diameter of about 200 km and speeds in the high velocity core of 175 cm/sec. Satellite imagery of 82-H following the cruise showed that it drifted WSW in the Slope Water region at almost 9 km/day, had at least one interaction with the Gulf Stream and was last observed on February 8, 1983, at 39°N, 72°W.

Prepared for: NSF under Grant
OCE80-16983 and NASA under Grant
NAGW-272.

WHOI Technical Report 86-15.

A TECHNICAL DESCRIPTION OF AN
ACOUSTIC DOPPLER BASED UPPER OCEAN
PROFILING SYSTEM

A. Cleo Zani and Nancy R. Galbraith

An acoustic Doppler profiler has been designed into a multi-sensor Acoustic Profiler of Ocean Currents system (APOC). All four major components of this data collecting ensemble are microprocessor based units, allowing programmatic flexibility. Various water column, meteorological, and navigation data are recorded in a raw and/or processed form. Plots and listings of processed data are generated and displayed in real-time for use by investigators. Once installed, the system requires only a periodic change of cartridge recording media. The equipment has collected data during five cruises, for a total of approximately 190 days at sea. A hardware and software description of the system is presented. Preliminary technical results are discussed and evaluated.

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OCE84-16197 and OCE84-00128.

WHOI Technical Report 86-13.

MARINE POLICY
AND OCEAN MANAGEMENT PROGRAM
James H. Broadus, Director

PROTECTING RHODE ISLAND'S COASTAL
SALT PONDS: AN ECONOMIC ASSESSMENT
OF DOWNZONING

Glen D. Anderson and Steven F. Edwards

In southern Rhode Island, there is growing concern that housing and recreational demands will soon overwhelm the capacity of the coastal salt ponds to absorb wastes, produce seafood, and maintain scenic qualities. As a result, coastal towns have been studying the feasibility of using land controls such as downzoning to protect these coastal amenities.

The paper presents an economic analysis of the downzoning program proposed in the town of South Kingstown. Hedonic price and contingent valuation methods are used to value coastal amenities. The estimated net present value of "swimmable" water is shown to be \$3.1 million.

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WHOI Contribution No. 6326.

FEDERAL CONSISTENCY
PRACTICE AND POTENTIAL

Jack H. Archer

The federal consistency provisions of the Coastal Zone Management Act of 1972, as amended, provide coastal states with approved coastal management programs substantial review authority over the activities of federal agencies affecting the coastal zone. Federal agencies have resisted assertion by coastal states of their right to review federal activities (notably outer continental shelf oil and gas activities), and decisions in the Ninth and Third Circuits have generally affirmed state consistency review authority under the Act. The National Oceanic and Atmospheric Administration has interpreted the consistency provisions to require substantial compliance by federal agencies with the federally-approved, enforceable policies of state coastal management programs. Future developments in federal consistency practice will likely concern the meaning of the statutory term consistent "to the maximum extent practicable" and challenges to state coastal policies as "enforceable policies" requiring consistency.

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THE CONCEPT OF COASTAL ZONE MANAGEMENT

Jack H. Archer

Competing pressures on the coastline of the United States led to the passage of the Coastal Zone Management Act of 1972. The Act recognized the roles of local, state, and federal government by establishing a partnership process for managing coastal resources. The federal role was designed to provide a degree of continuity and to assure that all states receiving federal financial assistance were complying with the basic objectives established in the Act. The states were provided the major role in developing and implementing coastal zone management programs, both meeting the national objectives while tailoring the program to meet the unique needs of each state. After ten years of operational experience, federal financial assistance is phasing down. The future success of the state Coastal Zone Management Programs will depend, in great part, on the degree of achievement realized to date. Achievements have been made in (1) permit simplification and streamlining; (2) development of ports and waterfronts; (3) prevention of loss of life and property due to improper development in coastal hazard areas; and (4) protecting natural resources.

Published in: Proceedings of the International Symposium on Utilization of Coastal Ecological Systems: Planning, Pollution and Productivity. N. Chao and W. Kirby-Smith, eds. U. of Rio Grande, Brazil and Duke Univ., pp. 27-38, 1985.

Supported by: J.N. Pew, Jr. Charitable Trust and the Marine Policy Center.

THE U.S. NATIONAL COASTAL ZONE
MANAGEMENT PROGRAM - THE NEXT PHASE

Jack H. Archer and Robert W. Knecht

Coastal Zone Management (CZM) in the United States is accomplished through a

cooperative federal and state program to manage and protect coastal resources. This paper examines the U.S. CZM program at the federal and state levels. It describes the major provisions of the Coastal Zone Management Act, the record of national program development in the 1970s and early 1980s, and setbacks to CZM which have occurred during the Reagan Administration. The authors propose basic policies which should, but do not, govern the conduct of the national CZM program. Specific applications of these policies to ocean and coastal issues and problems are discussed. The paper critically reviews the performance of the current federal managers in administering the national program and recommends actions which should be taken by the Congress and the coastal states to restore the integrity of the CZM process.

In press: Coastal Zone Management Journal.

Supported by: J.N. Pew, Jr. Charitable Trust and the Marine Policy Center.

WHOI Contribution No. 6359.

PROCEEDINGS OF THE WORKSHOP ON FISHERIES SOCIOLOGY

Conner Bailey, Craig Harris,
Clayton Heaton and Rosamund Ladner

The idea for an Exploratory Workshop on Fisheries Sociology emerged from informal discussions held at the 1983 Rural Sociological Society meetings. We sought to identify persons working in different areas of the sociology of fisheries who could present review papers on their areas of inquiry. The papers in this volume are the result of that effort.

Twenty-four sociologists attended the workshop and represented work in both industrialized and developing nations, in subsistence, recreational and commercial fisheries, and in aquaculture.

Supported by: American Sociological Society; NOAA, National Sea Grant College Program under Grant No. NA84-AA-D-00033(R/S-12); and the J.N. Pew, Jr. Charitable Trust.

WHOI Technical Report 86-34.

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

This paper will analyze and evaluate the issues that might emerge between the United States and both Canada and Mexico in the establishment of adjacent exclusive economic zones (EEZs). Given the ambiguity of the U.N. Convention language and historic differences in approach to law of the sea issues, it is likely that there will be differences in how each of these countries will manage and regulate activities within their respective zones. Since many of the resources and activities are transboundary in nature, the potential for conflict between states exists. The paper will serve to highlight existing areas of conflict and will evaluate the potential for future disagreements.

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SEABED MATERIALS

James M. Broadus

A large catalog of materials has been proposed as potential seabed resources, and some seabed materials such as hydrocarbons and tin already contribute to the world's economy. Scientific advances have increased our knowledge of other seabed prospects, but realization of their potential will be determined by their relative economic accessibility compared to rival resources on land. Examination of existing stocks of conventional resources, and of the economic process by which new resources are added, suggests that most potential sources of seabed materials will not be exploited in the near future. Strategic behavior in seabed materials development, however, implies that investment in exploration and R&D could proceed on a larger scale and at a more rapid pace than might be expected solely on the basis of apparent commercial potential.

In press: Science.

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NA84-AA-D-00033.

WHOI Contribution No. 6352.

DEVELOPING A U.S. RESEARCH STRATEGY FOR MARINE POLYMETALLIC SULFIDES

James M. Broadus and Robert E. Bowen

Marine polymetallic sulfides (MPS) are recently discovered mineral occurrences of hydrothermal origin. Design of an appropriate research strategy to investigate the MPS deposits is a policy issue that the paper seeks to help resolve. The paper describes the relevant nature of MPS, reviews what has happened in the early stages of MPS research, and examines market conditions to help specify a scientifically and economically effective research strategy. This strategy is examined in several key dimensions: science versus research and development (R&D); role of government and private industry; geographic concentration; focus in time; and the locus of responsibility and scope of participation. Because of the early stage of work on MPS and the scant scientific evidence available, expected results of R&D are extremely uncertain. In this context, a sequential scientific approach is favored for government support. The strategy suggested by the paper's analysis would permit geographically varied work sites and would incorporate diversification of research approaches, decentralization of discretionary decision-making, and a broad base of participation.

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International Law, 17, 1/2/3,
91-130.

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College Program under Grant No.
NA80-AA-D-00077(R/G-6).

COASTAL AND MARINE AREA MANAGEMENT IN THE GALAPAGOS ISLANDS

James M. Broadus and Arthur G. Gaines

The Galapagos Islands have long been the object of worldwide scientific interest. Increased demands on coastal and marine resources there, to serve a growing resident population and to accommodate potentially expanded tourism, signal a need for greater attention to the management of these resources. The paper provides a brief overview of the challenges facing integrated coastal and marine area

management in the Galapagos Islands of Ecuador, describes a cooperative project between the government of Ecuador and the Woods Hole Oceanographic Institution to devise concepts for improved management of the archipelago's coastal and marine resources, and reports on the findings of that study. 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. A two-zone management scheme for coastal and marine resources, proposed by Knecht (1984), is outlined. It avoids the establishment of complicated new systems of boundaries and institutions, instead adapting itself to the existing situation. Future directions for the cooperative research by Woods Hole and the government of Ecuador are indicated.

In press: Coastal Zone Management
Journal, 15.

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Pew, Jr. Charitable Trust.

WHOI Contribution No. 6371.

RIISING OF SEA LEVEL AND DAMMING OF RIVERS: POSSIBLE EFFECT IN EGYPT AND BANGLADESH

James Broadus, John Milliman,
Steven Edwards, David Aubrey and
Frank Gable

The projected worldwide rise of sea level during the next 100 years will be particularly hard-felt in deltaic areas where substantial areas are barely above sea level. Regional subsidence will increase the relative rate of sea level rise, and damming of large rivers could prevent sediment influx from compensating for regional subsidence, increasing coastal erosion. These effects will be felt most in developing countries, where the rivers are large, deltas extensive and inhabited, and proposed damming of large rivers may dramatically increase coastal erosion.

To help understand the potential consequences of sea level rise in the deltaic regions of the world, this paper concentrates on two areas that seem especially vulnerable: the Nile River delta in Egypt, which has already been dammed, and the delta of the complex Ganges-Brahmaputra-Meghna River system in Bangladesh, in which river damming has begun and is expected to increase during the next 15 years.

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THE PROBLEM OF GOVERNANCE OF
U.S. OCEAN RESOURCES AND
THE NEW EXCLUSIVE ECONOMIC ZONE

Biliana Cicin-Sain and Robert W. Knecht

This paper discusses major problems existing in the current ocean governance regime of the United States, many of which are rooted in the regime's single-purpose and fragmented nature. In the concept of the new 200-mile U.S. Exclusive Economic Zone (EEZ), proclaimed in March 1983 by President Reagan, with its notion of sovereign rights over essentially all resources within a common zone, may lie the seeds of a more effective, second-generation approach to ocean governance—one better suited to the increased ocean exploitation likely to occur in the coming decades.

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AN ECONOMICS PRIMER
FOR COASTAL ZONE MANAGEMENT:
BASIC CONCEPTS AND METHODS FROM
MICROECONOMICS, PUBLIC FINANCE, AND
ENVIRONMENTAL AND RESOURCE ECONOMICS

Steven F. Edwards

While the economic impacts of resource use pervade discussions of coastal zone management, most discourses tend to be ill-defined and incomplete and to lack a solid basis in economic theory. This primer was written to eliminate this confusion for those non-economists who seek insight into economic thought and into how economic analysis can contribute to coastal zone management. The first half of the report introduces readers to basic concepts and analytical methods in microeconomics, public finance, and environmental and resource economics. The foundation for monetary valuations becomes apparent as the concepts are explained. The realization that neither markets nor

prices are required for economic valuations is an important result of the explication. Consequently, one can assess losses associated with pollution, reduced access, and so on in units that are commensurable with market-oriented development.

The second half of the primer inculcates these basic concepts and methods through (1) critiques of several stereotypical, pseudoeconomic arguments, (2) a case study of the benefits of protecting water quality for recreation, and (3) a benefit-cost analysis of a hypothetical acquisition program that is intended to protect groundwater quality, to protect opportunities for aquatic recreation, and to reduce the growth in traffic.

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WHOI Technical Report, 86-1.

IN DEFENSE OF ENVIRONMENTAL ECONOMICS

Steven F. Edwards

The appropriateness of economic valuations of the natural environment is defended on the basis of an objective analysis of individuals' preferences. The egoistic model of "economic man" substantiates economic valuations of instrumental values even when markets do not exist and when consumption and use are not involved. However, "altruistic man's" genuine commitment to the well-being of others, particularly wildlife and future generations, challenges economic valuations at a fundamental level. In this case, self-interest and an indifference between states of the world are secondary and undefined, respectively, since preferences are not based on tradeoffs between the welfare of others and self. The appropriateness of economic valuations rests solely with the empirical validity of the assumptions that give rise to economic man.

In press: Environmental Ethics.

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WHOI Contribution No. 6323.

ETHICAL PREFERENCES AND THE ASSESSMENT
OF EXISTENCE VALUES:
DOES THE NEOCLASSICAL MODEL FIT?

Steven F. Edwards

Some of the implications of ethical preferences for traditional welfare analyses of existence values are discussed in this paper and illustrated with a lexicographic model for preference structures. Although willingness-to-pay and willingness-to-sell are well-defined, their connection with Hicksian surpluses is lost when a person is motivated by an ethical commitment to others' welfare. Researchers need to expand contingent valuation methods to collect information on underlying motives and types of preferences in order to identify respondents who fit the neo-classical model of egoistic man.

In press: Northeast Journal of Agricultural and Resource Economics.

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WHOI Contribution No. 6324.

OVERLOOKED BIASES IN CONTINGENT VALUATION
SURVEYS: SOME CONSIDERATIONS

Steven F. Edwards and Glen D. Anderson

Researchers have largely overlooked the potential for sampling error, non-response bias, and selection biases in contingent valuation studies. Consequently, little is known about the errors in estimates of the aggregate benefits of environmental policies that are estimated from nonrandom samples. We address this deficiency in a study of the benefits of managing water quality in coastal lagoons. While sampling and selection bias associated with omitting protest bids were not apparent, nonresponse bias resulted in at least an 11% overestimation of aggregate benefits despite the high, 72% response to the survey.

In press: Land Economics, 63.

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WHOI Contribution No. 6325.

THE FEDERAL CONSISTENCY DOCTRINE

Timothy Eichenberg and Jack H. Archer

When Congress enacted the Coastal Zone

Management Act (CZMA) of 1972, it created a federal-state partnership for managing ocean and coastal resources. There has been a good deal of controversy, however, as to the extent of authority delegated to the states under the CZMA partnership. At the heart of this controversy lies the federal consistency doctrine, under which states may determine whether federal and federally-permitted activities are consistent with federally-approved state coastal management programs (CMPs). This article examines the legislative history and rulemaking record of the federal consistency doctrine to determine the extent of the Congressional delegation. Key statutory terms such as, "directly affecting," "consistent to the maximum extent practicable," and "land uses and water uses of the coastal zone," are analyzed. The article also examines how consistency conflicts have been resolved by the courts and through administrative appeals filed with the Secretary of Commerce. Finally, the article discusses the federal consistency doctrine in the context of federal-state relations and with respect to national interest considerations. It concludes by summarizing recent federal policies that restrict state implementation of the CZMA and compares these policies with the original Congressional intent and the administration's general views on federalism.

In press: Ecology Law Quarterly.

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WHOI Contribution No. 6350.

ANTARCTICA AND
"THE COMMON HERITAGE OF MANKIND"

Christopher C. Joyner

For more than a quarter century, Antarctica and its circumpolar marine areas have been administered legally, and without any challenge to international authority, under the 1959 Antarctic Treaty arrangement. However, in the wake of the recently completed Third United Nations Conference on the Law of the Sea (UNCLOS III), a political movement appears to be surfacing in the United Nations which, arguably, might eventuate into a head-on confrontation between Third World states and the present Antarctic Treaty system's membership. Should this occur, questions undoubtedly will be raised concerning the current regime's legitimacy in exclusively overseeing political, economic, and scientific activities in the region.

The purposes of this paper are three-fold. First, a critical examination is made of the "common heritage of mankind" notion, its essential elements and the relevant legal effects which it would generate if applied to Antarctica. Second, treatment is given to the situation of CHM regions with respect to their legal status as property under international law. This analysis facilitates ascertaining the standing of the CHM notion in international law, as well as the contemporary legal ramifications produced by CHM for Antarctica. Third, consideration is devoted to appraising the current Antarctic Treaty System within the context of the political, economic and legal aspirations implicit in a CHM regime for that region. From this assessment, the contemporary intentions of the CHM concept are highlighted and, simultaneously, a better appreciation of the Antarctic Treaty regime is gleaned.

In press: American Society of International Law Proceedings.

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THE EVOLVING MINERALS REGIME FOR ANTARCTICA

Christopher C. Joyner

Increasing international attention is being focused upon Antarctica as a potential source of mineral deposits. Perhaps the most patent testimony of this heightening interest is the ongoing series of negotiations being undertaken by the Antarctic Treaty Consultative Parties (ATCPs). These negotiations, which have been carried out regularly and intensely since 1982, are specifically intended to fashion a special regime designed to administer and regulate the prospecting, exploration and exploitation of mineral resources--if they should ever occur--in the Antarctic area.

Given these developments, this study pursues three principal aims. First, it seeks to examine the institutional structure and functions of the Antarctic Minerals Regime as it is now unfolding. Second, the study supplies an assessment of the political-economic implications of the ATCPs creating an Antarctic Minerals Regime in light of current international realities and priorities. Third, the study treats the unavoidable environmental costs and liabilities that are bound to occur should mineral exploitation go forward in Antarctica, irrespective of the nature of the regulatory regime in place.

In press: The Antarctic Legal Regime.

Martinus Nijhoff Publishers, The Hague, 1987.

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WHOI Contribution No. 6345.

PROTECTION OF THE ANTARCTIC ENVIRONMENT: RETHINKING THE PROBLEMS AND PROSPECTS

Christopher C. Joyner

The Antarctic is an area of extremes and superlatives. It is the highest, most remote, inaccessible, and barren region on earth; it is also the last continent that man has explored. Because of this delay, coupled with the harsh physical and climatic conditions, the Antarctic environment remains in relatively pristine condition. The need to minimize the environmental effects of research activities, logistics operations, and extended settlement on the continent has long been recognized as a major concern by the Antarctica Treaty Consultative Parties. In recent years, however, enhanced prospects for resource-related activities such as harvesting of circumpolar fisheries, mineral exploration, and hydrocarbon development have posed potentially significant threats to the indigenous Antarctic environment.

The purpose of this paper is to place these threats into clearer perspective, to assess their likelihood, and to survey the possible legal and political options available to prevent their occurrence.

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RECONCILING SDI WITH AMERICAN TREATY COMMITMENTS

Christopher C. Joyner

The question of SDI all too easily demonstrates a fundamental reality of our modern times, namely the profound difficulty which the process of international law has in keeping up with, much less regulating, the phenomenal leaps in contemporary technological advancement. Even so there is a body of available international law that clearly is relevant and applicable to arms control and particularly the Strategic Defense Initiative.

The general focus of this paper is on international law and outlines generally the relevant tenets of international law

which are affected by the SDI program. The paper concludes with remarks about the recent controversy concerning the revised interpretation by the Reagan administration of the ABM Treaty as well as the implications that reinterpretation might pose for arms control.

Published in: The Strategic Defense Initiative: New Perspectives on Deterrence. Westview Press, Boulder, CO, p. 65-72.

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CONFLICTING JURISDICTIONS
IN THE SOUTHERN OCEAN:
THE CASE OF AN ANTARCTIC MINERALS REGIME

Christopher C. Joyner
and Peter J. Lipperman

Eventual exploitation of submarine mineral resources of the Southern Ocean--mainly manganese nodules and hydrocarbons--could become subject to the conflicting jurisdiction of two emerging legal regimes. The fact that one regime aspires to universal authority over the world's oceans, while the other is limited only to portions of the Southern Ocean, raises interesting questions concerning the applicability of ad hoc treaty-made law set against the evolution of customary norms regarding exploitation of submarine mineral resources.

The purpose of this article is to examine the inherently problematic legal questions stemming from potentially conflicting jurisdictions over submarine resources between the emergent International Sea-Bed Authority and an Antarctic Treaty System minerals regime.

In press: The Virginia Journal of International Law, Vol. 27, no. 1.

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WHOI Contribution No. 6348.

THE UNITED STATES AND ANTARCTICA:
RETHINKING THE INTERPLAY OF
LAW AND INTERESTS

Christopher C. Joyner and Ethel R. Theis

One significant outcome of the Third United Nations Conference on the Law of the Sea (UNCLOS III) was the United States decision not to sign the Convention when it was opened for signature in Jamaica in

December 1982. The United States' rejection of the Convention signaled an unfortunate end to over a decade of American efforts to produce a comprehensive and universally acceptable ocean regime. The decision, however, sensitized American policy-makers to the importance of formulating policies on international regimes that promote United States interests. Presently, the United States is faced with another situation where it must examine U.S. interests in terms of competing international legal regimes. Antarctica stirs up many of the same fundamental issues presented by the Conference on the Law of the Sea. The question turns on how much the United States has learned from its previous experience.

This article contends that the best way to protect United States interests in Antarctica is to ensure that the 1959 Treaty framework is sustained. In order to respond to the proponents of the "common heritage" concept, the United States must articulate a coherent position in advance. Recognition of this need for a prompt response compels a cogent reevaluation of United States Antarctic policy.

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WHOI Contribution No. 6402.

ASSESSING THE IMPLEMENTATION
OF FEDERAL COASTAL POLICY

Kem Lowry

Implementation of plans and programs has been the subject of increasing scholarly inquiry in recent years. Some scholars have suggested that particular statutory, administrative, and socioenvironmental conditions are necessary for effective implementation. Applying one framework (that of Mazmanian and Sabatier) of such conditions to the federal Coastal Zone Management Act and its implementation reveals that in the 1970s the prospects for effective implementation of the act by the Office of Coastal Zone Management has been at least a partial success, judged in terms of the goals of the act, largely because of the incentives for state participation in the program, the general political support for coastal resource management, and the substantial political and managerial skills of OCZM officials. The history of CZMA also suggests that implementation theory needs to address ways to create the conditions that foster the learning processes

necessary to carry out broad and innovative programs.

Published in: Journal of the American Planning Association, 51, 3, 288-298.

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ASSESSING INTERGOVERNMENT COORDINATION IN COASTAL ZONE MANAGEMENT

Kem Lowry and Timothy Eichenberg

One of the primary incentives to state governments to participate in the national coastal zone management program is the legal requirement that federal resource use activities as well as federal projects and federally-permitted activities that affect state ocean and coastal areas must be consistent with federally-approved state coastal programs. The "consistency provisions" are among the most innovative attempts to insure intergovernmental coordination in resource management. In assessing the implementation of the consistency provisions, we find that this legal requirement has led to the development of a variety of formal and informal collaborative mechanisms for intergovernmental coordination in ocean and coastal management. While these mechanisms have led to the resolution of the vast majority of federal-state conflicts in coastal areas, some important federal-state conflicts have not been resolved. This has more to do with the character of these particular conflicts than the general effectiveness of the mechanisms for collaboration that have been established.

In press: Policy Studies Journal.

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THE EVOLVING INTERNATIONAL LAW OF ENVIRONMENT: TRENDS IN NATIONAL AND INTERNATIONAL DECISION-MAKING

Kilaparti Ramakrishna

The onset of the 1970s saw a world-wide awareness of the need to take effective measures for the protection of the environment. This was reflected in the measures adopted at the national, bilateral, regional and global levels. Emphasis was increasingly placed on concerns such

as the protection and preservation of marine environment, a desire to avoid/minimize transnational effects of ultra-hazardous activities, controlling trans-frontier air pollution, and the protection of international rivers. The high water mark, however, was the United Nations Conference on the Human Environment, 1972 (UNHE). This Conference was followed by several more conferences, by the creation of new institutions at the global, regional and bilateral levels, and finally, by an enormous effort of international treaty-making. All this naturally brought to the fore the question of the norms and processes of international law and their potential for safeguarding the environment. This question was widely researched. However, their approach tended to be piecemeal and lacking in the necessary holistic approach.

This study attempts to determine how a principle of environmental law gets to be accepted as such. The normal practice has been to look at the hierarchical order provided in Article 38 of the statute of the International Court of Justice (ICJ) whenever confronted with such questions and to determine its exact legal value. It is felt that the enumeration contained therein of the sources is inadequate for assessing the evolving international law of environment. This is because of the following reasons. As mentioned at the outset, the awareness of the global community to the problems of environmental protection is of recent origin. The customary principle mainly enshrined in the maxim *sic utere tuo ut alineum non laedas* has hardly reached any refinement. The conventional law on the subject, given the time frame, is enormous. However, these seldom provided for anything other than cooperation, avoiding and mitigating environmental damage. Likewise, the general principles of law recognized by civilized nations lagged far behind in introducing any major principle for the protection of environment in the international arena. Under these circumstances one should look beyond these traditional sources of international law.

The basic argument in this book is that the international law of environment evolved not only through the so-called formal sources of law but also through different intergovernmental bodies like the United Nations, various regional organizations and non-governmental organizations like the International Union for the Conservation of Nature and Natural Resources and the International Law Association. The study does not adopt any particular persuasion in finding solutions for international legal problems of environmental protection. It follows a purely

functional approach and attempts to find answers within the existing international state system with the help of the various tools that are available.

In press: Springer-Verlag and the Institute for International Affairs, University of Hamburg.

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OUTER LIMITS OF CONTINENTAL SHELF:
A LEGAL ANALYSIS OF CHILEAN AND
ECUADORIAN ISLAND CLAIMS AND U.S. RESPONSE

Kilaparti Ramakrishna, Robert E. Bowen
and Jack H. Archer

This article highlights the legal and geomorphological difficulties in interpreting Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS), as it pertains to the delimitation of outer limits of continental shelves of islands, in light of recent Chilean and Ecuadorian claims and the U.S. responses. It concludes that both Ecuador and Chile have put forward claims cognizable under UNCLOS and that the treaty provisions characterizing jurisdiction "on submarine ridges" will continue to give rise to conflicting claims.

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58-68.

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WHOI Contribution No. 6358.

OCEAN RESOURCES AND U.S. INTERGOVERNMENTAL
RELATIONS IN THE 1980s

Maynard E. Silva

The chapters in this volume represent revised versions of papers presented at a workshop, "Ocean Resources and Intergovernmental Relations in the 1980s," held in September of 1985. Specifically, they examine the roles of the federal, state, and local governments of the United States in the management of ocean and coastal resources.

The impetus for the workshop came from two presentations at very different fora. The first was a 1982 conference sponsored by the University of Rhode Island's Center for Ocean Management Studies. The second was a roundtable on the "Reagan Federalism" conducted at the 1984 annual meeting of the American Political Science Association.

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CO.

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A BIBLIOGRAPHIC LISTING
OF COASTAL AND MARINE PROTECTED AREAS:
A GLOBAL SURVEY

Maynard E. Silva, Ellen M. Gately
and Ingrid Desilvestre

This document is the result of a survey of over 600 books, articles, technical reports and personal correspondence reviewing approximately 1,000 coastal and marine protected areas in 87 countries and, in turn, was intended to support a larger project that had been undertaken by the Marine Policy and Ocean Management Center of the Woods Hole Oceanographic Institution in conjunction with the Government of Ecuador to consider the establishment of protected status for the marine area of the Galapagos Archipelago. To provide background for this larger project, a review of existing or proposed marine protected areas was initiated. This bibliographic listing is one result of this review.

In addition to a short introduction, the listing consists of four parts: (1) Table I - a country-by-country listing of marine protected areas; (2) Table II - a listing of special topics from the bibliography; (3) a numerical listing of sources; and (4) an alphabetical listing of sources.

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WHOI Technical Report 86-11.

BOOTSTRAPPING SPATIAL POINT PATTERNS

Andrew R. Solow

The bootstrap is used to estimate the sampling distributions of two estimators of inverse intensity for three small data sets. The results are compared to those found by randomizing the sampling plan. The bootstrap achieves modest success at estimating the standard deviations of the sampling distributions. Preliminary results indicate that the bootstrap also performs well at providing interval estimates.

In press: Biometrics.

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Trust and the Marine Policy Center.

DETECTING CLIMATE CHANGE

Andrew R. Solow

Statistical tests for climate change occurring at a specified time may suffer from the problem of data-dredging. In particular, the statistical significance of an observed pattern in the data may be substantially exaggerated when the hypothesized time of change is specified with reference to the same data on which the test is based. A Monte Carlo simulation experiment is carried out to illustrate this effect. An alternative test, in which it is not necessary to specify the time of change, is described and applied to a short temperature series.

In press: Journal of Climate and
Applied Meteorology.

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Trust and the Marine Policy Center.

WHOI Contribution No. 6278.

ON ESTIMATING UNDISCOVERED OFFSHORE OIL RESOURCES: AN APPLICATION OF BAYES' THEOREM

Andrew R. Solow

United States Government estimates of offshore oil resources have been based largely on subjective information. Through time, results of exploratory drilling become available, and the estimates are updated. Although this situation strongly suggests the use of Bayes' Theorem, this approach has not been taken. In this paper, the problem is explicitly framed in terms of Bayes' Theorem, and two simple exercises are performed on actual results to demonstrate the usefulness of the approach.

In press: Proceedings of the NATO
Advanced Seminar Institute on
Statistical Treatment for
Estimation of Mineral and Energy
Resources. C. F. Chung et al,
eds. Reidel, Dordrecht, Holland.

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Trust and the Marine Policy Center.

WHOI Contribution No. 6218.

THE APPLICATION OF EIGENANALYSIS TO TIDE-GAUGE RECORDS OF RELATIVE SEA LEVEL

Andrew R. Solow

Eigenanalysis has been applied in the past to analyze tide-gauge records of relative sea level. The purpose of this analysis has been to detect "coherent modes" of sea level change among the records. By applying eigenanalysis to simple models of the records, it is shown that the results can be misleading. In particular, these results can depend on differences in noise variance, noise correlation, and period of observation among the records, and not only on the information-rich component of the records. When the records have the same rate of change, differences in these factors cause eigenanalysis to attribute different rates of change to them. When the records have different positive rates of change, eigenanalysis tends to underestimate the extreme rates. For the purposes of policy formulation to deal with sea level rise, this underestimation can have serious consequences.

In press: Continental Shelf Research.

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WHOI Contribution No. 6229.

GRADUATE STUDENTS

Abstracts of papers or theses submitted in 1986 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.

Abstracts of papers or reports submitted in 1954 by members of the Society for the Study of the History of the Physical Sciences and the Society for the Study of the History of the Life Sciences. The abstracts are arranged in two columns. The first column contains the title of the paper or report, the author's name, and the name of the organization or institution to which the paper or report was submitted. The second column contains a brief summary of the paper or report.

NONLINEAR DIFFRACTION OF OCEAN GRAVITY WAVES

Yehuda Agnon

In an irregular sea, waves having different wave numbers interact nonlinearly, giving rise to long waves at the difference frequency and wavenumber. The long waves are associated with motions that have large characteristic time and space scales.

The method of multiple scales in time and in space, in conjunction with perturbation expansions, enables us to separate the flow into components for the general case when there are wave-trains propagating in different directions. In particular, it is of great interest to study the effect of modification of the short waves by diffraction, refraction, reflection and radiation. Using the method of matched asymptotics, we determine the long-wave that consists of forced waves travelling with the short-wave groups of an additional wave that propagates away from the "zone of modification" at the long-wave velocity $(gh)^{1/2}$. The resulting theory has a wide range of applications. We have studied the following problems.

- a) Slow Sway of a Moored Floating Body in Water of Finite Depth
Both large and small amplitude cases were studied as well as the effect of different geometries and mooring stiffness. New analytical results for a block with small clearance underneath are included and the existence of resonance is displayed. Periodic and different transient inputs were studied.
- b) Wave Trapping on a Shelf
Normal and obliquely incident slowly varying waves were studied, retaining short wave reflection. For the obliquely incident waves trapping can occur. This trapped wave cannot be excited from off the shelf by any linear mechanism. The shelf response is computed and singular resonance is found. The transient response, however, is finite. It too is determined.
- c) Excitation of Interfacial Waves in the Lee of a Breakwater
The method of multiple scales is used to determine the non-resonant interaction of surface waves with internal waves in a two layer fluid. We study the effect of diffraction by a long breakwater. While the short waves are decaying

behind the breakwater, free long internal waves are propagating directly into that shadow zone.

The present method of analysis, and in particular the multiple scales expansion, proves to be a useful tool in studying modulation and nonlinearity in several aspects at wave propagation, and can be extended to the study of a heretofore unexplored aspect of harbor resonance. The ideas will be sketched in the Epilogue.

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ACCELERATED SETTLING OF PARTICULATE MATTER BY 'MARINE SNOW' AGGREGATES

Vernon L. Asper

Samples from time-series sediment traps deployed in three distinct oceanographic settings (North Pacific, Panama Basin, and Black Sea) provide strong evidence for rapid settling of marine particles by aggregates. Particle water column residence times were determined by measuring the time lag between the interception of a flux event in a shallow trap and the interception of the same event in a deeper trap at the same site. Effective sinking speeds were determined by dividing the vertical offset of the traps (meters) by the interception lag time (days). At station Papa in the North Pacific, all particles settle at 175 m day^{-1} , regardless of their composition, indicating that all types of material may be settling in common packages. Evidence from the other two sites (Panama Basin and Black Sea) shows that particle transport may be vertical, lateral, or a combination of directions, with much of the Black Sea flux signal being dominated by lateral input.

In order to ascertain whether marine snow aggregates represent viable transport packages, surveys were conducted of the abundance of these aggregates at several stations in the eastern North Atlantic and Panama Basin using a photographic technique. Marine snow aggregates were found in concentrations ranging from $\sim 1 \text{ mm}^3 \text{ liter}^{-1}$ to more than $500 \text{ mm}^3 \text{ liter}^{-1}$. In open ocean environments, abundances are higher near the surface (production) and decline with depth (decomposition). However, in areas near sources of deep input of resuspended material, concentrations reach mid-water maxima, reflecting lateral transport. A model is proposed to relate the observed

aggregate abundances, time series sediment flux and inferred circulation. In this model, depthwise variations in sediment flux and aggregate abundance result from suspension from the sea floor and lateral transport of suspended aggregates which were produced or modified on the sea floor. Temporal changes in sediment flux result from variations in the input of fast-sinking material which falls from the surface, intercepts the suspended aggregates, and transports them to the sea floor.

A new combination sediment trap and camera system was built and deployed in the Panama Basin with the intent of measuring the flux of marine snow aggregates. This device consists of a cylindrical tube which is open at the top and sealed at the bottom by a clear plate. Material lying on the bottom plate is illuminated by strobe lights mounted in the wall of the cylinder and photographed by a camera which is positioned below the bottom plate. Flux is determined as the number of aggregates arriving during the time interval between photographic frames ($\# \text{ area}^{-1} \text{ time}^{-1}$). Results show that essentially all material arrives in the form of aggregates with minor contributions of fecal pellets and solitary particles. Sinking speeds (m day^{-1}), calculated by dividing the flux of aggregates ($\# \text{ m}^{-2} \text{ day}^{-1}$) by their abundance ($\# \text{ m}^{-3}$), indicate that the larger (4-5mm) aggregates are flocculent and sink slowly ($\sim 1 \text{ m day}^{-1}$) while the smaller aggregates (1-2.5mm) are more compact and sink more quickly ($\sim 36 \text{ m day}^{-1}$). These large, slow-sinking aggregates may have been re-suspended from the sediment water interface at nearby basin margins.

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CHANGES IN MIDGUT GLAND MORPHOLOGY
AND DIGESTIVE ENZYME ACTIVITIES
ASSOCIATED WITH DEVELOPMENT
IN EARLY STAGES OF THE AMERICAN LOBSTER
Homarus americanus

Patricia M. Biesiot

The development of the digestive system, specifically in relation to the midgut gland (hepatopancreas), in early life history stages of the American lobster Homarus americanus is examined in the present study by means of two separate but complementary approaches. A histological study on the light microscope level details the morphological changes which take

place among the different cell types which form the midgut gland. Included in this portion of the study are scanning electron micrographs of the midgut gland of stage IV larva. Secondly, a biochemical study correlates changes in the activities of digestive protease, lipase, and amylase with the observed changes in the cells of the midgut gland. A sensitive method for detection of crustacean lipase was developed for this study. In order to optimize the assay conditions for measurement of digestive enzyme activities, a series of control tests was performed to determine the effects of several physical and chemical factors.

The developmental stages of the lobster which are examined in these studies include: well-advanced embryos at approximately three days prior to hatching, hatching prelarvae, newly hatched and intermolt stage I larvae, intermolt stage II, III, and IV larvae, and intermolt stage V and VI postlarvae. Particular attention is paid to specific transitional stages during development. These include: (1) the changeover from yolk metabolism by the embryos to the dependence on exogenous food by newly hatched larvae; (2) the alteration in body form which occurs at the molt from larval stage III to IV; and (3) the change in habitat from the plankton to the benthos which occurs at the molt from stage IV to V.

Results of the present study demonstrate that the R-cells (resorptive cells) of the earliest developmental stages, embryo through larval stage III, do not show the characteristic morphology classically ascribed to this cell type. Presumably because young lobsters do not begin to store excess lipids derived from the diet until stage IV, the R-cells do not contain large numbers of lipid vacuoles. By stage VI, however, the R-cells achieve the classic appearance. A previously unreported function for R-cells, that of storage of lipid derived from yolk metabolism in the embryo, is described. F-cells (digestive enzyme synthesizing cells) are present in the midgut gland of embryos a few days prior to the hatch while B-cells (enzyme secreting cells) have developed by the time of hatching. Thus, morphologically the stage I lobster larva appears to possess digestive capabilities prior to ingestion of the first meal.

Changes in digestive enzyme activities during early development correlate well with the morphological changes observed in the midgut gland. Activities of protease, lipase, and amylase are very low in the well-advanced embryo and increase slightly by the hatching stage. Enzyme activities more than double by the time the stage I larva attains intermolt, regardless of

whether the larva is fed or fasted. Digestive enzyme activities increase further by the time the stage II larva reaches intermolt; in general there is no significant difference in the levels of enzyme activities measured in the older stages (II through V).

The results of a more detailed time course examination of the levels of digestive enzyme activities in relation to first feeding by the stage I larvae are presented. Although there is a trend for slightly increased protease and amylase activities as the stage I larvae get older, the lipase activity is constant.

Lobster larvae normally hatch in late spring and early summer but larvae can be induced to hatch during the winter by maintaining the eggs at higher than ambient water temperatures. There is no consistent difference in digestive enzyme activities measured for larvae which hatch during the summer compared to those which hatch during the winter.

The influence of molt stage on the activity of digestive enzymes in wild stage IV larvae is also discussed. Only minor variations in lipase and amylase activities are detected during intermolt and premolt and in general there is no significant effect. Protease activity is significantly greater at D₀.

This work describes new findings on several aspects of digestion among early life history stages of a marine decapod crustacean and has added to our understanding of the functional morphology of the midgut gland during early development.

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THE PHYSIOLOGY OF DORMANCY
AND GERMINATION IN CYSTS OF THE MARINE
DINOFLLAGELLATE *Scrippsiella trochoidea*

Brian J. Binder

Cysts of *Scrippsiella trochoidea* are representative of the thickwalled non-motile resting cells produced by many dinoflagellates. Although the influence of cysts on the biology and ecology of dinoflagellates may be significant, little is known of the factors controlling cyst dormancy and germination or of the metabolic foundations of these processes. This study addresses these issues using cysts produced and manipulated under defined conditions in laboratory culture.

Scrippsiella trochoidea cysts experienced a period of dormancy, lasting approximately 25 days, during which germina-

tion did not occur. The duration of this period was not affected by temperature. Cysts which had completed their dormancy period remained quiescent until permissive environmental conditions were established. Quiescent *S. trochoidea* cysts remained viable at 3°C in the dark for at least 350 days.

Germination in quiescent *S. trochoidea* cysts was photomorphogenically controlled; cysts deprived of light but otherwise provided with optimal environmental conditions failed to germinate. The light requirement was satisfied to a large extent by a single, brief, low intensity exposure (a photon fluence of 0.2 $\mu\text{mol m}^{-2}$ "white" light elicited a 50% response). Yellow-green light ($\lambda \approx 550\text{nm}$) was found to be most effective.

Temperature exerted significant control over germination as well. Germination rate was maximal above 14°C; it decreased rapidly as temperature decreased below this level. Ultimate achieved germination frequency, in contrast, was relatively insensitive to temperature. The temperature range optimal for cyst germination did not precisely coincide with that for vegetative growth. Thus germination was greatly retarded at low temperatures which supported good vegetative growth, but on the other hand proceeded optimally at high temperatures which completely inhibited such growth.

The most conspicuous compositional attribute of *S. trochoidea* cysts was their increased carbohydrate content, which was 10 times that of exponentially growing cells. Cysts contained significantly less protein and chlorophyll-a than vegetative cells, while the lipid content of the two forms was comparable. The respiratory activity of quiescent cysts was estimated to be approximately 1.5% of that in vegetative cells. Although chlorophyll-a persisted in quiescent cysts, no photosynthetic activity could be detected therein.

The germination of *S. trochoidea* cysts was accompanied by an immediate increase in respiratory activity, with carbohydrate serving as the principal substrate. Protein synthesis became apparent within 24 hr of activation, followed by a dramatic increase in both chlorophyll-a and photosynthetic activity just prior to excystment.

Encystment and germination in *S. trochoidea* represent developmental patterns which are regulated by specific, albeit not yet well understood, environmental and biological parameters. The further elucidation of these processes and their regulation will lead to a better understanding of the dynamics of dinoflagellate populations in nature, as well as of the biology of dormancy and quiescence generally.

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THE ROLE OF COLLOIDAL ORGANIC MATTER IN THE MARINE GEOCHEMISTRY OF PCBs

Bruce J. Brownawell

Polychlorinated biphenyls (PCBs) were used as model hydrophobic organic compounds (HOC) to study physical-chemical processes which affect the speciation and fate of HOC in coastal environments. The focus of this study is on the sorption of PCBs with colloidal organic matter in seawater and the influence of this process on the distribution of PCBs in coastal sediments. Laboratory and field experiments were used to make quantitative estimates of PCB-organic matter sorption, and to test predictions of three-phase equilibrium models.

A static headspace partitioning method was developed to measure the sorption of several individual chlorobiphenyls with colloidal organic matter enriched from coastal seawater by hollow fiber ultrafiltration. This technique directly measured the dissolved phase fugacity of PCBs in experimental bottles and avoided uncertain separation techniques often used in isolating various chemical phases. Colloidal organic carbon normalized partition coefficients (K_{oc}) were determined from linear sorption isotherms, increasing from 1.9×10^4 (L/Kg) for 2,4'-dichlorobiphenyl to 3.5×10^5 for 2,2',3,4,5'-pentachlorobiphenyl. Sorption tended to increase with increasing octanol-water partition coefficients (K_{ow}) of the sorbate, and values of K_{oc} were within a range of those reported in other experimental sorption studies with sediments and dissolved humic substances. Experimental partitioning results support the hypothesis that HOC-organic colloid sorption is similar to HOC sorption by sediment organic matter.

PCBs were measured in the interstitial waters and sediments of three box cores obtained from New Bedford Harbor and Buzzards Bay, Massachusetts. The three sites studied had a wide range of sediment PCB concentrations, and reducing conditions provided environments containing high concentrations of colloidal organic matter. Dissolved organic carbon (DOC) and total sediment organic carbon (TOC) were measured in two cores to test the role of organic matter on the observed partitioning of PCBs. PCB concentrations, particularly those of less soluble chlorobiphenyls, were highly elevated in interstitial waters compared to water column concentra-

tions at all three sites. The measured apparent distribution coefficients (K'_d) of individual chlorobiphenyls did not increase with hydrophobicity (K_{ow}) and indicate that a large fraction of PCBs in interstitial waters must be sorbed to organic colloids. A three-phase equilibrium sorption model, in which dissolved PCBs are in a dynamic equilibrium with colloidal and sediment organic matter, accounts for many aspects of the field data. There is good agreement of observed partitioning at New Bedford Station 67 and Buzzards Bay Station M with model calculations based on predictions derived from laboratory experiments of HOC sorption with sediments and organic colloids, but model calculations underpredict K'_d at Station 84 in New Bedford Harbor.

The sediment-interstitial water results were contrasted with a study of PCB partitioning in the water column at two stations in New Bedford Harbor. Measured K'_d s of PCBs in the water column increased with K_{ow} and approached predictions based on two-phase, water-suspended particulate partitioning when the effect of organic colloids on high K_{ow} PCBs was considered.

The effect of a mobile colloid-sorbed PCB phase on a general sediment transport model was evaluated. Enhanced migration of highly sorbed PCBs can be included in an apparent diffusivity term when steady-state conditions exist. Model calculations showed that diffusive migration of PCBs in typical coastal sediments is minor over 20 yr timescales. Comparisons with the ^{210}Pb profile provided additional evidence that the solid phase depth profiles of PCBs at Station M were controlled by biological mixing of the sediments and not pore water migration. Predictions based on results from Station M indicate that sediment diffusion and bioturbation of colloid-sorbed PCBs in surface sediments could provide a potentially important flux of PCBs across the sediment-water interface to the water column in Buzzards Bay.

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A COUPLED HYDRODYNAMIC AND ICE FLOW MOVEMENT MODEL

Michael S. Bruno

A coupled ice-ocean model has been developed for use in the short term (order

of days) prediction of the movement of the water and overlying ice floes of the shallow Arctic continental shelf. Our interest in shallow waters has permitted the use of the depth-averaged momentum equations for the water circulation component of the coupled model, while at the same time introducing the complication of quantifying finite depth effects in the formulation. Since the offshore activities which this model is intended to assist (ie, shipping and resource exploration) are confined to the open water season, the forces due to the ice-ice interaction have been assumed negligible. The short time and spatial scales with which we are concerned have allowed the neglect of thermodynamic effects such as ice formation and melting, but necessitate much finer model resolution than that employed by large scale, seasonal models of the ice movement. The derivation of the coupled equations of motion has also led to the development of a simple methodology for the estimation of the drag coefficients at the air-ice and ice-water interfaces. We have demonstrated, through idealized case studies, the influence of finite depth effects (i.e., increased bottom friction in a wave-current flow) on coastal circulation. The alteration of the air-water momentum exchange in the presence of ice flows, and the resulting effects on the underlying water motion have also been illustrated. Model comparisons with actual measurements of ice floe movement in the Beaufort Sea have been extremely encouraging, especially with respect to the predictions afforded by the often-used wind-factor method. These comparisons have also served to illustrate the errors associated with neglecting circulation effects. The use of the depth-averaged formulation of the water circulation equations have been found to weaken the model's ability to simulate ice movement in a windfield rapidly varying in time. We therefore suggest the adoption of a multi-level circulation scheme as a future model refinement.

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PLUTONIUM ISOTOPES IN THE NORTH ATLANTIC

Ken O. Buesseler

The artificial radionuclide Plutonium (Pu) has been introduced into the environment primarily as fallout from atmospheric nuclear weapons testing during the 1950's and 1960's. Earlier studies of Pu geochemistry are generally based upon the measurement of the combined activities of

^{239}Pu and ^{240}Pu (detected by alpha-counting and written as $^{239,240}\text{Pu}$) and assume an identical geochemical behavior for Pu from any of its fallout sources. A major focus of this thesis is the development of a mass spectrometric (m.s.) technique for the analysis of Pu in marine sediments, pore waters, sediment trap material and sea water from the North Atlantic. With the m.s. technique, not only is the detection limit for $^{239,240}\text{Pu}$ increased by over an order-of-magnitude, but the ^{240}Pu and ^{239}Pu isotopes can be separated as well.

The increased sensitivity for Pu provided by m.s. allowed me to measure Pu in deep-sea pore waters for the first time. Pore water studies are sensitive indicators of early diagenetic reactions, and can be used to examine the unresolved question of the extent of Pu remobilization out of marine sediments. Along a transect of cores ranging from highly reducing muddy sediments on the shelf to more oxic and carbonate-rich sediments in the deep-sea, I have found that the solubility of Pu is predominantly controlled by the distribution of Pu in the solid phase. The calculated $^{239,240}\text{Pu}$ distribution coefficients (K_d = dpm per kg on solids/dpm per kg in solution) range from $0.2\text{--}23 \times 10^4$, with some suggestion of a trend towards lower values in the deeper cores (K_d 's in cores from water depths greater than 2500m). Diffusive flux calculations based upon the observed Pu pore water gradients suggest that since its introduction, negligible Pu has been remobilized out of the sediments at all of the sites. On a time scale of $10^2\text{--}10^3$ years however, Pu remobilization may be significant.

A large suite of sedimentary Pu and $^{210}\text{Pb}^{ex}$ inventory data are also examined from the Northwest Atlantic shelf, slope and deep-sea sediments. Comparisons between Pu and ^{210}Pb are of interest since both isotopes are predominantly supplied by atmospheric delivery to coastal waters and since both isotopes are used to study recent accumulation and mixing processes in marine sediments. Inventories of these tracers will reflect their source function, removal efficiencies, and lateral transport in water and particles. A major conclusion is that the sediment inventories decrease with increasing water depth, reflecting a decrease in the net scavenging of these elements off-shore. Pu sediment inventories drop-off with increasing water depth much more rapidly than $^{210}\text{Pb}^{ex}$ inventories, due to either the shorter residence time of ^{210}Pb compared to Pu with respect to water column removal processes, or due to comparisons between the naturally occurring

^{210}Pb steady-state scenario and the more recently introduced fallout Pu. When Pu and $^{210}\text{Pb}^{\text{ex}}$ inventories are summed over water depths out to 4000 m in the Northwest Atlantic, the sediments can account for roughly $24 \pm 8\%$ of the expected Pu and $83 \pm 15\%$ of the expected $^{210}\text{Pb}^{\text{ex}}$ inputs.

The $^{240}\text{Pu}/^{239}\text{Pu}$ ratio data provided by the m.s. provide a unique insight into the relationship between the specific sources of fallout Pu and its geochemical behavior in the oceans. I find a systematic decrease in the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio in sediments from 0.18 on the shelf to 0.10 in deep-sea (4500-5000 m) sediments from the Northwest Atlantic. This trend is consistent with a model whereby Pu from surface based testing at the Nevada Test Site ($^{240}\text{Pu}/^{239}\text{Pu} = 0.035$) is carried by tropospheric fallout particles of a distinct physical/chemical form which are rapidly removed from the water column at all depths, in contrast to global stratospheric fallout ($^{240}\text{Pu}/^{239}\text{Pu} = 0.18$) which is only efficiently deposited to the sediments in the shallower cores where scavenging is more intense. This two source model was chosen since there is no evidence for the present day fractionation of ^{239}Pu from ^{240}Pu in the water column and sediment trap data.

This two source model is supported by the analysis of $^{240}\text{Pu}/^{239}\text{Pu}$ ratios in marine sediments from the 1950's and 1960's which show lower or equivalent $^{240}\text{Pu}/^{239}\text{Pu}$ ratios than present day samples from the same locations (Nevada fallout was confined to 1951-1958 while global fallout inputs peaked in 1961/62). Also, while all of the North Atlantic deep-sea sediments show some evidence of the Nevada inputs (i.e. $^{240}\text{Pu}/^{239}\text{Pu}$ less than 0.18), the net inventory of Pu from the Nevada source can be shown to decrease with increasing distance away from the Nevada source. Using the observed sediment $^{240}\text{Pu}/^{239}\text{Pu}$ ratios and a two end-member mixing model, the Pu supplied by the Nevada source in deep Northwest Atlantic sediments (greater than 4500 m) is shown to account for roughly 40% of the total sediment $^{239,240}\text{Pu}$ inventory. The very low inventories of $^{239,240}\text{Pu}$ in the deep-sea sediments in general serves to accentuate the Nevada fallout signal at these sites.

A pronounced dis-equilibrium is observed between the solid phase $^{240}\text{Pu}/^{239}\text{Pu}$ ratios (which range from 0.10-0.18) and the pore water $^{240}\text{Pu}/^{239}\text{Pu}$ ratios (which are constant at ≈ 0.18) at all sites. The low ratio Nevada fallout Pu is apparently more tightly bound by its solid phase carrier than Pu from global fallout sources and is

therefore not participating in the general solid/solution exchange reactions.

Within an individual sediment profile, the $^{240}\text{Pu}/^{239}\text{Pu}$ ratios are relatively constant from core top to core bottom. Using a sediment mixing model which combines the Pu activity data and the resulting $^{240}\text{Pu}/^{239}\text{Pu}$ ratios given the two Pu sources, I have been able to constrain the input function of Pu to the slope and deep ocean sediments. The data are consistent with a model which suggests that the bulk of the Pu deposited to the deep ocean sediments arrived early-on in the fallout record.

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THE FLYING FISH, A PROTOTYPE OCEANOGRAPHIC SENSOR PLATFORM WITH ACOUSTIC HOMING CAPABILITY

Joshua K. Hoyt

The Flying Fish is an autonomous, streamlined, gravity driven underwater vehicle of high speed (15 knots) vertical excursions to depths of 6000 meters. This prototype uses short baseline acoustic interferometry to guide itself to a monochromatic acoustic beacon at the surface. Phase difference measurements made on two orthogonal axes are used to deduce the relative bearing to the beacon. An autopilot uses this information to actuate control surfaces and correct vehicle attitude. This thesis describes the oceanographic context in which the vehicle will be used, translates the scientific mission into a set of coherent engineering specifications, describes a prototype design that meets these specifications, and demonstrates proof-of-concept with a series of sea trials. Some recommendations are made for future refinements.

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A STUDY OF THE REMINERALIZATION OF ORGANIC CARBON IN NEARSHORE SEDIMENTS USING CARBON ISOTOPES

Ann P. McNichol

A study of the remineralization of organic carbon was conducted in the organic-rich sediments of Buzzards Bay, Mass. Major processes affecting the carbon chemistry in sediments are reflected by changes in the stable carbon isotope ratios of dissolved inorganic carbon (ΣCO_2) in

sediment pore water. Six cores were collected seasonally over a period of two years. The following species were measured in the pore waters: ΣCO_2 , $\delta^{13}\text{C}-\Sigma\text{CO}_2$, PO_4 , $\Sigma\text{H}_2\text{S}$, Alk, DOC, and Ca. Measurements of pore water collected seasonally show large gradients with depth, which are larger in summer than in winter. The $\delta^{13}\text{C}$ (PDB) of ΣCO_2 varies from 1.3 o/oo in the bottom water to approximately -10 o/oo at 30 cm. During all seasons, there was a trend towards more negative values with depth in the upper 8 cm due to the remineralization of organic matter. There was a trend toward more positive values below 8 cm, most likely due to biological irrigation of sediments with bottom water. Below 16-20 cm, a negative gradient was re-established which indicates a return to remineralization as the main process affecting pore water chemistry.

Using the ΣCO_2 depth profile, it was estimated that 67-85 gC/m² are oxidized annually and 5 gC/m²-yr are buried. The amount of carbon oxidized represented remineralization occurring within the sediments. This estimate indicated that approximately 20% of the annual primary productivity reached the sediments. The calculated remineralization rates varied seasonally with the high of 7.5×10^{-9} mol/L-sec observed in August 84 and the low (0.6×10^{-9}) in December 83. The calculated remineralization rates were dependent on the amount of irrigation in the sediments; if the irrigation parameter is known to $\pm 20\%$, then the remineralization rates are known to this certainty also. The amount of irrigation in the sediments was estimated using the results of a seasonal study of $^{222}\text{Rn}/^{226}\text{Ra}$ disequilibria at the same study site (Martin, 1985). Estimates of the annual remineralization in the sediments using solid-phase data indicated that the solid-phase profiles were not at steady-state concentrations.

The isotopic signature of ΣCO_2 was used as an indicator of the processes affecting ΣCO_2 in pore water. During every month, the oxidation of organic carbon to CO_2 provided over half of the carbon added to the ΣCO_2 pool. However, in every month, the $\delta^{13}\text{C}$ of ΣCO_2 added to the pore water in the surface sediments was greater than -15 o/oo, significantly greater than the $\delta^{13}\text{C}$ of solid-phase organic carbon in the sediments (-20.6 o/oo). The $\delta^{13}\text{C}$ of ΣCO_2 added to the pore water in the sediments deeper than 7 cm was between -20 and -21 o/oo, similar to the organic carbon in the sediments. Possible explanations of the ^{13}C -enrichment observed in the surface sediments were:

- a) significant dissolution of CaCO_3 ($\delta^{13}\text{C} = +1.7$ o/oo);

- b) the addition of significant amounts of carbonate ion from bottom water to pore water;
- c) an isotopic difference between the carbon oxidized in the sediments and that remaining in the sediments.

The effect of CaCO_3 dissolution was quantified using measured dissolved Ca profiles and was not large enough to explain the observed isotopic enrichment.

An additional source of ^{13}C -enriched carbon was bottom water carbonate ion. In every month studied, there was a net flux of ΣCO_2 from pore water to bottom water. The flux of pore water ΣCO_2 to bottom water ranged from a minimum of 10×10^{-12} mol/cm²-sec in December 83 to a maximum of 50×10^{-12} mol/cm²-sec in August 84. However, because the pH of bottom water was about 8 while that of the pore water was less than or equal to 7, the relative proportion of the different species of inorganic carbon (H_2CO_3^* , HCO_3^- , CO_3^{2-}) was very different in bottom water and pore water. Thus, while there was a net flux of ΣCO_2 from pore water to bottom water, there was a flux of carbonate ion from bottom water to pore water. Because bottom water ΣCO_2 was more ^{13}C -enriched than pore water ΣCO_2 , the transfer of bottom water carbonate ion to pore water was a source of ^{13}C -enriched carbon to the pore water. If the $\delta^{13}\text{C}$ of CO_2 added to the pore water from the oxidation of organic carbon was -20.6 o/oo, then the flux of CO_3^{2-} from bottom water to pore water must have been 10-30% of the total flux of ΣCO_2 from pore water to bottom water. This is consistent with the amount calculated from the observed gradient in carbonate ion.

Laboratory experiments were conducted to determine whether the $\delta^{13}\text{C}$ of CO_2 produced from the oxidation of organic carbon ($\delta^{13}\text{C}-\text{OC}_{ox}$) was different from the $\delta^{13}\text{C}$ of organic carbon in the sediments ($\delta^{13}\text{C}-\text{SOC}$). In the laboratory experiments, mud from the sampling site was incubated at a constant temperature. Three depths were studied (0-3, 10-15, and 20-25 cm). For the first study (IE1), sediment was stirred to homogenize it before packing into centrifuge tubes for incubation. For the second study (IE2), sediment was introduced directly into glass incubation tubes by subcoreing. The second procedure greatly reduced disturbance to the sediment. Rates of CO_2 production were calculated from the concentrations of ΣCO_2 measured over up to 46 days.

In both studies, the values of R_c in the deeper intervals were about 10% of the surface values. This was consistent with

the field results, although the rates decreased more rapidly in the field. In all cases, the remineralization rates during the beginning of IE1 were much greater than those at the beginning of IE2. The sediment for IE1 was collected in February 84. The measured value of R_c in the surface sediment of the laboratory experiment (24×10^{-9} mol/L-sec) was much greater than the value of R_c observed in the field in another winter month, December 83 ($.62 \times 10^{-9}$). The sediment for IE2 was collected in August 85. The measured values of R_c in the surface sediment ($6.6\text{--}12 \times 10^{-9}$ mol/L-sec) were consistent with the field values from August 84 (7.5×10^{-9}). The ΣCO_2 results indicated that IE2 reproduced field conditions more accurately than IE1 did.

The isotopic results from the experiments strongly suggested that $\delta^{13}C\text{-}OC_{ox}$ in the surface sediments ($-17.8 \text{ o/oo} \pm 1.9 \text{ o/oo}$) was greater than $\delta^{13}C\text{-}SOC$ ($-20.6 \pm 0.2 \text{ o/oo}$). The magnitude of the observed fractionation was small enough that the observed values of $\delta^{13}C\text{-}\Sigma CO_2$ in the pore waters could be explained by fractionated oxidation coupled with the diffusion of carbonate ion from bottom water to pore water. The observed fractionation was most likely due to the multiple sources of organic carbon to coastal sediments. A study of the natural levels of radiocarbon in these sediments indicated that the carbon preserved in the sediments is approximately 30% terrestrial while the rest is from phytoplankton.

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ANALYSIS OF CERTAIN INVISCID FLOWS ON THE BETA PLANE

Boris Moro

An investigation of the properties of the solutions of the steady state inviscid quasigeostrophic vorticity equation in a rectangular basin was performed for various assumed functional relationships between potential vorticity and the streamfunction. All solutions that were found, which have slow interior flow and satisfy the Arnol'd-Blumen condition, are qualitatively similar to Fofonoff's inertial gyre. A new class of solutions with a small vortex near the boundary current is described. Such solutions are not stable under finite amplitude perturbations, but the vortices have life-time much longer than their characteristic time. The relationship between bottom friction and wind

forcing and the westward motion of vortices is established. It is shown that friction may act as a mechanism for conversion of kinetic energy of rotation into kinetic energy of translation. It is argued that friction may be among the causes of westward motion of the mesoscale eddies. It is also shown that the inertial boundary current may be much wider than in Fofonoff's model, due to the appearance of a countercurrent on its seaward side.

Several solutions describing steady general circulation in two-layer models are found. We discuss strongly baroclinic, long-living vortices and pure baroclinic mode of general circulation.

A simple approach to the numerical solution of some systems of nonlinear elliptic partial differential equations, depending on several parameters, is also described.

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ACOUSTIC MODE COHERENCE IN THE ARCTIC OCEAN

John J. Polcari

The dual issues of modal decomposition for tonal sound fields and the temporal coherence of the modal amplitudes are investigated for the case of the central Arctic sound channel at very low frequencies (15-80 Hz). A detailed study of the Arctic modal structure for these frequencies reveals the central role played by the strong Arctic surface duct. The performance of each of four different modal beamforming algorithms when applied to the vertical array deployed during the FRAM IV Arctic Acoustic Experiment is analyzed. A multiple beam (or decoupled beam) least squares processor produces the most acceptable results for Arctic conditions. The modal decomposition is sensitive to vertical array tilt caused by hydrodynamic drag; a technique for its estimation from the acoustic data is developed.

Tonal data taken from both the horizontal and vertical arrays deployed during FRAM IV is analyzed. Horizontal array results confirm the modal amplitudes generated from vertical array data. The rough surface scattering from the ice canopy places an upper limit of 40 Hz on efficient surface duct propagation. Attenuation measurements for the first mode show excellent agreement with predictions made for ice scattering using the method of small perturbations and experimental ice statistics. The high levels of coherence observed (0.95 to 0.99) show that tonal signal propagation in the Arctic channel

is essentially deterministic for time periods well in excess of one hour. The various modes may then be considered to maintain a constant phase relationship over time.

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LEAD AND CADMIUM GEOCHEMISTRY OF CORALS:
RECONSTRUCTION OF HISTORIC PERTURBATIONS
IN THE UPPER OCEAN

Glen T. Shen

Twentieth century trace element chronologies for the western North Atlantic, Pacific, and Indian Oceans have been reconstructed from annually-banded scleractinian corals. Elements analyzed include lead (4.60 nmol/mol Ca), cadmium (0.3-6 nmol/mol Ca), barium (4.6 μ mol/mol Ca), zinc (3.10 nmol/mol Ca), and vanadium (90.120 nmol/mol Ca). A rigorous preparative/cleaning protocol enabled removal of detrital, organic, and handling associated contaminants in five of seven coral genera studied. Prior to analysis, samples were dissolved and residual lattice bound metals (except Ba) non-selectively coprecipitated as dithiocarbamate chelates in the presence of a cobalt carrier. This procedure isolates metals of interest from the coral calcium matrix to allow more precise analysis by graphite furnace atomic absorption spectrophotometry. The cleaning techniques used also permitted determination of stable Pb isotopic distributions in a variety of corals. Samples analyzed by mass spectrometry were purified by anion exchange chromatography.

Measurements of lattice-bound Pb in sequential coral bands have revealed temporal changes in surface water Pb concentrations and Pb isotopic ratios. Perturbations are observable in all specimens studied, attesting to global augmentation of environmental Pb by industrialization. In the western North Atlantic, Pb perturbations have occurred in direct response to the American industrial revolution and the subsequent introduction and phasing-out of alkyl Pb additives in gasoline. Surface ocean conditions near Bermuda may be reliably reconstructed from the coral data via a lead distribution coefficient (KD) of 2.3 for the species *Dioloria striatosa*. Based on ^{210}Pb measurements, a similar distribution coefficient may be characteristic of corals in general. Surface Pb concentrations in the pre-industrial Sargasso Sea were about 15-20 pM. Concentrations rose to near 90 pM by 1923 as a result of metals manufacture and fossil fuel combustion. Beginning in the late 1940's, increased utilization of

lead gasoline eventually led to a peak concentration of 240 pM in 1971, representing an approximate 15-fold increase over background. Surface ocean concentrations are presently declining rapidly (128 pM in 1984) as a result of curtailed alkyl Pb usage. Lead isotopic shifts parallel the concentration record indicating that characteristic industrial and alkyl Pb source signatures have not changed appreciably in time. Industrial releases recorded in the Florida Straits reflect a weaker source and evidence of recirculated Pb (5-6 yrs old) from the North Atlantic subtropical gyre. An inferred background concentration of 38 pM suggests influence of shelf and/or resuspended inputs of Pb to waters overlying this coral reef.

In remote areas of the tropical and South Pacific and Indian Oceans, industrial signals are fainter and the corals studied much younger than their Atlantic counterparts; consequently, historic trends are more difficult to ascertain. Contemporary Pb concentrations implied by coral measurements (assuming $K_D=2.3$) are 40-50 pM for surface waters near Tutuila and Galapagos in the South Pacific, and 25-29 pM near Mauritius in the Indian Ocean. A single coral band from Fiji (1920 $\pm$ 5 yrs) suggests a pre-industrial surface water concentration of 16-19 pM Pb for the South Pacific. In view of actual surface water measurements (Flegal and Patterson, 1983) and the North Atlantic coral data, the past and present Pacific coral extrapolations may be slightly high (estimated minimum pre-industrial surface Pb concentration = 10 pM). This could be a result of small variations in K_D among different coral genera, or incorporation of diagenetic Pb by corals sampled in coastal environments.

Surface ocean Cd levels near Bermuda have also been enhanced by North American industrial activity. Three to four-fold peak increases over background occurred at ca. 1920 due to unexploited Cd-rich flue dusts originating from zinc production, and again near 1970 as a result of heightened metals production and waste incineration. Natural modulation of surface seawater Cd levels in the eastern Equatorial Pacific has also been measured in Galapagos Islands coral, *Pavona clavus*. Implied dissolved Cd concentrations over the past 20 years of 15.65 pM based on $K_D = 1.0$ closely resemble the observed range in adjacent surface waters. Close correlation of the coral Cd record to sea surface temperature and Southern Oscillation indices suggests a route to paleo-ENSO (El Niño Southern Oscillation) reconstruction.

Thus far, only Pb and Cd have demonstrated clear temporal variability associated with industrialization and/or natural

perturbations in ocean circulation. Distributions of Zn and V in the Sargasso Sea and Ba and ^{210}Pb in Florida Straits surface waters appear to have undergone little or no change over the past century. Addition of Cd and particularly Zn (+2 ionic radius only 80% that of Ca^{2+}) to the growing list of cations which appear to be indiscriminately precipitated by corals with respect to their seawater distributions, suggests a common incorporation mechanism. A thermodynamic basis is not evident since expected differences in chemical speciation favor widely varying K_p 's. More likely, the precipitation process is kinetically controlled within the supersaturated, possibly reducing micro-environment of the coral ectoderm.

Application of the coral Pb concentration and isotopic record of Bermuda to the ventilated thermocline model of Jenkins (1980) and Boyle et al. (1986) places important constraints on the geochemical transport of Pb in the oceans. Conservative models dominated by lateral ventilation on ^3H and ^3He -based time scales cannot account for observed distributions of Pb and ^{210}Pb simultaneously. More compelling, though, are model discrepancies from the vertical distribution of Pb isotopes reported in this thesis. The measured $^{206}/^{207}\text{Pb}$ profile below 600 m clearly requires mixing of ventilated Pb with Pb of more recent origin (ca. 1920-1965). Regeneration of surface-derived Pb in proportion to apparent oxygen utilization rates improves the model fit considerably. Beyond a 12% net recycling efficiency (balanced by a scavenging residence time of 70 yrs), however, the fit to the data cannot be further improved. Diapycnal mixing may constitute a secondary mechanism which forces deep water $^{206}/^{207}\text{Pb}$ ratios toward measured values by diminishing the influence of very recent (post-1965) Pb inputs. Alternatively, the possibility exists that Pb isotope fluxes exhibit mild spatial variability. Quantification of these variations along with source water Pb and ^{210}Pb concentration gradients will comprise the next step in model refinement.

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BORON ISOTOPE GEOCHEMISTRY

Arthur J. Spivack

An investigation of the major aspects of the boron isotope geochemical cycle was carried out. Particular emphasis was directed at developing a reproducible, high

precision method for the determination of boron isotope ratios in geologic materials and determining the processes that influence the boron isotope composition of seawater. Isotope ratios ($^{11}\text{B}/^{10}\text{B}$) are reported as per mil deviations ($\delta^{11}\text{B}$) from NBS SRM 951.

A method for the determination of the isotopic composition of boron by thermal ionization mass spectrometry of $\text{Cs}_2\text{B}_4\text{O}_7$ is described. The method is capable of producing isotope ratio analyses with a standard deviation of 0.12 o/oo. Procedures for the separation and chemical isolation of boron from silicates and aqueous solutions are also described. Careful attention has been paid to the analysis of blanks and other procedural artifacts.

Samples analyzed for boron content and isotopic composition included: seawater, unaltered mid-ocean ridge basalts (MORB), altered MORB (dredge and core samples), serpentinized peridotites, marine sediments, marine sedimentary pore waters, hydrothermally altered sediments, oceanic hydrothermal solutions, rainwater, river water and suspended sediments, island arc volcanics and a soil profile.

Atlantic and Pacific surface seawater and Pacific seawater collected from 2,500 meters have analytically indistinguishable $\delta^{11}\text{B}$ with an average of 39.52 o/oo. Unaltered MORB recovered from the East Pacific Rise (EPR) at 21°N and 13°N have boron contents of 0.39 ± 0.03 and 0.46 ± 0.03 ppm and $\delta^{11}\text{B}$ of -3.64 ± 0.36 o/oo and -2.24 ± 0.6 o/oo respectively.

Large scale boron exchange between seawater and the oceanic crust has been demonstrated. Oceanic hydrothermal solutions emanating from the seafloor at ten separate vent locations on the EPR at 21°N and between 10° and 13°N have boron concentrations variably enriched relative to seawater by 11 to 35 percent and have $\delta^{11}\text{B}$ between 29.95 ± 0.36 and 36.81 ± 0.36 o/oo. Based on mixing relationships, it is shown that in these systems boron was extracted from basalts with no resolvable isotopic fractionation (-5.6 ± 4.8 o/oo). High temperature water-rock ratios (W/R) based on boron concentrations are between 0.33 and 1.9 while lower temperature ($<150^\circ\text{C}$) W/R ratios are greater than ~310 for nine vents and greater than ~150 for the remaining vent. The maximum hydrothermal flux into the ocean is estimated to be between 0.43×10^9 and 1.3×10^9 moles/yr.

Basalts altered at low temperature (dredge and core samples) and serpentinized are variably enriched in boron. The boron content of altered whole rock basalt samples strongly correlates with $\delta^{18}\text{O}$ indicating that boron content varies with the degree of alteration. Altered basalts

(n=7) containing between 8.9 and 69 ppm of boron were analyzed for boron isotopic composition and have $\delta^{11}\text{B}$ from 0.06 ± 0.36 to 9.18 ± 0.36 o/oo. Serpentinized peridotites (n=4) with boron contents between 50 and 81 ppm have $\delta^{11}\text{B}$ of 8.25 ± 0.39 to 12.62 ± 0.36 o/oo. Based on model calculations W/R ratios in DSDP Hole 418A were greater than ~100. The flux of boron into the oceanic crust via low temperature alteration is estimated to be $\sim 1.3 \times 10^{10}$ moles/yr. Based on model calculations it is suggested that the maximal boron diffusive flux into the oceanic crust through sediments is 6.7×10^8 moles/yr with a $\delta^{11}\text{B}$ of ~43 o/oo.

Marine sediments contain two isotopically distinct boron fractions. There is a desorbable component, $\delta^{11}\text{B}$ from 13.9 ± 0.4 to 15.8 ± 0.5 o/oo, (n=6) and a non-desorbable component $\delta^{11}\text{B}$ from -4.28 ± 0.36 to 2.77 ± 0.36 o/oo. Based on adsorption experiments, an adsorption coefficient, K, for the adsorption of boron onto Mississippi River suspended sediments of 1.54 ± 0.05 was determined, with a fractionation factor, α , of 0.975 ± 0.003 . Empirical values of K based on the analysis of marine sediments varied between 3 and 4. The flux of boron adsorbed onto detrital sediments is estimated to be $\sim 9.2 \times 10^{10}$ moles/yr. Based on pore water analyses, adsorption experiments and comparative size fraction analyses (Mississippi suspended sediments vs Mississippi Delta sediments), there is no evidence of low temperature boron incorporation into detrital sediments. However, the high boron content of sediments from the Bauer Basin are interpreted as due to the incorporation of seawater boron in authigenic silicates. The $\delta^{11}\text{B}$ of the authigenic boron is estimated to be 1.5 ± 3 o/oo.

Sediments from DSDP Hole 477 (Guaymas Basin, Gulf of California) were analyzed. Hydrothermally altered sediments have variable boron concentrations ranging from depleted values of ~1 ppm to values similar to unaltered sediment, ~33 ppm. Recrystallized sediments have $\delta^{11}\text{B}$ which are more negative than unaltered sediments from the same core, as low as -8.99 ± 0.36 compared to ~ -1.4 o/oo.

Hydrothermal solutions (n=4) emanating through sediments in the Guaymas Basin have boron concentrations elevated by a factor of 3 to 4 over seawater. The $\delta^{11}\text{B}$ of the additional boron is estimated to be between 10 and 15 o/oo which is consistent with the fractionation observed in Hole 477 sediments.

Boron has been partially mobilized in an oxisol formed on a very coarse-grained granite. The profile is interpreted in terms of an easily weathered fraction and a refractory fraction. There is a small

isotopic offset, ~2.5 o/oo, between bed-rock and soil.

The concentration of boron in the tributaries of the Orinoco River and in a number of the world's larger rivers are relatively restricted with a flux weighted average of 460 nmol/kg. There is no correlation between boron concentration and either major ion chemistry or geology. Concentrations are, however, coincident with reported rain concentrations. It is concluded that riverine boron is dominated by atmospherically derived boron. Rain samples (n=5) have a large $\delta^{11}\text{B}$ range, 0.80 ± 0.53 to 34.99 ± 0.40 o/oo. River water (n=6) $\delta^{11}\text{B}$ are between 9.20 ± 0.43 and 14 ± 1.0 o/oo. It is suggested that rivers integrate continental rain and that the flux weighted average, 12.5 o/oo, may be equal to the average $\delta^{11}\text{B}$ of the flux into the atmosphere.

A limited number of volcanics from three island arcs were analyzed, Halmahera arc (n=4), Lesser Antilles arc (n=4) and Kermadec arc (n=1). The $\delta^{11}\text{B}$ of the Halmahera samples range from 0.93 ± 0.36 to 3.37 ± 0.36 o/oo, while the Lesser Antilles samples are between -5.25 ± 0.63 and -1.04 ± 0.36 o/oo and the Kermadec sample is 6.35 ± 0.36 o/oo.

There is no resolvable boron isotopic fractionation between estimated values for the mantle, average crust or total exogenous inventory. The boron isotopic composition of seawater is consistent with steady state models which either assume recycling of boron into the mantle or assume a closed exogenous system. The isotopic offset between seawater and the major boron reservoirs is a result of the isotopic fractionations associated with sea-floor alteration and/or net sediment boron incorporation.

Perturbations in the steady state seawater $\delta^{11}\text{B}$ are predicted to result from variations in the geochemical cycle (continental weathering and erosion rates). Variations in sea-floor spreading are not expected to perturb seawater $\delta^{11}\text{B}$, however, crustal alteration is expected to dampen perturbations.

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ACOUSTIC MONOPOLE IN A FLOATING ICE PLATE

Peter J. Stein

Transient elastic waves radiated from a monopole source in a floating ice plate are studied. The model consists of a homogeneous plate of ice bounded by a vacuum on one side, and an infinite half-space of water on the other. Although the intended

application is the analysis of signals from nearby ice cracking events in Arctic acoustic data, much of the material has application to the study of ice absorption, and thus reflectivity and long range propagation.

One theoretical area deals with the modes of propagation in the ice/water system; solutions are derived for arbitrary Poisson's ratio and include the effects of ice absorption. It is determined that only the flexural, longitudinal, and what I label the acoustic mode need be accounted for in the study of far-field sound radiation from ice fractures, since all other modes attenuate faster than 0.1 dB/m for ice 3 m thick. The acoustic mode specifies the radiation from the modes of propagation in the ice, which occur in addition to their plane-wave limits, as a result of spatial gradients imposed by a localized excitation. It is shown that the acoustic mode is the most important in terms of modelling Arctic ocean ambient noise.

Another theoretical area gives the solution for a monopole source in the ice. An analytical expression for the acoustic mode at low frequencies is derived. The radiated pressure in each mode is studied as a function of frequency, range, and source depth. The acoustic mode directivity is that of a dipole at least up to grazing angles of 40°, however, the dipole source strength is not as one expects for a monopole source near the free surface of a fluid half-space. Instead, it is maximum when near the ice surfaces and has a null which at low frequencies is 15% of the ice thickness below the ice midplane. The far-field flexural wave is important only close to the ice and would be undetectable in the Arctic data analyzed. The longitudinal wave may be important out to a range which depends on frequency and absorption, after which it exponentially decays.

Three ice events and one nearby explosive charge are interpreted. Events are located to within an accuracy of 25 m. Estimates from event and charge interpretations give values for the bulk dilatational wave speed of 3500 m/s, for the bulk shear wave speed of 1800 m/s, for the bulk dilatational wave absorption of 0.13 dB/m/kHz, and for the bulk shear wave absorption of 0.87 dB/m/kHz. The values of wave speeds are as expected, while those of absorption are respectively two and four times that of current empirical values.

No firm support or negation of the monopole source as a model for an ice event is given through plotting arrival amplitude versus range; many more events need to be analyzed before a firm conclu-

sion can be reached. Using a Gaussian volume velocity time function, equivalent compact monopole source volumes and depths are estimated for each of the ice events studied. However, it is not known how or if these can be related to the details of the event. For one Arctic ice event, a monopole source small compared to ice thickness, located in a homogeneous ice plate, is shown to be a poor model in that the relative arrival amplitudes of the modes are not correctly predicted.

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CENOZOIC GEOLOGY OF THE CONTINENTAL SLOPE AND RISE OFF WESTERN NOVA SCOTIA

Stephen A. Swift

The outer continental margin of Nova Scotia is divided by a diapir province, 40-110 km wide and ~1000km long, that trends subparallel to the shelf edge along the upper continental rise and slope. The growth pattern for a small region of this margin (61°-64°W) during the Late Cretaceous and Cenozoic was studied using seismic stratigraphy and well data. Structure maps show that a steep continental slope existed landward of the diapir province (~2200-3800 m water depth) from Early Cretaceous until Miocene time when onlapping upper rise sediments reduced the gradient. Shelf edge canyons were cut during the late Maestrichtian-early Paleocene, Eocene-Oligocene, and Pleistocene. Extensions of Tertiary canyons onto the slope are poorly defined, but small Paleocene fans of interbedded chalk and mudstone on the upper rise indicate that slope canyons existed at that time. Abyssal currents eroded the upper rise and smoothed relief on the continental slope in the Oligocene and middle(?) Miocene. In the Miocene, turbidites may have ponded on the upper rise landward of seafloor highs uplifted by salt ridges or pillows. Pliocene-Pleistocene sediments drape over pre-existing topography. At the beginning and end of the Pleistocene, turbidity currents, caused by delivery of large sediment loads to the shelf edge by glaciers, eroded the present canyon morphology.

The late Cenozoic section of the lower continental rise thins seaward from ~2 km near the diapir province and rests on Horizon A^u, a prominent unconformity eroded during the Oligocene by abyssal currents. The morphology of the lower rise is largely due to construction by down-slope deposits shed in the Miocene-Pliocene from uplift of the diapir prov-

ince. Abyssal currents episodically eroded sediment, but current controlled deposition formed only a thin (<300 m) deposit in the Pliocene(?). Uplift in the diapir province accelerated during the Pleistocene and olistostromes up to 300 m thick were shed onto the lower rise. In the latest Pleistocene, sediments transported down-slope by near-bottom processes accumulated west of a sharp boundary running near 62°30'W from 500 m seaward to the abyssal plain. To the east, hemipelagic sediments accumulated above 4300 m, while turbidity currents, originating in deep canyons to the east, and abyssal currents reworked sediments below 4300 m. A glacial sediment source and relict shelf morphology controlled sedimentation processes and, thus, the location of depocenters on the slope and rise.

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THE HILBERT-HANKEL TRANSFORM
AND ITS APPLICATION TO SHALLOW WATER
OCEAN ACOUSTICS

Michael S. Wengrovitz

In the shallow water acoustics problem, a time-harmonic source is placed in the ocean and a hydrophone records the acoustic pressure field as a function of range from the source. In this thesis, new techniques related to the synthetic generation, acquisition, and inversion of this data are developed.

A hybrid method for accurate shallow water synthetic data generation is presented. The method is based on computing the continuum portion of the field using the Hankel transform and computing the trapped portion analytically. In the related problem of extracting the reflection coefficient, it is shown that the inversion can be highly sensitive to errors in the Green's function estimate. This sensitivity can be eliminated by positioning the source and receiver above the invariant critical depth of the waveguide.

The theory of a new transform, referred to as the Hilbert-Hankel transform, is developed. Its consistency with the Hankel transform leads to an approximate real-part/imaginary-part sufficiency condition for acoustic fields. An efficient reconstruction method for obtaining the complex-valued acoustic field from a single quadrature component is developed and applied to synthetic and experimental data. The Hilbert-Hankel transform is a unilateral version of the Hankel transform and its application to this problem is

based on the outgoing nature of the acoustic field. The theory of this transform and its one-dimensional counterpart can be applied to a wide class of problems.

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* student