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A STUDY OF THE SEISMIC STRUCTURE OF UPPER OCEANIC CRUST
USING WIDE-ANGLE REFLECTIONS

by

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Submitted to the Department of Earth and Planetary Sciences,
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ABSTRACT

The lateral homogeneity of oceanic crust on the scale of a seismic experiment is a condition that most methods of seismic interpretation depend on. Whether this condition is in fact true is largely unknown and only recently have efforts been made to test this hypothesis. This thesis is part of that effort and is focussed on determining with as much resolution as possible the seismic structure of upper oceanic crust, i.e. Layer 1 and the uppermost part of Layer 2. This portion of the crust is of interest, because of the effect of the sediment-basement interface on the transmission and conversion of seismic energy, also because of the possibility of detecting lateral heterogeneities in upper Layer 2 caused by faulting, hydrothermal circulation etc. The data employed are a set of wide-angle reflections from oceanic crust 130 m.y. old in the western North Atlantic Ocean southwest of Bermuda. First, the sedimentary structure is determined by stacking the data along hyperbolae and interpreting the stacking velocities and two-way normal incidence travel-times for interval velocities. This method has not been applied to deep sea marine data before; it gives a more detailed velocity structure of the sediments than does a traditional study of the basement reflections' travel-times. Second, the same data are mapped into tau-p space in order to measure the velocity gradient in oceanic basement; unfortunately the scatter in the tau-p picks caused by the topography of the basement reflector combine with the properties of the tau-sum inversion to make such a measurement impossible. Third, the amplitudes of the basement reflections observed on three seismic lines are modelled by synthetic seismograms; each can be matched by velocity-depth models which contain a transition zone between the sediments and the basement. The different thicknesses of this transition zone near the three receivers is an indication that the top few hundred meters of Layer 2 are laterally heterogeneous on a scale of 3 to 8 km.

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Chapter 1

Introduction

Methods of interpreting the seismic structure of oceanic Layers 1 and 2 (Raitt, 1963) from wide-angle reflections are investigated in detail in this thesis. As technical and tectonic knowledge have increased, seismic experiments of increasing resolution and sophistication have been performed in order to investigate the structure and evolution of oceanic crust. The travel times of wide-angle reflections recorded on sonobuoys have been used extensively in the investigation of the velocity structure of Layer 1, yet in many regions our knowledge of the sediments' velocity structure is limited to an average value of their velocities (Houtz, 1980). In chapter 2 an analytic technique (Taner and Koehler, 1969) widely and successfully used on multi-channel data collected on continental shelves is adapted to data collected by an ocean-bottom hydrophone in the deep sea in order to resolve the velocity structure within Layer 1. Another question being addressed in marine seismology is the scale of lateral homogeneity of oceanic crust (Purdy, 1982). Lateral heterogeneity of the uppermost Layer 2 on the scale of a few km is examined by interpreting wide-angle reflections from the sediment-basement interface. In chapter 3 the reflections are mapped into tau-p space in order to interpret the velocity gradient in Layer 2. In chapter 4 the amplitudes of basement reflections are modelled in order to interpet the velocity structure of the sediment-basement interface.

An aim of seismic studies is to investigate the seismic velocity structure of the earth. The end result of many studies is a velocity-depth function which characterises the earth or a specific region of the earth, and an interpretation of this structure's relation to geophysical or geological data and processes. The methods of interpreting velocity structures from seismic data vary; most involve the travel-times of seismic waves (Kennett, 1977), and more recently their amplitudes have been used (Helmberger and Morris, 1970). In any case, some understanding or physical model of how energy propagates through the earth must exist in order to model or invert seismic data. Additionally, one must be able to implement these models mathematically and numerically. Many geologic structures are so complicated that either adequate physical models do not exist or we do not yet have the ability to implement them.

While geologists and geophysicists have been studying the structure of continental crust for at least one hundred years, the structure of oceanic crust has only been studied in the last few decades and is comparatively poorly known. Technological advances coupled with military interest in the ocean basins led to many marine seismic refraction experiments being performed in the 1950's (e.g. Ewing et al., 1952; Katz and Ewing, 1956; Hersey et al., 1959). Large shot spacing and the interpretation of the travel-times in terms of homogeneous layers resulted in a view of oceanic crust which seemed to be uniform in all ocean basins (Raitt, 1964). Four layers were discerned; the highest standard deviation of the velocities occur in Layer 2. In the 1960's widespread use of disposable sonobuoys (Houtz, Ewing and LePichon, 1968) led to increased detail measured in the structure of Layer 1; these interpretations were based on the travel-times of wide-angle reflections from reflectors within Layer 1 and the top of Layer 2.

Since the formulation of the plate tectonics paradigm for the earth sciences, studies of oceanic crust have largely been directed towards investigating the implications of plate tectonics. Experiments to determine the structure of plate boundaries, how crust ages once it has been formed and whether the spreading center creates crust of uniform structure both in time and space have all been carried out in the past few decades. Once a map (Fig. 1.1) of the age of oceanic crust and its present and fossil plate boundaries had been constructed, it became apparent that the seismic refraction experiments of the 1950's had been performed at random with respect to age and direction of structure and over several features which plate tectonics predicts should have different structures. Thus our picture of oceanic crustal structure is highly generalised and averaged.

Seismic experiments with increasing resolution are now being carried out. The four layer model of oceanic crust has been subdivided into many more layers (Houtz and Ewing, 1976) and the ability to model the amplitudes of seismic arrivals has resulted in a model of oceanic crust based on velocity gradients rather than single velocity layers. The question of lateral heterogeneity, however, remains unresolved. The scale of these heterogeneities may occur over a thousand kilometers as in the aging of Layer 2 (Houtz and Ewing, 1976) and may well occur over the space of a few km (Spudich and Orcutt, 1980; Purdy and Rohr, 1979). This latter scale is important in the interpretation of seismic data since most inversion and modelling methods assume that the oceanic crust covered by the experiment is homogeneous. The difficulty in measuring heterogeneities, if they exist, lies in the resolution of the seismic energy (wavelengths used are typically 0.5 to 1.0 km) and the lack of ablilty to model waves travelling through heterogeneous media.

Other developments in seismology include the examination of the data in spaces other than the time-distance space. Seismic data have been mapped into amplitude-frequency space (Dorman et al., 1960), stacking velocity-two-way normal incidence travel-time space (Taner and Koehler, 1969) and tau-p space (Stoffa et al., 1980) for additional insights into the velocity structure through which the seismic energy has travelled.

*

This thesis is part of an experiment designed to measure the lateral homogeneity of oceanic crust formed at a spreading center. Here the focus is on the resolution of the structure of upper oceanic crust, Layers 1 and 2. Measurements of deeper crust are limited by knowledge of the structure of the crust that lies above it; variability in the amplitides or travel-times of refractions from Layer 3 or Moho could be caused by variability in the structure of Layer 1 or Layer 2. The experiment was carefully located south of a fracture zone on crust ~140 my old (Fig. 1.1) which had been formed during an episode of constant velocity spreading at ~1.0 cm/yr (Schouten and Klitgord, 1982). Eight ocean-bottom hydrophones were deployed in a 10 x 15 km cross-shaped pattern and a variety of seismic experiments were performed (Purdy, 1982b). In each of the three following chapters the wide-angle reflections produced by a 0.66L (40 in^3) airgun are interpreted by different methods, and these methods' properties and ability to resolve seismic structure are discussed.

In the second chapter the structure of Layer 1 is resolved by mapping wide-angle reflections from sedimentary reflectors and the sediment-basement interface into stacking velocity-two way normal incidence travel-time. Working in this domain has been of great help to exploration seismologists interpreting data from continental shelves, but has not previously been used to investigate the velocity structure of deep-sea sediments. Here, instead of using just the semblance function, the stack and semblance functions are combined in the manner suggested by Stoffa et al. (1980) for mapping data into tau-p space. In this region sonobuoy studies (Houtz, 1980) have measured an average velocity of sound in the sediments but have not been able to resolve the seismic structure associated with reflectors A^c, A* and Beta. These reflectors are observed on the normal incidence seismic reflection records (Tucholke, 1981) and elsewhere are associated with increases in seismic velocity (Houtz, LePichon, and Ewing, 1968).

In the third chapter the data are mapped into tau-p space (Stoffa et al., 1980) in order to measure the velocity gradient in the uppermost Layer 2. Here, the mapping is designed to preserve the amplitude of the stack in the most coherent subarray in the final tau-p map so that postcritical events can be distinguished from precritical events. In tau-p space one can distinguish seismic arrivals reflecting off a sharp velocity discontinuity from arrivals which have turned in a velocity gradient by the positive curvature of the former and the negative curvature of the latter. Once the arrivals have been identified, they can be inverted for a velocity-depth function.

Chapter 4 investigates the structure of the uppermost Layer 2 by modelling the amplitudes of reflections from the sediment-basement interface. Igneous crust (Layers 2 and 3) is most often interpreted from seismic refractions; unfortunately refractions from the uppermost Layer 2 are rarely observed except by instruments, such as borehole seismometers (Stephen, 1980), located within or below this structure. Earlier arrivals tend to interfere with the first refracted arrivals (Stephen, 1982). Alternatively, the velocity structure in the uppermost Layer 2 can be inferred from refractions which have passed through it deeper into the crust (Ewing and Purdy, 1982). Wide-angle reflections from the interface between Layer 1 and 2 respond to structure approximately a wavelength in scale at