DETAILED STRUCTURAL INTERPRETATIONS OF THE PACIFIC OCEANIC
CRUST USING ASPER AND OCEAN-BOTTOM SEISMOMETER METHODS

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF
THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN GEOLOGY AND GEOPHYSICS
DECEMBER 1972

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ABSTRACT

The ASPER (Airgun-Sonobuoy-Precision Echo Recorder) seismic refraction exploration technique has provided an inexpensive means of obtaining numerous crustal velocity determinations with greater structural resolution than conventional two-ship explosion methods. In conjunction with ocean bottom seismometers, precise data has also been obtained with the added advantage of sensitivity to shear wave arrivals. Analysis of 66 seismic refraction stations obtained in the central and southwest Pacific Ocean from 1968 to 1971 demonstrate the improvement in geologic interpretations provided by the detailed velocity information. The South Fiji Basin and East Caroline Basins have more complex crustal and upper mantle structure than was identified by previous explosion studies, and present a distinctly different type of crust than is found on the lithospheric plates that formed at mid-ocean spreading centers. However, on the Ontong Java and Manihiki Plateaus, identification of previously unresolved consistency in the upper crust has permitted correlation and geologic interpretation of these regions. Similarly, ASPER stations have shown the crustal section to be more uniform across the Murray Fracture Zone than previously thought. The combination of ASPER and OBS data on the continental rise off California has produced one of the most detailed oceanic crustal interpretations yet reported, including both shear and compressional velocity
structure. These data have prompted additional speculation on the geology of the oceanic crust including the hypothesis that regional lithospheric fabric resulting from slight petrologic variations in essentially isotropic source material along spreading mid-ocean ridges, as opposed to preferred orientation of anisotropic crystals in the mantle, may be the cause of mantle velocity anisotropy.
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INTRODUCTION

The revolutionary theory of sea-floor spreading, and its implications regarding the understanding of the processes of marine geotectonics, has placed new emphasis on the need for increasingly precise measurement of the geophysical parameters of the earth. Geologic and geophysical evidence supporting the concept of sea-floor spreading and demonstrating the results of the tectonic processes is voluminous. However, to refine the theory we must better understand its mechanics. Paramount to this understanding, is the need of precise determination of the structure of the lithosphere and its evolution through crustal genesis, spreading, and ultimate destruction. In particular, it is no longer adequate, for the determination of crustal structure using seismic refraction techniques, to estimate crustal thickness and a velocity structure constrained to two or three layers and averaged over 70 or 80 km of ocean. This paper will demonstrate how better data can be obtained, and will show that they can add new precision to geologic interpretations based on marine seismic refraction methods.

Interpretations of 66 modern seismic refraction stations carried out in the Pacific Ocean are presented here (see chapter on RESULTS). They not only augment the many crustal velocity structure models that already have been reported for the Pacific (see McConnel and others, 1963, and Shor and others, 1970, for a summary), but also demonstrate seismic
refraction measurement techniques which yield potentially more detailed interpretations than are possible with conventional two-ship explosion seismic procedures. This work has approached the requirement for more precise refraction velocity determinations through development of measurement and interpretation methods that allow delineation of small-scale crustal structure. The use of ocean-bottom seismometers for a portion of the work has also augmented the precision of crustal interpretation through analysis of shear wave arrivals for determination of the Poisson's Ratio of the various layers.

As is often the case, the improved data presented here have led to conclusions that not only have served to increase the understanding of some aspects of oceanic crustal geology, but also have raised new problems concerning other aspects of this area of study.

A significant offshoot of these studies has been the refinement of observational techniques so that a single ship can make seismic refraction measurements of crustal structure as deep as the Mohorovicic Discontinuity, concurrent but without interference with other shipboard research. These inexpensive and convenient measurements should, therefore, result in an appreciable increase both in quality and in quantity of marine crustal seismic refraction investigations.
DEVELOPMENT OF MARINE SEISMIC REFRACTION METHODS

After the pioneering work of Ewing and others (1950) in the Atlantic, the first-reported seismic refraction studies in the Pacific were made by Raitt (1956). These early studies were conducted using two ships; one ship deploying one or more hydrophones to receive the signals, the other ship detonating explosive charges along lines ranging out to 180 km from the receiver. The first efforts in the Atlantic, by Ewing and his co-workers, showed a crust composed of only one interface with a velocity of 7.58 km/sec beneath the sediments. Workers in the Atlantic later reported a two-layer crust, with a layer of about 6.5 km/sec velocity and 3.5 km thickness between the sediments and the Moho with a velocity of about 7.9 km/sec (Officer and others, 1952; Hersey and others, 1952; Ewing and others, 1954). In the case of Raitt's work in the Pacific, a three-layer crust with the sediment underlain by an approximately 5.2 km/sec layer of 1.6 km thickness, overlying a 6.7 km/sec layer with a thickness averaging 5.1 km, was measured. The 4.5-5 km/sec upper layer, first detected in the Pacific because of its greater thickness, was later found in the Atlantic (Ewing and others, 1959).

Since that time, although equipment and interpretive techniques employed in marine refraction have gradually improved, the observational procedures have generally evolved with little major change from the early work. The
vast majority of all measurements continue to be made with two ships, usually alternating the work of shooting explosives and listening for seismic arrivals. Consequently, the data from these experiments have improved, but still generally depict simple and fairly consistent crustal structure (Shor and others, 1970). This paper shows that many of these simplified models are the consequence of the measurement technique, and often are not representative of the actual geologic situation.

LIMITATIONS OF CONVENTIONAL REFRACTION STUDIES

There are several factors which limit the improvement of marine seismic results based on conventional two-ship explosion refraction techniques. Although these factors are all mostly interrelated, they can be individually identified as follows:

(1) The necessary use of over-simplified models. A fundamental problem with refraction interpretive techniques is the generally assumed property of plane, dipping, homogeneous layers. In an attempt to circumvent this problem, analysis of velocity anisotropy (Raitt and others, 1969; Morris and others, 1969; Morris, 1969) and time-term methods (Scheidegger and Willmore, 1957; Willmore and Bancroft, 1960) have been employed with encouraging success. However, both approaches are extremely time-consuming, require more elaborate field efforts than conventional
studies, and have been used primarily to resolve only Moho velocity and depth. Furthermore, the delay time method has seldom been used at sea. Since practically all previous reliable oceanic work has been based on first-arrival information, seismic lines have had to be reversed over distances approaching 70 to 80 km. The ensuing models are therefore in reality a crude averaging of a 70- to 80-km section of crust into the required plane dipping layers. Consequently, even moderately detailed structure is not resolved. Because of this structural insensitivity, most seismic lines have been aligned, where possible, parallel to structural trends so as to facilitate interpretation of the data. The most informative way to study geology is, of course, transverse to the strike, not parallel to it. Because of their interpretative peculiarities, seismic refraction studies are the only discipline in exploration geology and geophysics that, unfortunately, often requires work parallel to strike.

(2) Detection of thin layers. The interpretation of the thin oceanic crust (Fig. 1) presents a second difficulty to exploration seismic refraction, especially as compared with similar work on the continents. The predominant Layer 3 (Raitt and others, 1963) generally appears as a first arrival on a typical travel-time plot for ranges spanning about 30 km. Layer 2, the "basaltic layer," usually appears for 5 km or less as a first arrival from the short-range close-in shots. Other arrivals are seen
Figure 1. Average Pacific Ocean basin crustal velocity structure from ASPER (Sutton and others, 1971) and conventional explosion (Shor and others, 1970) stations. Note the increased resolution of the average ASPER station, particularly the widespread 7.47 km/sec layer, and the less commonly encountered 6.00 km/sec layer, both of which are not delineated by the explosion studies.
PACIFIC BASIN
CRUSTAL VELOCITY STRUCTURE

AFTER SUTTON AND OTHERS (1971)

0 km

KM

1.5

2.08

2.10

4.46

5.15

6.00

6.74

5.15

7.47

6.82

8.28

8.15

*OCCASIONALLY DETECTED

AFTER SHOR AND OTHERS (1970)
intermittently as second arrivals. A deep layer, as much as 2 km thick but located, for instance, between the 6.8 km/sec layer and the mantle, and with an intermediate velocity, would be seen as a first arrival for only a very few kilometers. The layer would, therefore, generally not be identified by explosion studies. In effect, then, if any relatively thin layers occur in the oceanic crust, they will tend to not be represented by first arrivals on a travel-time plot long enough to be identified and incorporated in the ensuing models.

(3) Density of data. This problem is related to the thin layers, and to the use of explosions as signal sources. Although the explosions yield energy over a wide frequency band, the higher frequency signals are quickly attenuated in the earth. At the shot-to-receiver ranges necessary to detect oceanic crustal refractions, it has been the writer's experience that the predominant arrivals are in the frequency range of about 7 to 20 Hz, with the greatest signal amplitudes at frequencies around 10 Hz. At these frequencies, the various refraction arrivals from the oceanic crust will all arrive within a very few cycles of the first arrival, and consequently are very difficult to distinguish.

Additional complications are introduced by the logistic problems involved in the use of explosives. Aside from time delay incurred in physically preparing each charge, there is also the time delay to permit sound reverberations in the water to subside sufficiently between explosions to enable
the receiver to distinguish low-level refracted ground arrivals. The resultant minimum shot spacing while underway limits the data points normally obtainable on a seismic shooting traverse, and as a consequence often means that the points along some sections of the travel time plots are insufficient to delineate thin crustal layers. The wide spacing between shots (in practice, this spacing is usually at least 2 km at critical ranges) also makes correlation of various phases arriving in the wave trains of successive shots very difficult.

(4) **Effect of the oceanic environment.** Near the surface, the ocean is a noisy environment because of water waves and faunal noise. Porpoises, shrimp, squid, and other marine life seem to be attracted to hydrophones dangling in the water and they are a major source of background noise. However, under any but ideal weather conditions, water-wave and wind-induced noises are the over-riding factors, and they will totally obliterate seismic signals under poor weather conditions. The common dependence on hydrophones suspended within a few hundred feet of the ocean surface as seismic receivers is an undesirable recording technique.

Moreover, near-surface phones will drift with the ocean current. Incoming signals, therefore, are radiated back up through a constantly changing bottom. If bathymetric or structural relief is great, as is often the case in geologically interesting areas, the drifting receiver will introduce scatter and inaccuracy to the data. If the
hydrophone is suspended from a ship or large surface buoy, this problem can be further compounded by the increased drift caused by the effect of wind on the large floating object. This wind-set will also drag the hydrophone through the water—and with the ship or surface buoy acting like a sail—cause an increase in background noise.

(5) Usefulness of hydrophones. Hydrophones have a fundamental limitation in that they do not, by themselves, yield the particle motion information that is ordinarily obtainable on land from three component seismometers. It has been the ability to differentiate compressional and shear arrivals, and the ability to more clearly identify arriving seismic phases by analysis of particle motion, that has enabled some of the more definitive seismic studies to be done on the continents.

Although all the aforementioned problems have been alleviated by either the ASPER (Airgun-Sonobuoy-Precision Echo Recorder, to be described later in this paper) technique, ocean-bottom seismometers, or combinations thereof, these tools have each largely overcome some of the problems. In brief, the ASPER method shortens to less than 50 km the shot-to-receiver ranges needed to obtain sufficient data for detailed complete crustal interpretations through the use of greatly enhanced second arrivals and tremendous data density. The ocean-bottom seismometer (OBS) enables the user to have a sensitive three-component geophone system at a fixed point on the relatively noise-free ocean bottom.
THE NEED FOR MORE DETAILED CRUSTAL STUDIES

Before now, most oceanic seismic investigations have been content with determining crustal thickness and depicting variations of a simplified crust (Raitt and others, 1963; Shor and others, 1970) composed of a sediment layer underlain by two rock layers, the upper "Layer 2" or "basaltic layer" and the lower "Layer 3" or "oceanic layer," underlain by Layer 4, the uppermost mantle (Fig. 1). This structure is often considered to be fairly continuous and essentially universal in the ocean basins.

The actual situation, however, is more complex, Sutton and others (1971) and Maynard (1970) have reported that an additional basal crustal layer, with a thickness averaging 3.1 km and a velocity averaging 7.4 km/sec, exists under much of the Pacific basin. The 21 stations, mostly observed and interpreted by this author, and described in the paper by Sutton and others (1971) yield an average crustal column (Fig. 1) quite unlike that by Shor and others (1970). Much of the difference in these average crustal sections (including the increased crustal thickness in Sutton's column) can be attributed to second arrivals revealed by the ASPER technique that were missed in the earlier explosion studies used in the model of Shor and others.

The detail in the Sutton column still needs to be refined. Additional layers, although generally not as
consistent as the 7.4 km/sec layer, have been defined using the ASPER and OBS instruments and will be reported later in this dissertation.

This increasing resolution is vital to the identification, geologically and petrologically, of the layering in the crust. To understand sea-floor spreading, it is imperative that this layering be traced from its formation through its transport across the plates to its destruction in the subduction zones. It is necessary that structure within the crust be delineated well enough to see changes in layer characteristics across plate boundaries, at aseismic ridges, across bathymetric relief, and so forth. Much of the surficial crustal effect of sea-floor spreading has been resolved. What occurs within the underlying crust and upper mantle must now be determined in order to resolve the mechanics of spreading.

THE PURPOSES OF THIS DISSERTATION

This dissertation describes new observational data and interpretive techniques that have yielded more definitive crustal models.

The crustal models presented here are from many different physiographic regions within the Pacific. The sections of crust will be considered separately within each region to evaluate geologic trends, and then compared
between the regions to try to ascertain the overall characteristics of each area, and how regional similarities and contrasts may reflect on the origins of the various portions of the Pacific Ocean basin.

The most detailed crustal models, from data obtained off the coast of California where ASPER was used in conjunction with OBS techniques, will be used to speculate on the geology of the crust. This crustal section off California combines both compressional and shear velocity structures to obtain possibly the most complete oceanic crustal interpretations yet reported.

EXPERIMENTAL TECHNIQUES

The experimental techniques used to collect the data for this paper, although still evolving, are described below. More recent innovations, as well as projected experiments related to these studies, are described in later chapters.

ASPER

The ASPER method is an outgrowth of wide-angle reflection and refraction experiments using sonobuoys and repetitive sound sources that has been reported by other authors (Houtz and Ewing, 1963; Houtz and others, 1968; Le Pichon and others, 1968). The Hawaii Institute of Geophysics first used sonobuoys in conjunction with a 7000-joule sparker for wide-angle reflection and refraction studies.
on the Ontong Java Plateau in 1967 (Maynard, Ph.D. thesis in preparation). In late 1968 the system was upgraded with a forty-cubic-inch airgun and installed on the R/V MAHI, after which the first successful ASPER runs were made in the Central Pacific Basin.

The system employed on the MAHI consisted of a forty-cubic-inch airgun fired at a ten-second repetition rate, U. S. military SSQ41A sonobuoys, and a military ARR52 sonobuoy receiver with commercially supplied directional antennas and antenna preamplifiers. The received signal was processed by splitting it into three channels which were separately filtered and amplified (Fig. 2). These processed signals were then recombined, clipped, half-wave rectified, and printed on an Alpine continuous wet paper seismic recorder sweeping once every 10 seconds.

The separate signal processing of the three channels is designed to individually enhance the three types of data (each with a different signal frequency spectrum) necessary for analysis of the ASPER record (Fig. 3). The water wave channel passband is used exclusively for shot-to-receiver distance control. Experience has shown that the signal received from the air gun and sparker through direct (D) and reflected (R1, R2, etc.) pure water paths is concentrated in the 500-1500 Hz frequency range.

The intermediate frequency passband is particularly useful for receiving reflections from layers within the sediment and uppermost crust. These signals have a
Figure 2. Block diagram of ASPER (Airgun-Sonobuoy-Precision Echo Recorder) signal processing system. Filter settings are varied according to signal source, variations in geology, and the peculiar response characteristics of individual sonobuoys. The settings shown are, however, typical.
Directional Antenna

Ant. Preamp → Receiver → Filter (500-1500 Hz) → Amp → Filter (500-1500 Hz)

Intermediate Frequency Channel

Filter (30-60 Hz) → Amp → Filter (30-60 Hz) → Combiner → Clipper → 1.4 v p/p

Low Frequency Channel

Filter (15-30 Hz) → Amp → Filter (15-30 Hz)

Tape Recorder

ASPER BLOCK DIAGRAM

Continuous Recorder
Prints half wave only.
concentration of energy in the 30-60 Hz range for reflections from the uppermost crust, and are emphasized during the first few minutes of the ASPER run to enhance the reflection hyperbola curves, labeled RIA, R1B in Figure 3. If wide-angle reflection data from the sediment column is of primary importance at any particular ASPER station, energy in the 50-100 Hz range is of predominant interest, and the intermediate passband filter would be set to emphasize that energy.

During an ASPER traverse, after the ship has reached sound-source-to-sonobuoy ranges where the refraction arrivals (G1, G2, G3, etc.) are expected to be observed, the gain of the intermediate channel is progressively reduced and the low-frequency (10-35 Hz) gain is increased. The recombined, or mixed-frequency signal gain is kept at a level just high enough so that background noise is slightly above 1.4 volts peak-to-peak, and therefore the entire received signal is clipped. The signal-to-noise (S/N) amplitude ratio of ground-refracted arrivals (G arrivals) is generally close to or less than unity because of the long ranges at which the relatively low-power airgun source is used. Reducing all the incoming signals and noise to the same amplitude by clipping, has the effect of discriminating the seismic signals from the background of random noise by visual phase correlation on the continuous record.

The reliance on phase, rather than amplitude, correlation is the basis of the ASPER method. A sample
Figure 3. Ray-trace diagram showing paths of various arrivals through a typical oceanic section, and the resultant travel-time plot. To simplify the travel-time plot reflections from the 1.5 km/sec (sediments) and 3.6 km/sec layers, as well as refractions from the 1.5 km/sec, 3.6 km/sec, and 4.9 km/sec layers, are omitted.
record is shown in Figure 4. The reader will find a
detailed description of the various arrivals on this record
prepared by this author for the paper by Sutton and others
(1971). Also, the crustal model derived from Figure 4 was
used as the basis for the theoretical travel-time plot in
Figure 3, which therefore illustrates the various arrivals
in the actual record (Fig. 4).

Most of the ASPER stations described in this paper were
made using the instruments on the R/V MAHI. The data from
1971, however, was collected aboard the R/V KANA KEOKI,
although with virtually the same system as was on the MAHI.
However, improvements to the KANA KEOKI included a maximum
usable airgun size of 300 cubic inches, which significantly
increased the power of the signal source. The height of the
ship's receiving antennas was also increased from 65 to 81
feet, which slightly increased the possible range at which
the transmitting sonobuoy can be received. In addition,
the data were also recorded in FM form on magnetic tape as
well as on the paper record, providing a capability for
laboratory playback of selected records. Some modifications
to the sonobuoys were also attempted and are described later
as part of Recent Innovations.

Advantages of the ASPER technique. The greatest single
advantage of the ASPER method is the multitude of arrivals
and information that can be obtained from one record.
Normally an ASPER run is made at a ship's speed of about
Figure 4. Sample ASPER record (station M, 1969, Central Pacific Basin). This section was originally presented in Sutton and others (1971), where it is completely described. The interpretation of M was used as the basis for Figure 3, so this observed record (Fig. 4) can be compared to the preceding theoretical travel-time plot and ray tracings (Fig. 3).
7 knots, with the airgun firing every 10 seconds. This results in one shot occurring about every 35 m, compared to conventional explosion refraction studies where shots are generally spaced at intervals greater than 1 km at short ranges, and at long ranges are typically separated by intervals of at least 5 km.

The high data density obtained from the ASPER work is readily phase-correlated (as was discussed earlier), so that low-level second and later arrivals, masked in explosion studies, can often be delineated. This delineation of second arrivals provides the opportunity to use a variety of interpretive methods, including the well-known conventional analysis of the slopes and zero-time intercepts of the refracted arrivals (for descriptions of this method see Ewing and others, 1939; Nettleton, 1940; Dobrin, 1960; Grant and West, 1965), wide-angle reflection analysis of the $t^2 - x^2$ method (see Durbaum, 1954; Dix, 1955; Le Pichon and others, 1968), and the critical-angle reflection step-out procedure of Sutton (1971), all applicable to the same record. The capability of analyzing a single set of data by these different techniques gives versatility to the interpretation, and can greatly enhance the reliability of the resultant crustal model.

Careful use of the second arrival information also permits calculation of complete crustal sections down to the Mohorovicic Discontinuity, even from records where shot-to-receiver ranges are less than 35 km. These
short-range stations are most valuable for work in areas of complex geologic structure where longer ranges would entail the averaging of more structure into the final model. A good example of the effects of this averaging is contained in a later discussion of the South Fiji Basin.

Finally, the ASPER stations are inexpensive compared to conventional explosion seismic studies. The expendable sonobuoys are low priced, a second ship is not required, explosives are unnecessary, and the stations can be made without interference to and at the same time as other geophysical profiling measurements.

Disadvantages of the ASPER technique. The only recurring disadvantages of ASPER refraction studies are the constraints of the relatively small sound-source and the line-of-sight range limits on the commonly used high frequency (around 170 MHz) sonobuoy radio transmitters. The energy output of the airgun is not always sufficient to penetrate the deep crust and reach sufficient range to delineate refractions from the Moho and other deep interfaces. On the other hand, useful seismic signals are sometimes still arriving even after the ship has moved beyond the effective radio range of the sonobuoy, thereby terminating the run. Both these problems are presently near solution; the first by using larger air guns, and the second by modifications to the buoy transmitter and the shipboard receiving system to augment the buoy transmission range.
Recent innovations in the ASPER technique. The signal source limitations inherent in the ASPER method are being solved primarily by a brute-force approach involving simply obtaining more and larger air guns. No other relatively inexpensive signal source has yet been found to efficiently produce large, low-frequency, repetitive pulses in the water.

The problem of increasing the radio transmission range of the buoys, however, has had a long history of experimentation with widely varying degrees of success. In order to help other researchers avoid the same series of unsatisfactory experiments, the attempts to augment the buoy radio range are recounted here.

After the shipboard receiving system was carefully adjusted so as to utilize its full range potential of about 35 km, emphasis was placed on physically elevating either one or both receiving and transmitting antennas. This added elevation serves to increase the distance to the rf horizon and overcomes the line-of-sight limitation. In 1968, several buoys were modified with some success by raising the transmitting antenna about 100 feet using a helium-filled balloon, which extended the useful range of the buoy to over 50 km. The modification was not continued routinely, however, because the construction of each of the expendable buoy/balloon units was very laborious, and because the method could be used only during very calm weather with virtually no wind.
In 1970 several attempts were also made to fly aerodynamically shaped balloons above the ship, thereby raising the receiving antenna up to 500 feet above the water. Two variations of this system were tried: one that sent the antenna-received signal by coaxial wire down to the ship, and a second that received, frequency-shifted, and retransmitted the data down to the ship. All attempts using these approaches failed due to problems associated with mooring balloons to the moving ship.

In 1971 large, yet expendable, spar buoys that lifted the entire buoy electronics package around 20 feet above the water were also tried. Successful records were made, but no appreciable increase in radio range was gained. Apparently part of the range of the unmodified buoys is due to a channeling effect along the ocean surface, the benefit of which was lost at the 20-foot elevation, thus effectively cancelling any theoretical increase in range.

Also in 1971 a commercially available sonobuoy (Aquatronics Corporation, Dallas, Texas) was tested. This buoy transmitted at a lower carrier frequency of around 80 MHZ, and it was hoped that this lower frequency would be less limited by radio line-of-sight constraints and could be received at a greater distance than the 170 MHZ military buoys. These buoys were found to yield useful data at ranges approaching 50 km, but were impractical due to their increased expense as compared to the military versions.
Attempts to design a modification of the military buoy transmitter to the lower carrier frequency proved to be complex and inefficient.

In early 1972 a commercially available transmitter booster module, which would increase the military buoy output from about 1 watt to over 5 watts, was tested. On the first run (SB 147, IDOE Nazca Plate) this buoy yielded useful data to a range of almost 80 km (Hussong and others, 1972; Hussong, 1972b). Although four later attempts to duplicate this experiment resulted—because of attendant electronic problems—in only one other long-range run, it does appear that this simple procedure of greatly increasing transmitter output power, when made electronically reliable, will alleviate the limited-range problem of the ASPER and other sonobuoy-based work. The solution of this range problem would permit Pn signals to be well established as clear first arrivals (at ranges on the order of 80 km), and thus make practical even single-ship anisotropy studies, which are dependent on precise first-break identification.

EXPLOSION REFRACTION STUDIES USING SONOBUOYS

Military sonobuoys are now used extensively by the Hawaii Institute of Geophysics for explosion seismic studies. In many cases ASPER runs have been extended with explosives after refracted signals from the air gun source have been lost. In these cases the arrivals are recorded as individual
wiggly-line traces.

Sonobuoys are also used in conventional two-ship explosion refraction experiments by HIG. The buoys are placed sufficiently far from the recording vessel to be beyond the region influenced by noise from the ship. More importantly, a widely spaced array of buoys can be deployed, producing in effect several different recording points. The use of arrays of buoys greatly improves the usefulness of the data by providing several receiving points for each shot and improving the accuracy of the travel-time determinations through cross-array signal correlation. Moreover, correlation across the array allows picking of low-level signals that might be missed in a single receiver trace (Husson, 1972b).

The use of sonobuoys as receivers also releases the listening ship for continuation of other work, such as coring, dredging, etc., at distances far enough from the buoys so that there is no interference from these noise-generating operations to inhibit the reception of seismic signals.

The only disadvantages in the use of sonobuoys for two-ship work are (1) the necessity to modify large numbers of buoys, primarily to increase the life expectancy of the instrument by adding batteries, and (2) the ship-time consuming deployment and retrieval of the buoy arrays.
OCEAN-BOTTOM SEISMOMETERS

Two types of ocean-bottom seismometers (OBS) were used for the collection of the data reported on in this dissertation.

In July 1969, a series of four explosion seismic lines were shot using the Columbia OBS located in 3900 m of water on the continental rise off the California coast north of San Francisco. This instrument contains a three-component, short-period seismometer with a matched coil hydrophone, a three-component, long-period seismometer with a matched crystal hydrophone, and accessory temperature, current, and tidal sensors (for a complete description see Sutton and others, 1965). For our work, data from the short-period geophones and the coil hydrophone were used. The OBS signals are carried by a submarine cable to a land recording site at Pt. Arenas, California. Quick-look strip chart recorders as well as magnetic tape recorders were used to store the data.

During Project Duet, a cooperative seismic refraction/anisotropy experiment carried out by HIG's R/V MAHI and the R/V VITIAZ from the Soviet Academy of Science in Moscow in November-December 1970, Russian-built OBS's were used, supplemented by HIG sonobuoys. The Soviet OBS is also a three-component, short-period unit, but, unlike the Columbia OBS, it had no hydrophone. The instrument was tethered to a surface buoy for deployment and retrieval. The data were recorded in analog form, on magnetic tape, in the bottom
package. The length of the tape restricted the recording duration of the Russian OBS to about 60 hours.

Advantages of OBS systems used for this data. Both the United States and Soviet OBS systems had many distinct advantages. Because they both received on the ocean bottom, they were far removed from surface wave and meteorological noise. They also were stationary recording sites so that the seismic structure under the receiving point was constant and the resultant interpretation was not degraded by averaging and attempting to correct for a changing bottom as was true of data from free-floating buoys. Both OBS's were three-geophone component units, which allowed differentiation of particle motion of ground arrivals. In the case of the Columbia OBS this readily permitted discrimination of shear wave arrivals from compressional arrivals. The Russian system, however, did not have as good response from its horizontal geophones, perhaps because they were mounted on free gimbals with the result that was probably absorbed much of the horizontal motion by the gimbal-mount.

Figure 5 is a representative record from one of the Columbia OBS traverses. As can be seen in this figure, the location of shear arrivals depends primarily on the horizontal traces. Similarly, the water-wave arrivals are most apparent on the hydrophone trace. The lack of a hydrophone in the Russian instrument made water-wave-arrival determination, and therefore shot-point location, extremely
Figure 5. Typical set of arrivals at the four-component Columbia ocean-bottom seismometer. Note the relative enhancement of the various types of arrivals on the different components. The following arrivals are marked for reference:

1) Pure compressional (P) arrival;

2) P wave converted to shear (S) at base of sediments, arrives at OBS as S;

3) Multiple conversion, travelled as S part of the way down through the sediments; refracted as P, reconverted to S at base of the sediments, arrives at OBS as S;

4) Multiple conversion, travels as P through sediment, refracted along Moho as Sn; reconverted to P on way back to surface, arrives at OBS as P. This arrival is also mixed in with reflection of first P arrival (1) off water surface;

5) Refracted S wave; travels as P to the bottom of the sediments, then as S all the way through to the OBS. This arrival is Sn;

6) Direct water wave (D);

7) Reflected water wave (R).
OBS 1969
SHOT #159
Range: 32 Kilometers
Shot Size: 10 Pounds

COIL

SPZ

SPH2

SPH1

Seconds
Disadvantages of OBS systems used for this data. The primary disadvantage of the OBS systems is their greater cost and deployment time as compared to sonobuoy receivers. However, it is felt that the superior data return more than compensates for these disadvantages.

The Russian system, aside from the lack of a hydrophone, is at a further severe disadvantage in that all the recording is remote, and after deployment of the unit there is no way to monitor the quality of the data being recorded. As frequently occurred with the Russians, this means that a lot of shooting was done in patterns around an OBS that was not functioning properly. These undetected failures of the unmonitored receiver are common, discouraging, and highly inefficient. Furthermore, shot sizes cannot be tailored to the quality of the signal being received at the OBS. This uncertainty generally results in the use of larger than needed shot sizes to provide plenty of signal, but these large charges often result in overloading the recording system and spoiling second arrival data.

The Columbia OBS is, of course, permanently deployed in one spot, and is not, therefore, truly an exploration tool.
DATA ANALYSIS

ASPER RECORDS

Much of the effort involved in interpretation of an ASPER station is associated with reduction of the raw data on the paper record, which approximates a distorted travel-time plot, to a correct undistorted travel-time plot. The distortion is due to variations in the ship's speed away from the sonobuoy and to warping of the paper record as it dries in the recorder. The Alpine PESR that is used for the ASPER data employs an electro-chemical writing process which requires that the recording paper be wet.

In cases where unusually severe warping occurs, the only satisfactory way of correcting the data is to pick the arrivals at some interval, in practice each 0.25 to 0.5 seconds of D time, and replot the data as a standard travel-time plot. This procedure is even more tedious than picking and correcting explosion seismic records, and can be a source of error.

If the records are only slightly distorted, they can be physically stretched and reoriented on a grid, and the appropriate arrivals can then be traced directly from the record to form a conventional travel-time plot. In some cases this removal of the distortion process is facilitated by wetting the record and then letting it dry properly shaped on the grid.
If $t^2 - x^2$ analysis of the record is made, the wide-angle reflections are picked from the record at close (general 0.20 sec or less) intervals. A complete discussion of the interpretation of wide-angle reflection ASPER records is given by Maynard (Ph.D. thesis, in preparation).

The ASPER records also yield an approximation of signal-amplitude levels. A common phenomenon is to observe a pronounced amplitude increase at the critical shot-to-receiver distance where the refraction curve emerges tangentially from the reflection. Figure 6, an enlargement of a portion of Figure 4, illustrates this increased signal at and just beyond the critical distance. The refraction signal will also fade in and out and will have a different S/N compared with its corresponding reflection curve depending on the characteristics of the velocity interface (I. P. Kosminskaya, personal communication). The amplitude information is not, of course, as definitive as calibrated wiggly-line records, but it is more readily observed on an ASPER record.

Errors that can commonly creep into analyses of ASPER records have been discussed by Sutton and others (1971). Briefly, they indicate that velocity determinations are very good, with errors normally expected to be less than ± 0.1 km/sec for first arrivals and less than ± 0.4 km/sec for refractions seen only as weak second arrivals. The interface-depth determination, however, can be less accurate
Figure 6. Enlargement of a portion of record M (Fig. 4), emphasizing the increase of energy of the arriving signals at their critical ranges, which are labeled here for the appropriate seismic interfaces.
because it is, in some cases, fairly easy to miss the first break of arrivals on the ASPER records, especially if the signals are emergent. If, for example, on a representative ASPER record the first break of a Moho refraction arrival is picked incorrectly by one cycle, this could result in an error of about 0.5 km for Moho depth. Of course, this error would represent an extreme case. The shallower, lower velocity layers would be less affected by a mispick of one cycle.

A good method of defining the first break of a refraction on an ASPER record is to fire an explosion charge at critical points during the ASPER traverse. This was frequently done during the collection of the data used in this paper.

EXPLOSIVE SOURCE SONOBUOY RECORDS

Arrivals at sonobuoys using explosive sources are recorded in the familiar wiggly-line format, and are interpreted, as previously mentioned, following standard procedures. It is reassuring, however, that in those cases where ASPER and explosion records were made concurrently at the same station (for example, see the Murray Fracture Zone, Ontong Java Plateau, and Fiji Basin stations discussed later) the interpretation of these two types of seismic data have yielded essentially the same models. This is not to say, however, that either of the methods may be disregarded. Rather, the explosion and ASPER records are complimentary;
the explosion data is still best-suited for long-range seismic runs to obtain good Moho information, whereas the ASPER records yield more precise crustal data over short distances.

OCEAN BOTTOM SEISMOMETER DATA ANALYSIS

Interpretation of the OBS data was not as straightforward as with the other types of data. In both the Duet and Columbia OBS experiments, the OBS data were reversed using surface sonobuoy data. Arrival times at the OBS had to be corrected by adjusting the apparent recording point of the OBS from the ocean bottom to the ocean surface in order to match the sonobuoy data. Since each type of water-wave arrival (D, R₁, R₂, etc.) travelled a different path according to the water column velocity-depth relationships, and each of the refracted-path arrivals (G₁, G₂, etc.) also would have to intersect the ocean bottom at a different angle on its path to the surface, each arrival at the OBS had to be individually corrected depending on which of the velocity layers it had travelled through (see Fig. 37). After these numerous corrections were applied, along with the conventional shot-break time, water-depth, and sediment-depth corrections, the OBS and sonobuoy data reversed perfectly (see Figs. 35 and 36).

The analysis of the OBS data for shear wave velocity ($V_s$) structure also required some special attention.
Consideration was given to all possible $V_p$ (compressional velocity) - $V_s$ (and vice versa) phase transformations at the various interfaces to check the $V_s$ interpretation. After the travel times were matched, the theoretical energy partition between the various possible reflected and refracted P and S waves at each interface was also considered to make sure that sufficient energy would be expected to be transmitted in the desired phases.

RESULTS

A summary of the 59 crustal structure models obtained through interpretation of the 66 seismic stations (7 of which were reversals) is shown in Table 1 (Fig. 7 locates these stations). To facilitate the treatment of the discussion of these results, they will be divided into six separate groups, each of which is loosely related geographically and physiographically within a region of the Pacific Ocean. These regions are: (1) the South Fiji Basin and Kermadec Trench region; (2) the Ontong Java Plateau, Lyra Basin, and East Caroline Basin; (3) the Murray Fracture Zone; (4) the Central Pacific Basin, Line Islands, and Fiji and Manihiki Plateaus; (5) the Northwest Pacific (Project Duet); and (6) the continental rise off California (Columbia OBS experiment). Some of the data from the Central Pacific Basin and the Murray Fracture Zone has already been published (Sutton and others, 1971) and will only be
Table 1: Summary of Seismic Refraction Stations

<table>
<thead>
<tr>
<th>Sta. Yr.</th>
<th>Region</th>
<th>Receiver Position</th>
<th>Azimuth Depth (km)</th>
<th>Velocity (km sec(^{-1})) over Thickness (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 68</td>
<td>Ontong Java Plateau</td>
<td>0°44'N 159°18'E</td>
<td>2.6</td>
<td>1.7 2.3 5.6 (6.7)</td>
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<td>1.7 2.3 2.6 5.3 (6.5)</td>
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<td>1.9</td>
<td>(1.7) 1.9 2.7 5.6 (6.3) &gt;12</td>
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<td>D 68</td>
<td>Ontong Java Plateau</td>
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<td>1.7 2.5 3.8 5.6 (6.5)</td>
</tr>
<tr>
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<td>1.7</td>
<td>1.7 2.5 3.3 5.6 (6.6)</td>
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<td>1.8 3.7 5.5 (6.7)</td>
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<tr>
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<td>Latitude Longitude</td>
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*Corrected for dip.
Table 1: Summary of Seismic Refraction Stations (Continued)

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**Was assumed to be basal crustal layer because of other data (see Sutton and others, 1971).
Table 1: Summary of Seismic Refraction Stations (Continued)

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Table 1: Summary of Seismic Refraction Stations (Continued)

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Figure 7. Location map of all ASPER and ocean-bottom seismometer stations assembled for this paper. For complete descriptions of each section see Table 1, pages 42-47.
discussed briefly. A preliminary analysis of the work on the continental rise off California was also published by Sutton and others (1971), but these data have been completely reinterpreted for this paper.

SOUTH FIJI BASIN-KERMADEC TRENCH AREA

Seven stations in the South Fiji Basin and three stations on the eastern side of the Kermadec Trench were obtained aboard the R/V KANA KEOKI in 1971, and serve as excellent examples of improvement in geologic interpretation made possible by the increased resolution of the ASPER technique (Hussong, 1972a).

Figure 8 locates the HIG ASPER stations as well as five crustal models obtained in the same general region by workers from Scripps Institution of Oceanography (Shor and others, 1971). The Scripps stations are designated N (they were obtained during Project Nova in 1967).

The five ASPER stations in the central portion of the South Fiji Basin are all within 200 km of one another; having been obtained during two site surveys for the JOIDES deep-sea drilling project. The ocean bottom in this area of the Basin is essentially flat; bathymetric relief was found to be less than 200 m in the survey region. Thus, for the purposes of interpretation of the refraction results, depth changes were seen to be insignificant along individual ASPER runs. The subbottom topography also appeared subdued.
Figure 8. Locations of stations in the South Fiji Basin-Kermadec Trench area. Line A-A' locates the composite crustal section depicted in Figure 13.
ASPER STATIONS
SOUTH FIJI BASIN
AREA

NOTE: N DENOTES DATA
FROM SCRIPPS PROJECT
NOVA

CONTOUR INTERVAL 2KM
The magnetic data from this area, on the other hand, is spectacular. Many anomalies of more than 500 gammas were observed during the site surveys (R. Zachariadis, pers. comm.). However, these large anomalies exhibited no apparent predominant fabric or stripe.

A composite of the interpreted crustal columns in the basin (Fig. 9) shows that although the arrivals for each record were clear and easily picked, there is very little correlation between stations. The only consistency among these closely spaced sections is a recurring velocity of about 6.7 km/sec. It is not possible, however, to envision this velocity as representing a coherent layer. The differences in depth to the layer create a paradox, in that the severe dips that would have to be assumed to connect the tops of the layer from station to station would produce apparent velocities varying up to ± 25 per cent.

Throughout all the columns, consideration of the direction of shooting and attempts at compensation and correction for possible dips on any correlated layers did not improve the fit. Unsuccessful attempts were also made to insert additional layers into some of the sections in order to improve correlation of layer depths on the assumption that some ASPER records may have missed some layers.

It was impossible not to conclude, however, that the models as presented in Figure 9—with no assumptions about dips or missed layers—are representative of the true
Figure 9. Crustal interpretations in the South Fiji Basin. Attempts at correlation of these geographically close columns were unsuccessful (see text). The crustal structure in the Basin is a melange of incoherent layers. Velocities in parenthesis are assumed, based on other data.
CRUSTAL INTERPRETATIONS IN THE SOUTH FIJI BASIN

DEPTH IN KILOMETERS

N24-N25  42  41  40  43  45  38  35  0

1.5  1.5  1.5  1.5  1.5  1.5  1.5  1.5

(1.6)  (1.6)  (1.6)  (1.6)  (1.6)  (1.6)  (1.7)  (1.7)

5.0  5.5  5.9  5.1  5.5  3.8  3.9  5.5

6.7  6.3  6.2  6.8  6.5  6.5  6.5  6.5

7.4  7.5  7.6  7.6  7.6

8.3  8.5  8.5  8.5  8.5  8.5  8.5  8.5

6.0  6.0  6.7  6.3  6.2  5.5  5.5  5.5

3.8  3.8  3.8  3.8  3.8  3.8  3.8  3.8

6.0  6.7  6.8  7.3  7.6  7.6  7.6  7.6

8.0  8.0  8.0  8.0  8.0  8.0  8.0  8.0

15  15  15  15  15  15  15  15
structural relationships. It can only be further concluded that beneath the flat basin there exists a very irregular, complex crustal structure. Since arrivals were individually strong, yet could not be correlated from record to record, the crust there must be a complex melange that is not at all like that commonly described from conventional studies, i.e. distinct, nearly flat layers.

Figure 10 is the record from ASPER station 42. The same record with the interpreted refraction lines highlighted is shown in Figure 11. The dashed lines in Figure 11 are where the refractions would have had to be picked to correlate with station 41, located only 50 km northeast of station 42. The striking difference in the data from the two adjacent stations shows that the discrepancies between the resulting models are again the result of the complex geology and could not be the product of observational errors.

It would have been difficult to have arrived at the above conclusion from conventional explosion techniques. Within the South Fiji Basin, conventional refraction stations would have to be run over much longer distances than ASPER stations, and any scatter in the arrivals would therefore have to be smoothed to produce a reasonable layered model. The previous work in the region by workers from Scripps did produce continuous layered models, although sometimes with steep dips. The results of the ASPER
Figure 10. ASPER station 42 was a typical record from the set which is interpreted in Figure 9. The arrivals are well defined.
Figure 11. ASPER station 42 highlighted. The solid black lines represent the interpretation of these data, while the dashed lines depict the interpretation of station 41, located only 50 km northeast of this station. Note the wide discrepancy in arrival times, indicating the large differences in crustal structure.
stations show that flat-layered interpretations can be misleading. In reality the South Fiji Basin crust is complex and discontinuous.

In remarkable contrast to the crustal models in the South Fiji Basin are the results shown in Figure 12 of the ASPER stations on the Pacific oceanic plate east of the Kermadec Trench. As might be anticipated across a portion of this older, more stable, deep-ocean plate, the ASPER records yield typical, familiar velocities and continuous layers. The structure is apparently very simple. The approximately 7.4 km/sec basal crustal layer that has been identified using the ASPER technique in other parts of the Pacific (Sutton and others, 1971) is again clearly identifiable.

It would be expected that conventional two-ship explosion seismic techniques would yield models reasonably consistent with the ASPER records in this old plate area, although explosion seismic interpretations would probably miss some of the layers seen in ASPER records, most notably the 7.4 km/sec layer. This omission of the basal crustal layer has commonly occurred in other deep-ocean areas where ASPER measurements have been made at or near sites previously studied by explosion methods.

A crustal section (Fig. 13) has been prepared along the line A-A' of Fig. 8 from the ASPER stations in the South Fiji Basin to those on the Pacific Plate. Certain Scripps
Figure 12. ASPER crustal interpretations on the Pacific Plate east of the Kermadec Trench. These typical oceanic sections, in contrast to the stations in the South Fiji Basin (Fig. 9), exhibit familiar velocity structure and well-defined layering.
ASPER CRUSTAL INTERPRETATIONS
EAST OF KERMADEK TRENCH

SOUTH

SB49

0

0

1.5

5

5

(1.6)

(5.6)

6.69

7.41

8.22

DEPTI. IN KILOMETERS

0

0

1.5

5

5

(1.6)

(5.6)

6.62

7.40

DEPTI. IN KILOMETERS

0

0

1.5

5

5

(1.6)

(5.0)

5.22

5.83

6.64

7.59

8.32

B NORTH

SB50

SB51

0

0

0
sections, designated N, around the trench (Shor and others, 1971) have been projected to A-A' to fill the gap in the ASPER work. The ASPER work on either side of the trench-island arc system is enlarged in the insets. In addition, the ASPER stations on the Plate are located at about the proper distance separation in the inset, whereas on the main cross section they appear compressed because of their projection onto A-A'.

The difference in crustal character across the trench is obvious. From the east, the flat-lying, continuous crustal layers from the Pacific Plate are in the process of being subducted into the Kermadec Trench. To the west, the thick, somewhat irregular crust under the island arc gives way to the exceptionally irregular crust in the Basin. Although the changes in the crust between ASPER stations in the Basin (Fig. 13) appear somewhat exaggerated (again due to the foreshortening effect of projection onto the cross section), the crustal irregularity is exceptionally great.

The above difference in character between the crust of the South Fiji Basin and that of the Pacific Plate probably results from the difference in origin of the two crustal types. The crustal veneer of the older Pacific lithospheric plate probably formed at a mid-ocean-ridge-type spreading center, such as that presently found at the East Pacific Rise. This type of crust is typical of that which is described later and throughout this paper as characteristic of deep, relatively undisturbed ocean basins.
Figure 13. Crustal section across the Kermadec Island Arc system. Note the transition from the well-correlated, coherent Pacific Plate crust (formed at a spreading zone such as the East Pacific Rise) to the jumbled melange of the South Fiji Basin formed by upwelling in the extensional crust.
SOUTH FIJI BASIN

KERMADEC RIDGE

KERMADEC TRENCH

DEPTHS IN KMS
VELOCITIES IN KMS/SEC

VERTICAL EXAGGERATION IS 20:1

ASPER STATIONS: HIG 1971

N STATIONS: SCRIPPS NOVA 1967
The crust in the Fiji Basin, however, is so different in character that it suggests a very different mode of origin. Karig (1970) postulated that portions of the Fiji Basin area are (based on the thin sediment cover and high heat-flow data), newly formed oceanic crust resulting from extensional tectonic movement in the area. Moberly (1972) suggests that this new crust is the result of upwelling of mantle material behind the Kermadec Island arc system which he envisions as advancing to the east. The mechanism for this island arc migration, and crustal extension behind the arc, is thought by Moberly to be caused by the dynamics of a situation where the Pacific Plate sinks under its own weight into the trench at a rate faster than the generation of the Plate at the East Pacific Rise. As a consequence, the trench migrates to the east, with the island arc being transported along with the trench.

The seismic evidence presented here, as well as the other available geophysical evidence, seems to support the concept of the South Fiji Basin being formed of mantle material, or a differentiate thereof, that is rising somewhat turbulently into the extensional region in the wake of the migrating island arc system. The very large magnetic anomalies not only indicate shallow crustal discontinuities in support of the seismic data, but also, by their magnitude, suggest a continuing process that includes cooling of scattered masses of rising mantle material, perhaps during different orientations of the earth's magnetic field.
In summary then, although the ASPER results cannot completely delineate the Basin structure, the complexities that can be identified by ASPER data have portrayed the contrasting crustal structure in the region of the South Fiji Basin and the Kermadec area. The result is a better geologic interpretation than would be expected to result from explosion seismic techniques.

ONTONG JAVA PLATEAU, LYRA BASIN, AND EAST CAROLINE BASIN

The Ontong Java Plateau has been extensively described by Kroenke (1972), who summarizes it as "... a broad shallow submarine tableland... [which] strikes northwest-southeast parallel to the Solomon Islands and is more than 800 km wide and over 1600 km long...". The Plateau, in its central portion, is typically less than 2 km below sea level and is characterized by nearly 1 km of flat-lying stratified calcareous sediments overlying an acoustic basement.

To the west of the Plateau is the Lyra Basin, described by Orwig and others (1972) as a "structural basin, step-faulted downward from the Ontong Java Plateau...". Sediments contained within the Lyra Basin appear on reflection records to be similar to, although only about half the thickness of, the Plateau sediments. The calcareous sediment, step-faulted margin, and recent faulting and slumping within the 4 to 5.5 km deep basin all suggest it to be a foundered section of the Ontong Java Plateau.
To the west of the Lyra Basin, and separated from it by the intervening Mussau Trough, is the East Caroline Basin. It approximates an 800-km-sided square, bordered to the west by the Eauripik Rise, to the north by the Caroline Islands, and to the south by the Manus Trough. The sediment cover is somewhat variable, with the lower layers apparently thickening to the east (toward the Mussau Trough) and the upper layers thickening to the west (toward the Eauripik Rise) while the total sediment column thickens from north to south (Mussells, ms. in preparation). The average water depth of the basin is about 4.5 km in the central part.

Figure 14 shows the location of the ASPER stations in these three adjacent regions, pertinent explosion refraction stations by other workers, and the cross sections to be discussed in the following text.

Ontong Java Plateau. The ASPER data from the Ontong Java Plateau was obtained in 1968 on board the R/V MAHI (lines A, B, C, D, E) and in 1971 on board the R/V KANA KEOKI (lines 13 and 16). In addition, two-ship explosion refraction studies were conducted on the Plateau in 1966-67 (Furumoto and others, 1970) and 1970 (Furumoto and others, ms. submitted to Tectonophysics). Maynard (Ph.D. thesis, in preparation) has also interpreted 19 wide-angle reflection ASPER records by $t^2 - x^2$ methods to calculate velocity-depth functions for the sediments on the Plateau (Fig. 15).

The interpretations of the 1968 ASPER stations, which were made using a 40-cubic-inch airgun and extended with
Figure 14. Locations of stations and cross sections on the Ontong Java Plateau, Lyra Basin, and East Caroline Basin.
Figure 15. Velocity-depth curve for Ontong Java Plateau from wide-angle seismic reflection studies (after Maynard, Ph.D. thesis in preparation).
explosives, are shown in Figure 16. The southwest to northeast composite crustal section depicts a sediment cover with varied and pinching layers, the correlations being based solely on velocity groupings. This pinching out of layers is not evident in the reflection records. The gross structure of the sediment column and the range of velocities do, however, agree with Maynard's work. But, the precise layering and the subtle variations in interface characteristics and velocity gradient through the sediments, which are largely responsible for specific refractions and reflections from various depths, remain elusive in both this and Maynard's work.

The remarkable consistency of the 5.5 - 5.6 km/sec layer in line A to E, based on both ASPER end explosion results, and verified by the 1971 ASPER stations (Fig. 17), has led Kroenke (in press, GSA) to hypothesize that this layer is composed of submarine flood basalts. He points out that this layer is similar in velocity and thickness to known flood basalts reported by Hill and Pakiser (1966) under the Western Snake River Plain of the continental United States. Kroenke goes on to suggest other evidence of tectonic activity on the Ontong Java Plateau to support the flood basalt concept.

It should be noted that the depth to the top of the 5.6 km/sec layer is generally somewhat greater in these refraction models than in the basement interpretations by
Figure 16. Upper crustal structure models across the Ontong Java Plateau. Note the consistency of the thick 5.6 km/sec layer (see text).
COMPOSITE SECTION ACROSS ONTONG JAVA PLATEAU

*FROM EXPLOSIVES

ASSUMING 8.2 KM/SEC VELOCITY
MANTLE DEPTH > 20 KM.
Figure 17. Crustal columns on the Ontong Java Plateau.

Note once again the consistency of the approximately 5.5 km/sec layer, except in the two-ship refraction stations (see text).
Kroenke, bolstered by DSDP data from site 64 (Winterer and others, 1971), and by Maynard (Ph.D. thesis, in preparation). This difference is, however, consistent with both the flood-basalt hypothesis and with observations of the ASPER records. The wide-angle reflection portion of the ASPER record shows that the arrivals, which make up the hyperbola corresponding to the normal incidence acoustic basement, arrive earlier than other differentiable reflection hyperbolae. The character of the later arrivals is unfortunately obscured by the wave train from the reflections off the interface at the base of the sediment column. The refraction from the 5.6 km/sec layer is tangent to the reflections from these slightly deeper layers. Kroenke has also pointed out numerous sills and discontinuous basement reflections on his normal incidence reflection records in the same area. The ASPER data therefore suggests that the top of the proposed flood basalts is a laminar series of sediment and basaltic layers. The reflections would thus be expected to correspond to the uppermost sediment-to-basalt interface, which may occur at the top of a very thin basalt layer. The refraction, however, would travel deeper in the column along the first basalt layer thick enough to propagate a refracted head wave.

A layer beneath the "flood basalts," with a velocity averaging 6.5 km/sec, was seen only on the explosion extensions of the ASPER runs. The dashed interfaces with
the arrows pointed down are based on relatively poorly
determined second arrivals, and are considered to be an
estimated velocity at a minimum depth.

Line C was extended far enough, using a balloon-
elevated sonobuoy transmitter antenna, to obtain a good
determination of the 6.3 km/sec layer. The Moho arrival
was, however, not detected at the maximum range of the buoy,
so that only a minimum depth for the occurrence of the mantle
interface is estimated here.

The northwest-southeast trending series of crustal
sections (Fig. 17) depicts a significant correlation problem.
ASPER stations 13, 16, and C (C being representative of
stations A through E), although widely separated, have the
same basic structural features, most notably the 5- to 6-km
thick 5.5 km/sec layer. The base of this layer, unfortunately,
is poorly determined, particularly at station 16. The thick,
very consistent 5.5 km/sec layer, which appears on the ASPER
stations everywhere on the Plateau, is, however, not well
defined by the explosion stations W (Furumoto and others,
ms. submitted to Tectonophysics) and B (Furumoto and others,
1970). Other stations by Furumoto and his colleagues
(lines R and O in the Tectonophysics paper, and lines
A-A* and C-C* in the 1970 paper) depict a comparable base-
ment layer with velocity ranging from 4.8 to 5.9 km/sec.
This velocity range disguises the significant correlation
of the layer identified by the ASPER work. Although the
two-ship explosion data unquestionably yields information
on deep structure not yet obtainable from ASPER stations, it
does not provide the precise information--available from
ASPER stations--on the upper 10 km or so of crust.

It is unlikely that the geologic interpretation of this
layer as a Plateau-wide flood basalt--with its inherent
implications to the understanding of both the present
structure and possible origin of the Plateau itself--could
have evolved from the previous explosion data in the area.

Lyra Basin. ASPER stations in the Lyra Basin to the
west of the Ontong Java Plateau are shown in part of
profile A-A' (Fig. 18) that extends into the northern
portion of the East Caroline Basin. Stations 8 and 10 were
made on the KANA KEOKI in 1971; station 87 was made on board
the MAHI in 1970.

None of the crustal models resulting from these
stations extend to the Moho. The 7.7 km/sec layer at
station 10 approaches mantle velocity, but is more likely
a high "apparent" velocity, resulting from structure, which
correlates with the 7.2 km/sec layer at station 87.

The upper crust in these models is not easily correlated,
and is probably quite irregular. No consistent layer has
the velocity or thickness of the postulated flood basalts
on the Ontong Java Plateau, suggesting that whether the
Lyra Basin foundered, or whether the Plateau were elevated,
it occurred before or perhaps concurrently with and as a
consequence of the outpouring of the flood basalts. Even
Figure 18. Section A-A'. Crustal structure from the Lyra to the East Caroline Basins using from ASPER data.
CRUSTAL STRUCTURE OF THE EAST CAROLINE AND LYRA BASINS FROM ASPER STATIONS

Scale in Kilometers
Vertical Exaggeration Approx. 20:1
though there is a considerable thickness (around 3 km) of low-velocity material in the Lyra Basin crust above a thin Layer 3 (after the nomenclature of Raitt and others, 1963), the data are not sufficient to warrant any speculation on the geology and crustal configuration of this region at this time.

**East Caroline Basin.** In contrast to the Lyra Basin work, the results of eleven ASPER stations from the 1970 MAHI cruise, five two-ship explosion models from Den and others (1971), and a single refraction profile by Gaskell and others (1958), can be combined to yield a fairly complete structural picture of the East Caroline Basin and its western margin, the Eauripik Rise.

Crustal section A-A’ (Figs. 14 and 18) includes three ASPER stations, one of which yields a model that is complete down to the mantle. The crust in this portion of the Basin appears to be characterized by two high-velocity layers, each about 2 km thick, each with velocities around 6.3-6.5 km/sec and 7.0-7.1 km/sec, respectively. The lower velocity layer could be either missed at station 89, or confused by the rough topography encountered at the western end of the profile. Station 89, as well as station 87 from the Lyra Basin, and stations 96 and 100 in the East Caroline Basin further west, were corrected for bottom topography at the time of interpretation. It was assumed for the sake of this correction that the bottom relief was on the acoustic basement.
Results of the CHALLENGER (1950-53) refraction station, reported by Gaskell and others (1958), are in agreement with those reported here, but do not reveal the crustal configuration below the 6.4 km/sec layer.

Crustal section B-B' originates 150 km south of the western extent of A-A' and extends west-northwest to the crest of the Eauripik Rise (Fig. 19). The crust, as can be seen in this cross section, appears more complex than that found farther north. The 6.5 - 6.7 km/sec layer in B-B' has thinned significantly, being supplanted primarily by a thick overlying layer having a velocity around 6.0 km/sec. Above the 6 km/sec layer, the thick, fairly consistent layer with velocity averaging around 4 km/sec is one that is not generally encountered in oceanic sections. The whole Basin is quite irregular compared to other ocean sections, but the velocities are nevertheless sufficiently consistent to encourage layer correlation as shown in Figure 19.

A section prepared by Den and others (1970), roughly parallel to and 200 km to the south of B-B' is shown in Figure 20. The data presented in this section was collected by two-ship explosion refraction methods, and was apparently of very high quality. Although the overall crustal thickness and the deepest crustal velocity found in the two-ship work agrees very closely with the ASPER interpretations, the details in the upper crustal portion of the two models differ markedly. The effect of the two-ship work has
Figure 19. Section B-B'. Crustal structure in the East Caroline Basin using ASPER.
CRUSTAL STRUCTURE OF THE EAST CAROLINE BASIN AFTER DEN AND OTHERS (1970)

Scale in Kilometers
Vertical Exaggeration Approx. 20:1
Figure 20. Two-ship explosion refraction studies after Den and others (1970). This section is parallel to and about 200 kms south of Figure 19. The explosion interpretations are similar to, but less complex than, the results of the ASPER stations (see text).
CRUSTAL STRUCTURE OF THE EAST CAROLINE BASIN FROM ASPER STATIONS

Scale in Kilometers
Vertical Exaggeration Approx. 20:1
apparently been to combine arrivals from the approximately 4 km/sec and 6 km/sec layers (as seen on the ASPER section) into a single thicker layer having a velocity of around 5.1 km/sec.

Den and his co-workers also may have missed the thin layer found in B-B' with a velocity of about 6.5 km/sec. It is possible, however, considering the marked thinning of this layer to the south between sections A-A' and B-B', that the layer has indeed pinched out before reaching the latitude of Den's work. A plausible geologic explanation for the pinching out of a major crustal layer would, however, be difficult to propose. In addition, it is interesting to note that there generally appears to be a better correlation of layers in the east-west direction than in the north-south direction within the East Caroline Basin. If this structure is indicative of a tectonic grain that is oriented roughly east-west, the origin of such a texture is not obvious.

The complex crustal structure of the East Caroline Basin is shown in considerably more detail in the ASPER composite sections than in the interpretations by Den and his colleagues. By avoiding the smoothing effect of the two-ship work, the greater resolution of the ASPER method makes geologic interpretation of the crustal structure even more difficult.

The crust within the East Caroline Basin does not seem to belong to the group of more simple models associated with normal oceanic plate structure such as those apparently
formed at spreading centers and which are discussed in the following sections on the Murray Fracture Zone, the Shatsky Rise, the Central Pacific Basin, and the continental rise off California. On the other hand, the crust is not an inconsistent melange such as that found in the South Fiji Basin.

It seems less than likely that the East Caroline Basin crust was formed at a sea-floor spreading rise system. The more likely conclusion, based solely on the crustal structure, is that the East Caroline Basin, like the South Fiji Basin, was formed in the wake of an old island arc system which formerly comprised what is now the northern coast of New Guinea, and the islands of New Britain and New Ireland, having migrated from the north, as Moberly (1972) has proposed. Expanding somewhat on Moberly's hypothesis, if the island arc system collided with and was arrested by the New Guinea portion of the Australian Plate in Middle Miocene time, then the crust has been relatively undisturbed by major tectonic movement for 20 million years. During this relatively quiescent period, the Basin could have undergone isostatic and, perhaps, some metamorphic readjustment of the crustal melange, producing the basement faulting found throughout the area, and resulting in the somewhat inconsistent, but nevertheless definable, crustal layering.

The remaining major unanswered problem associated with this hypothesis of the formation of the Basin in the wake
of an ancient island arc is an explanation, in this context, of the origin of the Eauripik Rise.

**Murray Fracture Zone.** The results of five ASPER stations near the Murray Fracture Zone at about 152°W longitude have been previously published (Sutton and others, 1971) with reference to the location there of the 7.4 km/sec basal crustal layer. These sections are discussed again here to point out some of their other geologically significant features. Figure 21 shows the orientation of the stations adjacent to the fracture zone, which is represented at this longitude by a more than 100-km-wide zone of pronounced, and somewhat confused, bathymetric relief.

The crust on either side of the fracture zone was found to be quite uniform, characterized by flat and consistent layers (Fig. 22). No appreciable mantle velocity anisotropy was detected.

Menard (1964), however, in describing the results of two-ship explosion refraction measurements at the same location as this ASPER data (and again straddling the fracture zone), shows a 2 km difference in crustal thickness on either side of the zone, with the southern crustal column appearing thinner than that to the north. Some of the foregoing discrepancy between Menard's models and the ASPER results may be due to the omission of layers not detected by the explosion studies. Menard's structural section depicts the thin crust south of the zone as being comprised
Figure 21. Location of ASPER stations straddling the Murray fracture zone.
Figure 22. Seismic velocity sections near, and oriented parallel and perpendicular to, the Murray Fracture Zone. Note the relatively uniform crustal structure across the fracture zone (see text).
152°W OVER MURRAY FRACTURE ZONE

NORTH

1.5
(1.6)
4.4
6.9
7.4
8.3

Km

0
5
10

SOUTH

1.5
(1.6)
4.4
6.5
6.9
7.5
8.2

Km

0
5
10

4.5
6.8
7.3
8.0

4.4
6.8
7.4
8.2

4.4
6.9
7.5
8.2

4.4
6.8
7.3
8.0

4.5
6.8
7.3
8.0
of only three layers: sediments, the oceanic layer, and the Moho. In contrast, ASPER data at the same location revealed five, and possibly six, crustal layers.

Central Pacific Basin, Line Islands, Fiji, and Manihiki Plateaus. Of the 18 crustal models (Fig. 23) grouped within this section, only four (those derived from stations 3, 4, 5, and 6; all from the vicinity of the Line Islands) have not been described in the paper by Sutton and others (1971). This previous work is included here in order that all the Hawaii Institute of Geophysics ASPER stations which have yielded significant deep crustal information can be compared and discussed.

The crustal models from the Central Basin, shown in Figure 24, and the Fiji and Manihiki Plateaus, shown in Figure 25, are also good examples of the straightforward but detailed crustal interpretations obtainable by use of ASPER techniques, and have been discussed in Sutton and others (1971). However, the analyses of stations 3 through 6 (which include the previously unreported interpretations) were not as straightforward. These data yield models (Fig. 26) which when considered as a group, are probably representative of the regional crust. Individually, however, these models are less reliable than interpretations in other areas. In particular, station 4 had strong, yet irregular (scallop-shaped) arrivals, and at station 5 an almost continuously curving, rather than the normal branched,
Figure 23. Location of stations in the Central Pacific Basin, Line Islands, Manihiki Plateau, and Fiji Plateau.
Figure 24. Crustal velocity interpretations in the Central Pacific Basin (after Sutton and others, 1971).
Figure 25. Crustal velocity interpretations on the Fiji and Manihiki Plateaus (after Sutton and others, 1971).
Figure 26. Crustal velocity interpretations near the Line Islands.
travel-time plot was recorded, which suggested possible

crustal gradients and velocity structure that was not

uniquely determined.

In addition, there is an aspect of the Fiji and

Manihiki Plateau data that was not previously discussed,

but is of particular interest, in light of the discussion of

the significance of the thick 5.5 - 5.6 km/sec layer on the

Ontong Java Plateau. The Manihiki Plateau (station 10,

Fig. 25) crustal section shows both a 5.4 km/sec layer and a

5.6 km/sec layer, with a total combined thickness of just

over 6 km--very similar to that found in the Ontong Java

Plateau section. Moreover, the three stations (20, 22, and

30) on the Fiji Plateau exhibit an upper layer which, although

not as thick, has about the same velocity as that found in

the Ontong Java section. Previous two-ship explosion studies

on the Fiji Plateau (Raitt, 1956) also show the upper layer

to have a velocity of 5.5 km/sec.

It is worthwhile, therefore, to consider the possible

crustal structure and origins of all three plateaus in

relation to Kroenke's suggestion that the structure of the

Ontong Java Plateau is the result of the emplacement of

flood basalts. Considering other geophysical evidence, in

particular continuous reflection seismic records, it would

seem unlikely that the Fiji and Ontong Java Plateaus are

as similar as the refraction data would suggest. The Fiji

Plateau appears highly deformed, with a discontinuous

sediment cover and irregular basement structure. In contrast,
the Manihiki Plateau has a flat, well-stratified, more or less continuous sediment cover overlying a possibly laminated, yet thick, 5.4 - 5.6 km/sec basement which appears very similar to that found on continuous seismic reflection profiles of the Ontong Java Plateau.

It seems reasonable, therefore, based on both the refraction and the reflection seismic data, that the Manihiki Plateau could also be capped with flood basalts, and perhaps was formed as the result of the emplacement of these basalts, in the same manner as the Ontong Java Plateau.

**Western Pacific (Project Duet).** Project Duet was a cooperative seismic experiment utilizing the previously described ocean-bottom seismometers of the Soviet Academy of Sciences and their research vessel, the R/V VITIAZ, as well as the HIG sonobuoy recording system on board the R/V MAHI. It was the first joint seismic refraction work between a Russian and an American research vessel. The objective was to precisely measure the crustal structure and to determine any upper mantle velocity anisotropy in a region of very old oceanic crust (estimated as Jurassic in age by Fischer and Heezen, 1971). In this paper only the crustal structure will be discussed pending completion of the upper mantle anisotropy portion of the experiment.

The location of the survey area in relation to major structural features of the Western Pacific Ocean is shown on a generalized physiographic map, Figure 27. The cruise
Figure 27. Generalized physiographic map of Northwest Pacific Ocean and Project Duet survey area.

Note that the cruise tracks drawn here are not to scale. The dashed lines are the approximate boundaries of the old, depressed oceanic crust discussed in the text.
track is shown in greater detail in Figure 28. The experiment was located in an area that was described by Malahoff and others (1971) as a depressed, undistorted, ancient crustal block which appears to have the effect of truncating the Shatsky Rise to the north, and which is characterized by faults bordering the edge of the Marcus-Necker Rise to the south.

The nearly 6 km deep ocean floor within this region is quite flat and is underlain by compacted sediment (red clays) about 250 m thick (Malahoff and others, 1971). Figure 29 shows tracings of typical seismic reflection records from the area. The only major relief on the bottom is the group of small seamounts at about 28°N, 153°45'E.

A residual magnetic anomaly map shown in Figure 30 (unpublished data provided by R. Zachariadis) reveals low-amplitude (less than 100 gammas) anomalies trending more or less east-northeast. The higher amplitude magnetic anomalies, located at about 28°N, 153°45'E, appear to be caused by the previously mentioned seamounts found within the northeast sector of the circular part of the track.

The reversed refraction lines were positioned perpendicular to one another (Fig. 28) at a common point, O, and reversed to points A to the south and B to the east. The VITIAZ, using the Russian three-component seismometer tethered to surface buoys, recorded at position O, while the MAHI recorded at position A and then at position B, using
Figure 28. Tracks of R/V MAHI during Project Duet. Lines 0-A and 0-B are the seismic refraction stations discussed in the text.
Figure 29. Normal incidence seismic reflection profile tracings from the Duet survey. The structure depicted here was typical of that encountered in the area, except for a group of isolated seamounts in the northwest portion of the anisotropy circle.
Figure 30. Residual magnetic profile of Project Duet survey. Note the low-amplitude anomalies, trending east-northeast. The large anomalies, at about 28°N, 153°30'E, are caused by seamounts (see text).
arrays of three U. S. Navy SSQ41A sonobuoys (modified for longer battery life).

Although the geophones in the Soviet OBS units provided excellent records from ground arrivals, the absence of a hydrophone precluded the reception of good water-wave arrivals, which prevented accurate shot-to-receiver distance determinations and thus degraded the quality of the data. In order to circumvent this problem, surface buoys with hydrophones were tethered above the OBS instruments deployed by the VITIAZ. However, because of adverse weather conditions encountered during the experiment, these anchored hydrophone systems were overloaded with noise and proved of little use.

The MAHI sonobuoy arrays, however, were better suited for use during poor weather conditions. The sonobuoys were free-floating and each had an excellent vertical compliance supporting the hydrophone, in effect isolating the phone from surface motion. The MAHI was therefore able to obtain good records which provided the large number of data points shown in the travel-time plot, Figure 31.

The crustal sections interpreted from this data are shown in Figure 32. A fairly thick, high-velocity crust was found overlying a relatively low-velocity upper mantle. No mantle anisotropy was apparent from the reversed profiles. The 7.4 km/sec layer was again identified, primarily because of the high density of data points provided by the MAHI records. Above the well-defined, approximately 6.9 km/sec
Figure 31. Project Duet travel-time plot (see text).
DIRECT WATER WAVE SECONDS

01 \cdot 8.87 + X/3.88
02 \cdot 7.80 + X/5.92
03 \cdot 8.48 + X/7.00
04 \cdot 8.79 + X/7.54
05 \cdot 9.08 + X/7.98
B1 \cdot 8.24 + X/3.71
B2 \cdot 7.96 + X/5.96
B3 \cdot 8.35 + X/6.93
B4 \cdot 8.68 + X/7.49
B5 \cdot 9.08 + X/8.00
Figure 32. Crustal velocity structure model resulting from Project Duet (see text).
CRUSTAL STRUCTURE

SOUTH–NORTH

WEST–EAST

DEPTH IN KILOMETERS

5

10

15

5

10

15

5

10

15

1.5

5.81

6.87

7.54

7.94

1.5

5.95

6.91

7.51

7.99

VELOCITIES IN KM/SEC

ESTIMATED VELOCITY = ( )
oceanic layer, a sub-basement layer with velocity of 5.8 to 5.9 km/sec was determined. This somewhat higher than usual velocity, when compared with normal values for Layer 2, may be due to a denser than usual basaltic layer thickening in the direction of the seamounts to the northwest.

Apparent shear arrivals showing a velocity of about 3.8 km/sec were also observed here, and are interpreted as having resulted from refractions along the top of the 6.9 km/sec (compressional velocity) layer, giving this layer a Poisson's Ratio of about 0.28.

Previous two-ship seismic studies in this region by Den and others (1969) provided a similar crustal interpretation to Figure 32, although these workers did not identify the 7.5 km/sec layer in the deep Pacific basin. Den and his colleagues did observe the basal crustal layer where it thickens beneath the Shatsky Rise. However, the travel-time plots for their profiles 1 and 2, which are closest to, and at the same depth as, the Project Duet profiles, have strong second arrivals at a range of about 65 km. These arrivals were neglected in their interpretation, but they are at the same range and arrival time that the MAHI recorded strong signals refracted along the basal crustal layer during the Duet study. Although the data of Den and his co-workers was therefore very similar to that obtained during Duet, the additional data density at MAHI sonobuoy
recording stations permitted the identification of a more complete crustal model.

Continental rise off the coast of California. Detailed measurement of seismic velocity structure of the crust and upper mantle using explosives in conjunction with an ocean-bottom seismometer operated by Columbia University (described earlier), was the objective of a project conducted in the summer of 1969 by the Hawaii Institute of Geophysics. Detailed knowledge of the crustal structure in the vicinity of the seismometer was required not only to determine nearby crustal and upper mantle velocity structure for this paper, but also to furnish the necessary corrections for the arrivals from long-range shots designed to delineate deeper mantle structure. The results of the long-range studies will be presented elsewhere (M. Odegard, Ph.D. thesis in preparation).

The Columbia University OBS is located on the continental rise in approximately 4 km of water, on a gentle turbidite slope (Curray, 1965) called the Delgada Fan, about 75 miles west of Pt. Arenas, California.

The ASPER method was used to reverse the north, west, and south shooting-lines around the OBS (see track chart, Fig. 33). The east line was unreversed. Shooting directions were aligned so as to correspond to the directions of maximum (east-west) and minimum (north-south) Moho velocity found by Raitt and others (1969) during the "Flora" experiment.
Tracks of R/V MAHI during near-refraction seismic shooting runs around the Columbia ocean-bottom seismometer. The solid tracks are explosive shooting runs, the dashed tracks represent other geophysical data collection. The dashed lines parallel to the tracks near the OBS site are ASPER runs.
Figure 34. Composite of arrivals on vertical geophone during shooting line to the east from the Columbia ocean-bottom seismometer.
on the Monterey Fan, a similar physiographic area located only about 350 km southeast of the OBS.

Figure 34 is a composite of arrivals received by the OBS vertical geophone, resulting from shooting along the line to the east, while Figure 35 shows a similar composite made from the same shots, but in this case recorded from a horizontal geophone. Very prominent compressional (P) wave arrivals characterize the records from the vertical geophone, whereas prominent shear (S) arrivals that were converted from refracted P waves at the base of the sediment column appear as the first arrival on the records from the horizontal geophone. S waves that travelled as refractions in the crust also appear as very strong late arrivals.

The ASPER records, while yielding no S-arrival data, were extremely valuable for reversing the OBS data and for delineating the late arrivals from the 4.04 - 4.31 km/sec layer and the 7.40 - 7.47 km/sec layer, which were not clearly seen in data from OBS.

The resultant travel-time plots for the OBS in all directions are shown in Figures 36 and 37. The calculated ray paths of the predominant arrivals at the OBS are shown in Figure 38. It can be seen that individual shot-to-receiver distances had to be calculated for each set of arrivals, depending on the path travelled through the crust, in order to correct the OBS data to the surface where reversals could be made using ASPER data.
Figure 35. Composite of arrivals on a horizontal geophone during explosion shooting-run to the east from the Columbia ocean-bottom seismometer.
Figure 36. North-south travel-time plot at the Columbia ocean-bottom seismometer.
DIRECT WATER WAVE SECONDS

0 10 20 30 40

SOUTH

S3 • 6.30 + X/6.42
S4 • 6.67 + X/7.38
S5 • 7.25 + X/7.81

NORTH

N3 • 4.09 + X/4.09
N4 • 6.31 + X/6.51
N5 • 6.87 + X/7.41
N6 • 7.26 + X/8.00

N7 • 5.40 + X/5.41
N8 • 6.26 + X/6.26
N9 • 9.05 + X/9.05

S1 • 3.62 + X/2.06
S2 • 5.50 + X/3.98
S3 • 6.30 + X/6.42
S4 • 6.67 + X/7.38
S5 • 7.25 + X/7.81

S6 • 6.55 + X/3.84
S7 • 9.64 + X/9.59
S8 • 9.64 + X/9.59
S9 • 9.64 + X/9.59

N1 • 3.61 + X/2.06
N2 • 4.41 + X/2.06
N3 • 5.50 + X/4.09
N4 • 6.31 + X/6.51
N5 • 6.87 + X/7.41
N6 • 7.26 + X/8.00

N7 • 5.64 + X/2.06
N8 • 8.26 + X/6.72
N9 • 8.26 + X/6.72
N10 • 9.65 + X/4.54
N11 • 9.65 + X/4.54

80 70 60 50 40 30 20 10 0 10 20 30 40
Figure 37. East-west travel-time plot at the Columbia ocean-bottom seismometer.
Figure 38. Ray paths for various arrivals at Columbia ocean-bottom seismometer through average crustal section at the station. P waves are solid lines, S waves are dashed lines.
Velocities shown in parenthesis in the travel-time plots were assumed, based on other measurements at the site. The sediment velocities were obtained by a $t^2 - x^2$ interpretation of ASPER station 30. The velocity of the lower sediment layer was also indicated by late refracted arrivals on ASPER record 28.

Although a preliminary crustal interpretation using this data had been previously reported (Hussong and others, 1969; Sutton and others, 1971), the data have now been reinterpreted based on a complete reevaluation of the records. The preliminary models evolved from travel-time plots picked from records made at the time of shooting, on which water-wave arrivals used for shot-to-receiver distance determinations were poorly reproduced. The models presented here, however, were evolved from records replayed from magnetic tapes and enhanced by more rigorous filtering. The resultant compressional velocity models, incorporating additional water-wave corrections, have basically the same layering as the preliminary work, but differ in that the velocities are somewhat lower (Fig. 39).

The crust under the Columbia OBS characterizes what appears, from the data in this paper, to be fairly typical oceanic crustal structure, including the 7.4 - 7.5 km/sec basal crustal layer. The Moho is shown to have relatively low compressional velocity, and exhibits no apparent velocity anisotropy. The apparent lack of velocity variation shown
Figure 39. Crustal structure around the Columbia ocean-bottom seismometer (see text). $V_p$ and $V_s$ values are shown; $V_s$ is underlined.
in these individual determinations does not preclude its existence, since a statistical determination of a large number of Moho arrivals from all azimuths is needed to define the anisotropy pattern in the scatter caused by other lateral velocity changes due to structural or crustal inhomogeneities. However, this lack of anisotropy was unexpected in light of the velocity variation of up to 0.3 km/sec found by Scripps (Raitt and others, 1969) during the "Flora" experiment.

The travel-time plots (Figs. 36 and 37) indicate that there is somewhat more scatter in the corrected first-arrival times on the north-south lines than on the east-west lines, which would suggest that there are more small-scale structural and velocity variations in the north-south directions. The possible implications of this scatter will be discussed in the next section.

Refracted shear velocity ($V_s$) determinations at the OBS site are shown in Tables 2 and 3, together with the resultant calculated values for Poisson's Ratio. As is also shown on the travel-time plots (Figs. 36 and 37), these velocities were actually measured only on those layers with average $V_s$ values of 2.22, 3.69, and 4.56 km/sec. The $V_s$ values for the sediment layers were determined from the delay time of arrivals that had been converted to shear waves at the base of the sediments after travelling to that point as P waves. A bulk $V_s$ for the sediments was then determined, and the two $V_s$ values in the two sediment layers, constrained by a constant Poisson's Ratio.
### TABLE 2

**SHEAR VELOCITIES AT COLUMBIA OBS SITE**

<table>
<thead>
<tr>
<th>Average Compressional Velocity</th>
<th>Shear Velocity</th>
<th>Average Shear Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North</td>
<td>South</td>
</tr>
<tr>
<td>2.06</td>
<td>0.4*</td>
<td></td>
</tr>
<tr>
<td>2.65</td>
<td>0.5*</td>
<td></td>
</tr>
<tr>
<td>4.14</td>
<td>2.19</td>
<td>2.24</td>
</tr>
<tr>
<td>6.56</td>
<td>3.64</td>
<td>3.67</td>
</tr>
<tr>
<td>7.44</td>
<td></td>
<td>4.2*</td>
</tr>
<tr>
<td>7.98</td>
<td>4.54</td>
<td>4.59</td>
</tr>
</tbody>
</table>

*Not measured directly (see text). Averaged for all directions.*
### TABLE 3

POISSON'S RATIOS AT COLUMBIA OBS SITE

<table>
<thead>
<tr>
<th>Average Compressional Velocity</th>
<th>Average Shear Velocity</th>
<th>Poisson's Ratio</th>
<th>Average Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.06</td>
<td>0.4</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>2.65</td>
<td>0.5</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>4.14</td>
<td>2.22</td>
<td>0.305 0.278 0.298</td>
<td>0.262 0.255 0.262 0.256**</td>
</tr>
<tr>
<td>6.56</td>
<td>3.69</td>
<td>0.273 0.257 0.260</td>
<td>0.255 0.262 0.259</td>
</tr>
<tr>
<td>7.44</td>
<td>4.2</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>7.98</td>
<td>4.56</td>
<td>0.263 0.236 0.262</td>
<td>0.259</td>
</tr>
</tbody>
</table>

**Average would be 0.261 if lowest value (South) neglected.**
The $V_s$ value through the 7.4 km/sec ($V_p$) basal crustal layer was determined by accepting the thickness of the layer from the $V_p$ model, and calculating the delay time (and consequently the velocity) of the $S$ wave through this known thickness.

**GEOLOGY OF THE OCEANIC CRUST**

Although not the primary objective of this investigation, it is interesting to speculate on the possible relationship of some of the crustal data assembled here to current ideas on the geology of the oceanic crust. The detailed crustal models, based on compressional and shear velocity data, obtained at the OBS site off the California coast, are particularly applicable to such a discussion.

The low values for $V_s$ (0.4 and 0.5 km/sec) determined for the sediments at OBS are in reasonable agreement with those measured in situ (Hamilton and others, 1970) and in laboratory experiments (Hamilton, 1971). The Poisson's Ratio observed for the sediments at OBS is 0.48, and Hamilton reports a Poisson's Ratio of 0.484 for an average of 54 samples of abyssal turbidites. The values for $V_p$ (2.06 to 2.65 km/sec) obtained for the sediments at the OBS site are, however, generally higher than those measured by Hamilton (1.50 to 1.79 km/sec). This difference in $V_p$ could be a function of compaction of the sediments. However, the high Poisson's Ratio indicates that none of
these sediments are lithified.

Beneath the sediments, material with a Poisson's Ratio of 0.30 is found. This layer, a little more than 1 km thick, has a compressional velocity averaging 4.14 km/sec, which appears low as compared to the Pacific-wide average of approximately 5.1 km/sec for Layer 2 (Raitt and others, 1963; Shor and others, 1970). The OBS value, however, is consistent with the basement velocity values previously reported in this same region of the Eastern Pacific (Shor and others, 1970). This layer is thought to be responsible for the characteristic magnetic anomaly lineations west of the California coast (Mason, 1958; Mason and Raff, 1961). The value of 0.30 for Poisson's Ratio falls within the wide range of values measured in the laboratory for unaltered basalts (Manghnani and Woolard, 1968). It thus appears reasonable, considering the magnetic and seismic constraints, that this layer consists predominantly of unaltered basalt.

The two lower crustal layers and the uppermost mantle under the OBS all have a Poisson's Ratio value of about 0.26. The results of laboratory measurements of $V_p$ and $V_s$, made at temperatures and pressures approximating those that would be encountered in situ, indicate that a wide range of rocks, from basic to acidic types, have velocities and Poisson's Ratio values within the ranges of those encountered at OBS (M. Manghnani, pers. comm., 1972).
The seismic data from this study does not, therefore, directly favor any of the presently proposed petrologic models for the deep crust and upper mantle. It does, however, suggest three points which are important to eventual determination of deep crust and upper mantle composition: (1) the apparent lack of obvious mantle anisotropy at the Columbia OBS site (a possible explanation of this seeming contradiction with the nearby Scripps data follows; (2) the shear velocity interpretations at the same OBS; and (3) the crustal structure in the South Fiji and East Caroline Basins, compared to that typical of plate material formed at spreading zones. The elaboration of each of these points follows.

The apparent isotropic mantle under the Columbia OBS. There is, as has been discussed, no evidence from the reversed refraction lines of anisotropy at the Columbia OBS site, or at the other perpendicularly oriented refraction lines reported here (Project Duet in the Western Pacific and the lines straddling the Murray Fracture Zone at 152°W Longitude). Although these observations apparently contradict the well-documented evidence of anisotropy measured by the Scripps workers, closer scrutiny is warranted.

The greater amount of scatter of seismic data points on the north-south, as compared with the east-west, profiles at the OBS has been noted in the description of the results of the experiment. This scatter is observed after the
arrival times are corrected for variations in bathymetry and sediment thickness. The relatively small-scale changes in structure and/or velocity which may be responsible for this scatter most likely occur in the crust and, perhaps, the upper mantle. Thus the crust would appear to have a grain, or fabric, striking east-west.

At first this suggested crustal grain seems in contradiction to the surficial evidence, which has shown that a pronounced magnetic anomaly stripe, or grain, strikes north-south and parallel to the supposed spreading zone (Mason and Raff, 1961; Raff and Mason, 1961). Similarly, the bathymetry has exhibited a grain which is expressed by longer wavelength relief in the north-south direction (Naughler and Rea, 1969). Why, then, would the fabric of the crust be expected to have a grain perpendicular to its surface features?

If one envisions a spreading zone, such as the East Pacific Rise, as a linear series of small spreading centers, each characterized by slight variations in magma, then each center would likely be the source of a particular type of crustal material. Each source would produce a crust of slightly varying composition and thickness. All of these spreading zones would contribute, perhaps spasmodically, to the genesis of the oceanic plate which they border. This constantly forming plate would be expected, therefore, to be composed of zones of material with a stripe or petrologic
plumes perpendicular to the linear spreading zone. Each stripe would be the result of the peculiar petrologic characteristics of its individual spreading source along the spreading zone. In effect, the lithosphere would have the appearance of the sky downwind from a row of chimneys, aligned perpendicular to the wind, each chimney spewing out its own peculiar type of smoke. The magnetic anomaly pattern would be largely independent of this fabric, as it is related to the earth's field polarization at the time of crustal genesis, as well as the rate of cooling and spreading of the crust.

A large-scale example of the product of a spreading source, or subzone, producing its own crustal type, might be the Sala-y-Cc:cz Rise trending across the Nazca Plate to the east, and the rise trending beyond Duice Island to the Gambier Islands to the west. It has been suggested that these features are, essentially, plumes spreading from the same source spot on the East Pacific Rise (Morgan, 1972). The typical spreading source would be a small-scale version of this feature, producing plumes with widths on the order of kilometers.

If one accepts this hypothetical crustal and upper mantle fabric striking perpendicular to the spreading zone, it could provide a feasible source of mantle velocity anisotropy. Velocity measurements across the fabric would yield a bulk velocity which is the average of all the
velocities traversed in the stripes, while measurements parallel to the stripes would tend to show higher or lower velocities. Because the first arrivals would have travelled a least-time path, they would be more likely to be observed having travelled along the stripes with higher velocities. The fabric could thus be the source of apparent anisotropy when velocities are measured through it at all different azimuths. However, a single seismic line, purposely aligned to be perpendicular to the magnetic anomaly stripe, might well be confined to one crustal fabric stripe. An observation of this type of anisotropy was observed by Woollard and others (1957), along metamorphic structure beneath the Atlantic Coastal Plain.

The above speculation does not contradict other explanations for the occurrence of mantle anisotropy, it merely proposes a possible source of apparent anisotropy caused by the structural or subtle compositional fabric of essentially isotropic materials. In this manner it would be possible to resolve the HIG OBS Moho velocity measurements, aligned parallel and perpendicular to the magnetic stripe, and the Scripps project Flora anisotropy measurements, measured in all directions.

Shear velocity data at the Columbia OBS site. The Moho shear velocities measured at the Columbia OBS site (Table 2) show no significant variation with direction, and result in values for Poisson's ratio (Table 3) which consistently
approximate 0.26. This value agrees with the Poisson's ratio calculated from oceanic Pn and Sn values estimated from surface-wave determinations (Ewing and others, 1962) and from other explosion refraction results (Houtz and Ewing, 1963), and is only slightly higher than the value for the North Pacific (0.25) from earthquake Pn and Sn data (Woollard and Sutton, 1971).

Much of the speculation on the causes of mantle anisotropy has centered around various possible preferred orientations of olivine crystals, based on the assumption that the mantle is of dunitic composition. However, these discussions have not taken into consideration the values of shear velocities in the various directions through olivine. Table 4 is a summary of the values of seismic velocities through a pure olivine crystal measured by Verma (1960). Morris (1969), considering compressional velocity only, has listed the three possible preferred crystal orientations which would produce the desired anisotropy (higher velocity east-west, lower velocity north-south) that would match the determinations on the Hawaiian Arch. These cases are summarized in Table 5.

In the OBS measurements, and, for that matter, in the case of any marine explosion seismic study, practically all the shear wave energy will be in the form of SV, or vertically polarized shear waves, as opposed to SH, or horizontally polarized shear waves. This occurs because
<table>
<thead>
<tr>
<th>Direction of Wave Propagation</th>
<th>Mode</th>
<th>Direction of Particle Motion</th>
<th>Velocity (km/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[100]</td>
<td>P</td>
<td>[100]</td>
<td>9.87</td>
</tr>
<tr>
<td>[010]</td>
<td>P</td>
<td>[010]</td>
<td>7.73</td>
</tr>
<tr>
<td>[001]</td>
<td>P</td>
<td>[001]</td>
<td>8.65</td>
</tr>
<tr>
<td>[100]</td>
<td>S</td>
<td>[010]</td>
<td>4.88</td>
</tr>
<tr>
<td>[100]</td>
<td>S</td>
<td>[001]</td>
<td>4.87</td>
</tr>
<tr>
<td>[010]</td>
<td>S</td>
<td>[001]</td>
<td>4.88</td>
</tr>
<tr>
<td>[010]</td>
<td>S</td>
<td>[100]</td>
<td>4.42</td>
</tr>
<tr>
<td>[001]</td>
<td>S</td>
<td>[100]</td>
<td>5.00</td>
</tr>
<tr>
<td>[001]</td>
<td>S</td>
<td>[010]</td>
<td>4.54</td>
</tr>
</tbody>
</table>
all the wave energy in the water propagates only in compressional form, and P waves can be converted only to SV waves at the liquid-solid and solid-solid interface below (Ewing and others, 1957).

Since all the shear waves will travel as SV, Verma's values from Table 4 can be applied to the possible orientations of the olivine crystals in Table 5 to find the anticipated shear velocity and calculate Poisson's Ratio values. The result, Table 6, indicates that there is no pure orientation of an olivine crystal which will give the desired distribution of compressional velocities and simultaneously yield a uniform Poisson's ratio approximating 0.26. The available data therefore suggest that olivine crystal orientation, as the source of mantle anisotropy, will not satisfy the observed shear velocity data.

Although the poor fit of the oriented dunite mantle model to the shear velocity data would not directly support any other petrologic model, it makes the widely supported dunite mantle hypothesis somewhat less attractive.

Variations in oceanic crustal structure. The striking contrast between the crustal structure of the Pacific Plate and the South Fiji Basin has been described in the previous chapter. A possible intermediate type of crust, represented by the East Caroline Basin, was also described as less confused than the structure in South Fiji Basin, but not as orderly as the oceanic plate crust that apparently was
TABLE 5
POSSIBLE PREFERRED ORIENTATION OF OLIVINE CRYSTALS
THAT COULD PRODUCE OBSERVED ANISOTROPY
(HIGH VELOCITY EAST-WEST, ETC.)

<table>
<thead>
<tr>
<th>Direction</th>
<th>East-West</th>
<th>North-South</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>[100]</td>
<td>[001]</td>
<td>[010]</td>
</tr>
<tr>
<td>Case II</td>
<td>[100]</td>
<td>[010]</td>
<td>[001]</td>
</tr>
<tr>
<td>Case III</td>
<td>[001]</td>
<td>[010]</td>
<td>[100]</td>
</tr>
</tbody>
</table>
**TABLE 6**

**POISSON'S RATIOS RESULTING FROM FIGURE 5 ORIENTATION**

<table>
<thead>
<tr>
<th>Direction of Measurement</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N-S</td>
<td>E-W</td>
<td>N-S</td>
</tr>
<tr>
<td>$V_p$</td>
<td>8.65</td>
<td>9.87</td>
<td>7.73</td>
</tr>
<tr>
<td>$V_{sv}$</td>
<td>4.54</td>
<td>4.88</td>
<td>4.42</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.309</td>
<td>0.338</td>
<td>0.257</td>
</tr>
<tr>
<td>Does Poisson's Ratio fit OBS measurements?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
formed at spreading zones such as the East Pacific Rise. It was suggested that the East Caroline Basin is an example of extensional crust that formed behind a migrating island arc, but has had on the order of 20 million years of stability in which to somehow adjust into relatively coherent layering.

If one accepts that these crustal types represent successive stages in the ordering with age of the extensional crustal melange, then this change must occur as the result of some form of either chemical or phase transformation. Since there is no evidence of widespread thermal activity in the East Caroline Basin, it is difficult for this writer to envision a mechanism which would foster chemical transformation that would involve actual transport of elements between parts of the crust. It is intuitively easier to visualize a change in composition to be the result of phase transformations, thereby eliminating the difficult task of actual transporting material within the crust. The interpretation of the origin of these contrasting types of oceanic crust encourages the hypothesis of a basalt-eclogite regime (such as proposed by Ito and Kennedy, 1970, among others) which may have the potential to reorder crustal make-up through long-term phase transformations.
SUMMARY OF CONCLUSIONS

The development and use of the ASPER technique and ocean bottom seismometers has provided the quality of data needed for higher resolution interpretations of oceanic crustal structure. These geophysical tools are being refined toward a level of efficiency that will promote their increased usage, thereby augmenting both the quantity and the quality of this important information. Examples of geologic interpretations resulting from this improved data are:

(1) The identification and differentiation of two distinct types of oceanic crust; one which apparently formed at spreading centers and is characteristic of the oceanic plates, and a second type which apparently formed in extensional regions behind migrating island arc systems. The first type of crust, formed at spreading centers, has well-defined layering with consistent velocities and appears well differentiated. Behind island arcs the crust has the confused character expected of the frozen, upwelling melange of mantle material filling the expanding crustal region. In the South Fiji Basin previous conventional seismic studies failed to demonstrate the difference in these crustal types.

(2) The correlation of other crustal structure, such as the widespread 5.5 - 5.6 km/sec layer on the Ontong Java Plateau. This layer was interpreted as flood basalts.
(Kroenke, ms. submitted to G.S.A.) largely as a result of its consistent correlation in the ASPER interpretations. ASPER work on the Manihiki Plateau now suggests that this feature may have a structure, and origin, similar to that of the Ontong Java Plateau. Similarly, the oceanic crust straddling the Murray Fracture Zone was found to be uniform from ASPER interpretations. Previous conventional seismic studies in both these areas failed to correlate significant structure, and therefore yielded faulty geologic conclusions based on the lack of crustal resolution.

(3) The further identification of consistent layers in the crust that are not prominent on conventional seismic records, notably the 7.4 km/sec layer throughout the Pacific, and the less commonly observed approximately 6.0 km/sec layer determined at many stations (East Caroline Basin, Duet, OBS, etc.).

The data discussed here will not independently resolve the question of the composition of the deep crust and upper mantle of the earth. However, several constraints which must be imposed on hypothesized petrologic models of these regions are suggested and are summarized as follows:

(1) The apparent disagreement of the detailed crustal velocity model at the Columbia OBS site with nearby Scripps anisotropy data prompts speculation that mantle anisotropy could be caused by lithospheric structural fabric of isotropic materials, rather than preferred orientation of
anisotropic minerals.

(2) The observed shear velocity values at the same OBS site will not satisfy a theoretical model of an upper mantle composed largely of oriented anisotropic olivine crystals.

(3) Crustal structure in the South Fiji and East Caroline Basins, compared with that on areas of the Pacific lithospheric plate, would be conveniently explained if some mechanism for crustal reordering, perhaps through a type of long-term phase transformation, could be employed to explain a possible trend in these basins which results in an apparent ordering of the crust with age from a confused melange of velocities to increasingly well-defined layers of fairly consistent velocities.
ACKNOWLEDGMENTS

Marine seismic refraction studies are notorious in geophysics because their success depends on a tremendous effort by a great number of people. This study, although largely employing simplified data collection procedures, was no exception and is the product of too many workers to acknowledge individually.

The cooperation and support of the captains, crews, and scientific complements of the R/V MAHI, R/V VITIAZ, and R/V KANA KEOKI was fundamental to the project and is deeply appreciated. In particular, the invaluable contributions of W. N. Ichinose, L. W. Kroenke, and G. L. Maynard toward the development of the ASPER technique are gratefully acknowledged. The assistance of I. P. Kosmanskaya, A. Malahoff, A. A. Nowroozi, M. E. Odegard, and G. B. Udintsev, among others, during Project Duet and the Columbia OBS field work is much appreciated. I am especially thankful for the assistance of S. P. Dang, G. L. Maynard, M. E. Odegard, and L. K. Wipperman, during the often tedious reduction of the data prepared for this dissertation.

Mrs. Ethel McAfee edited the manuscript, and L. W. Kroenke made many suggestions which contributed to the organization and clarity of the dissertation. Miss Betty Matsui and Mrs. Karen Oshiro typed the various drafts of this dissertation. S. P. Dang drafted most of the
illustrations. To these people, I give my particular thanks, because without their help the job of presenting this data would have been overwhelming.

This research was supported by the Office of Naval Research under contracts Nonr 3748(05) and N00014-70-A-0016-0001 and by the National Science Foundation under grants NSF-GA-15792, and NSF-1084.


REFERENCES CITED (Continued)


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