VERTICAL SEISMIC PROFILING (VSP) AND THE OCEAN DRILLING PROGRAM (ODP)

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CONVENED BY:

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I. EXECUTIVE SUMMARY

The potential role of Vertical Seismic Profiling (VSP) and other borehole seismic experimentation within the Ocean Drilling Program (ODP) was examined by a group of twenty-eight specialists, including academic marine and land-based seismologists, logging specialists, industry scientists and contractors at a two-day workshop sponsored by JOI/USSAC (see Appendices I and II). The venue was the Colorado School of Mines. The group achieved consensus on the following, which are presented here as recommendations for the development of a vigorous VSP program that would significantly enhance the scientific return of ocean drilling.

1. VSPs should become an integral part of ODP science because of their unique ability to:
   a) provide a direct tie between the drilled section, logged properties and surface seismics
   b) determine formation velocity structure
   c) determine anisotropy and heterogeneity, and resolve structural images in complex settings
   d) predict structure beneath the drill bit.
2. ZERO-OFFSET VSPs should be performed at all sites in structurally simple settings where sonic logs will also be run.
3. OFFSET VSPs such as walk-away VSPs, oblique seismic experiments, or single-offset VSPs should be performed for specialized applications in structurally complex settings. High density coverage of geophysical data is essential to the success of these experiments.
4. Substantial improvements in tools and analysis capabilities must be accomplished to ensure a viable program. These include:
   a) broad-band tuned source arrays
   b) three-component tools
   c) multi-element vertical arrays of geophones and hydrophones
   d) computer processing and modeling capability at sea and on shore.
5. A "U.S. National VSP Laboratory" should be established to carry out VSPs as required by the U.S. science community, coordinate development of VSP technology and analysis, and assist in specialized borehole seismic experiments.

II. INTRODUCTION

The combined efforts of the DSDP and ODP drilling have resulted in the sinking of more than 700 boreholes. The scientific objectives have varied widely from site to site; in some cases they were as simple as determining the age and nature of the sediments, others had more sophisticated paleontological, paleoclimatic or geochemical objectives, still others aimed to examine the origin of igneous basement. Typically, the drilling objectives were regional rather than site specific in nature. Extrapolation beyond the hole has usually been achieved by creating a tie of the drilled stratigraphic section to a regional grid of seismic reflection lines. As the drilling program evolved the need for adequate site surveys became increasingly clear, not only to ensure that the drilling information could be extended beyond the borehole, but also to ensure that sites were located so as to maximize the value of the drilling.

The link between the drilled geological datum and geophysical measurements was further strengthened when geophysical logging evolved to become a routine part of scientific drilling. At minimum, logging can be used to give information on parts of the section that were not cored. Beyond that, logging provides a wealth of physical and chemical property measurements of the section in situ that cannot be duplicated by laboratory measurements on incompletely cored sections (See summary of ODP's Logging Program, Appendix III). At present virtually all holes drilled to depths greater than 400 m are logged with a standard suite of tools, and many include special runs. Sonic logging, while not yet routine, is becoming an integral part of many down-hole experiments.

A very different type of borehole geophysical experiment that has seen a tremendous rise in application in the exploration industry is the Vertical Seismic Profile (VSP). In these experiments geophones are located in the borehole itself and record arrivals generated at the surface, thereby providing a precise and unequivocal tie between surface seismics and the drilled datum (Figure 1). Furthermore, because the geophone is actually within the drilled section and because relatively simple computer processing techniques can be used to analyze the recorded wavefield (separation of upwaves and downwaves by f-k methods, for instance) it is possible to recognize and eliminate coherent noise signals such as interbed multiples that are difficult to treat effectively in surface seismic data, and are a major source of interpretational difficulty in the analysis of MCS reflection profiles.

The seismic-to-borehole tie is perhaps the simplest, most straightforward, VSP application. It can be achieved entirely by drillship mounted equipment, and requires a minimum amount of data processing to achieve a result. However, the VSP methodology, particularly when developed into the OFFSET VSP experimental configurations (offset source VSP, walk-away VSP, or oblique seismic experiments), offers the potential of recovering a huge amount of information on the physical properties and structure around and beneath the drill string that could be immensely valuable to the scientific objectives of scientific ocean drilling.

For instance, scientific drilling objectives often lead to the location of boreholes in complicated structures such as rotated fault blocks on passive margins, or the tightly folded and faulted structure in an accretionary prism.

Seismic images created using VSP methods can produce much more accurate representations of the structure around a drill site than surface seismic imaging is capable of achieving and, of course, include a precise tie to the drilled section free from the confusions that may be caused by out-of-plane events such as side-swipe. In the exploration industry this technique has proved extremely valuable for the geologic interpretation of seismically imaged structure, and could be of considerable benefit to the science community for the same reason.

A wealth of physical property measurements that can also be derived from VSP data include intrinsic attenuation, crack porosity and orientation, permeability, detailed velocity depth models including P- and S-wave structure and, hence, Poisson ratios. VSP experiments can also be conducted to determine structural and physical property heterogeneity, and anisotropy around a drill hole.

While the value of the VSP experiment to the exploration industry has been extensively described and their application is virtually commonplace, the method has seen little use in ODP. VSP's are presently run as specialized experiments; only two zero-offset experiments, and a handful of nonzero offset experiments have been run. Each of these originated through individual initiatives on the part of several scientists who were generally not principal investigators on the drilling legs on which the VSPs were acquired. Hence, VSPs have been conducted as "add-on" experiments, rather than as an integral part of the science associated with scientific drilling (see Section IV below).

In late August, 1987, under sponsorship of JOI/USSAC, we gathered together a group of VSP experts from the exploration industry and academic seismologists knowledgeable of ODP and its objectives. We were charged with the task of assessing the potential that VSP experiments could have in achieving ODP's science objectives, and perhaps even extending the scientific value of ocean drilling. This report summarizes the results of our deliberations, and outlines the elements of a plan for the regularizing of VSP acquisition as an integral component of the ocean drilling program, both in terms of shipboard and shore-based facilities, and as an operational strategy. We begin by providing some discussion of the VSP technique itself illustrated with examples from commercial and scientific applications (Section III), then outlining the VSP work conducted thus far in DSDP (Section IV), before specifically describing the potential benefits of VSP in the ODP and, finally, discussing an implementation plan.

III. VERTICAL SEISMIC PROFILING

Vertical seismic profiling (VSP) is the seismic technique that bridges the gap between surface reflection work and well logs. The method involves use of standard seismic sources, such as air guns or water guns, with the receiving array comprising geophones in a borehole, instead of on the surface (Figure 1). The seismic energy is thus detected "in the medium" that is being studied. Adding this "third dimension" to the seismic technique yields many benefits which will be described below. Even without elaboration we can see that VSP gives us a method of observing seismic energy in "the process of becoming" reflected arrivals. By these experiments we can learn much about how to make the reflection image better, and we can learn a great deal that cannot be recovered from surface reflection data.

When a VSP is carried out, the resulting seismogram appears to comprise the energy from shots at the surface detected by a large array of geophone elements (Figure 2). This "array" covers the entire borehole and we can see the first arriving energy (P wave in this case) propagating down through the medium. We also see that downgoing energy is reflected upward at many interfaces.

Two basic variations in the technique are represented by Figures 1 and 3. The placement of the source makes a major difference in the uses of VSP and, especially offshore, the effort required to do a VSP. If the source is close to the borehole and does not move during the experiment, the experiment is described as a ZERO-OFFSET VSP (Figure 1). If the source is at a large distance from the borehole, then it is termed an OFFSET VSP (Figure 3). In both of these illustrations it is assumed that the borehole is straight. In the ZERO-OFFSET VSP, we examine the structure that immediately surrounds the borehole, while OFFSET VSP's allow one to investigate the medium at some distance from the borehole. In marine investigations this is a major distinction, as it requires a second platform.

In the following we illustrate some of the scientific applications for which the VSP method provides significant advantages over surface seismic experiments.

Velocities

Correct velocities are vital to the study of the Earth. Incorrect velocities not only give us false information about the Earth, they also distort the image of the Earth created by the reflection method. VSP allows us to use the downgoing pulse to determine the velocities. In Figure 4, the white line is the velocity determined from a ZERO-OFFSET VSP, using the times observed in the downgoing pulse, plus the amplitudes of the reflected and transmitted pulses at every interface. The reflection and transmission coefficients themselves depend on the velocities on either side of the interface. Thus the times and the amplitudes in VSP can constrain the velocities much better than one can by using only the times (along a hyperbola) in reflection work.

VSP-derived velocities can also be more accurate than those determined from sonic logging. In the logging technique very high frequency (~20 kHz)

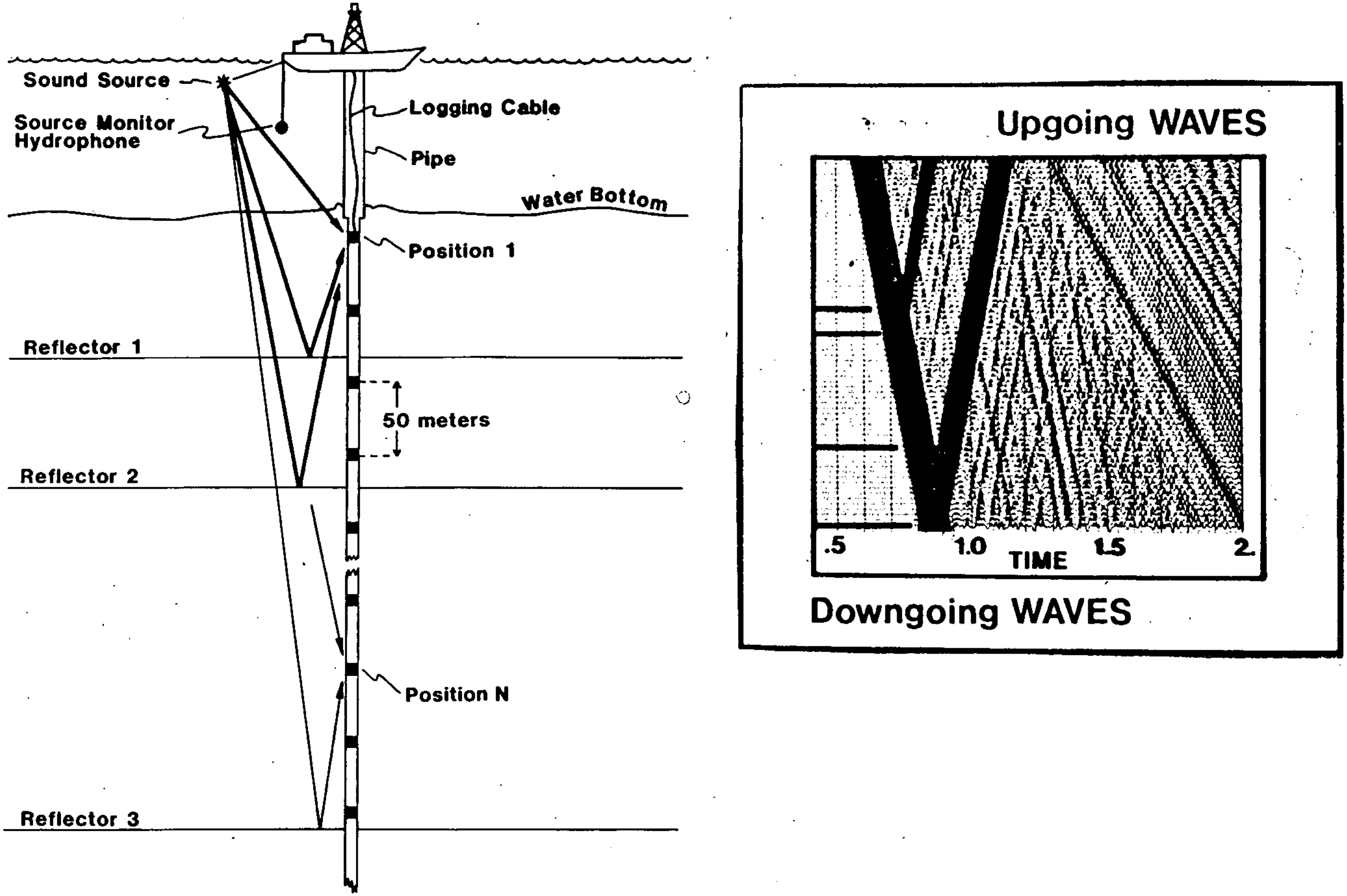

FIGURE 1 SCHEMATIC DESCRIPTION OF THE VERTICAL SEISMIC PROFILING TECHNIQUE. NOTE THAT THE DOWNGOING WAVES AS WELL AS THE UPGOING SIGNALS ARE RECORDED. ONE CAN SEE THE CREATION OF THE REFLECTIONS SEEN IN CONVENTIONAL SURFACE DATA.

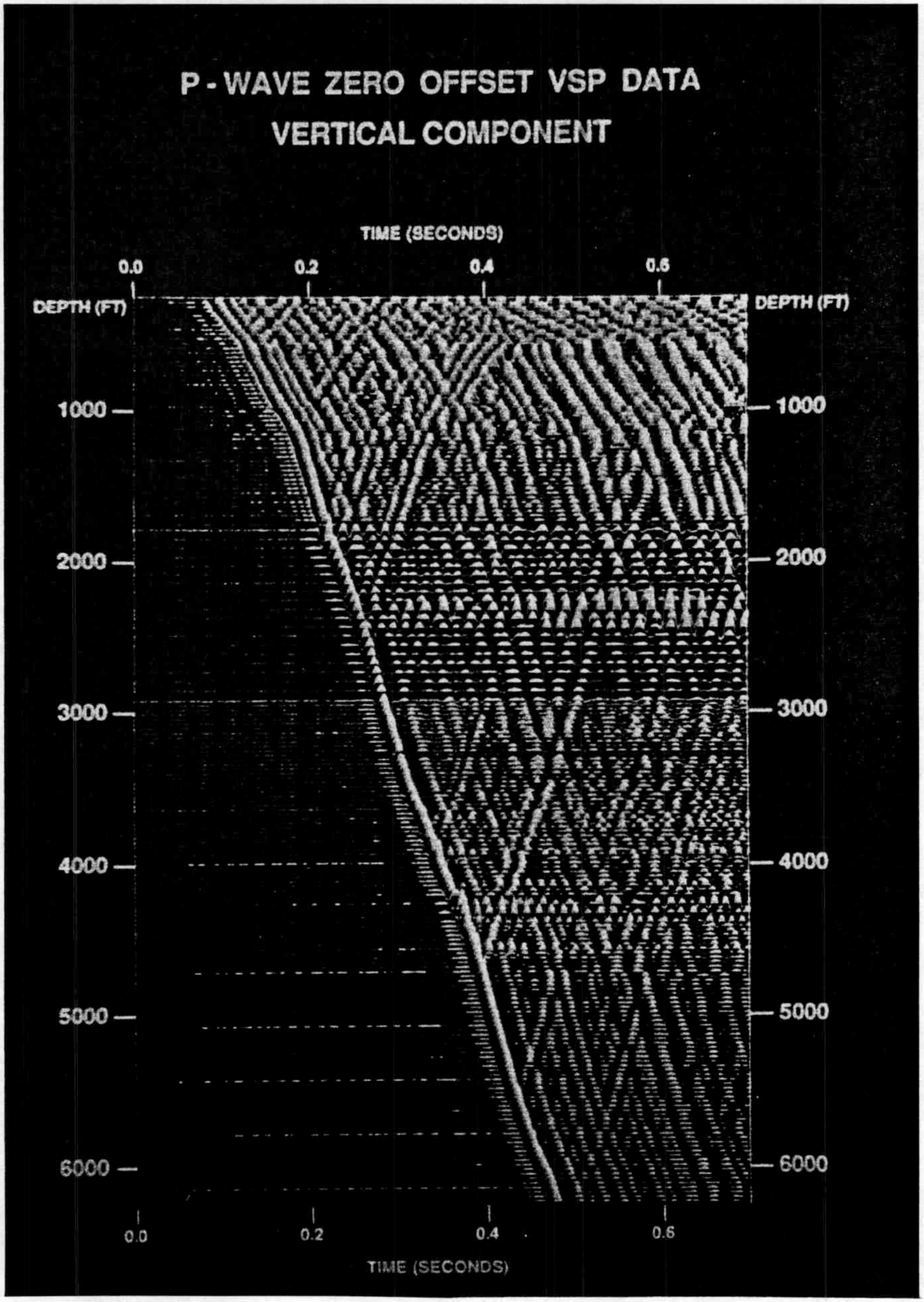

FIGURE 2 COMPLETED VSP. NOTE THAT THE SPACING BETWEEN THE CLAMPING LEVELS IS NOT UNIFORM. FOR LOGISTICAL REASONS THE SPACING IS 60 FT. IN A SMALL REGION WHILE BEING 30 FT. OVER THE MAJORITY OF THE SURVEY.

OFFSET VSP EXPERIMENT

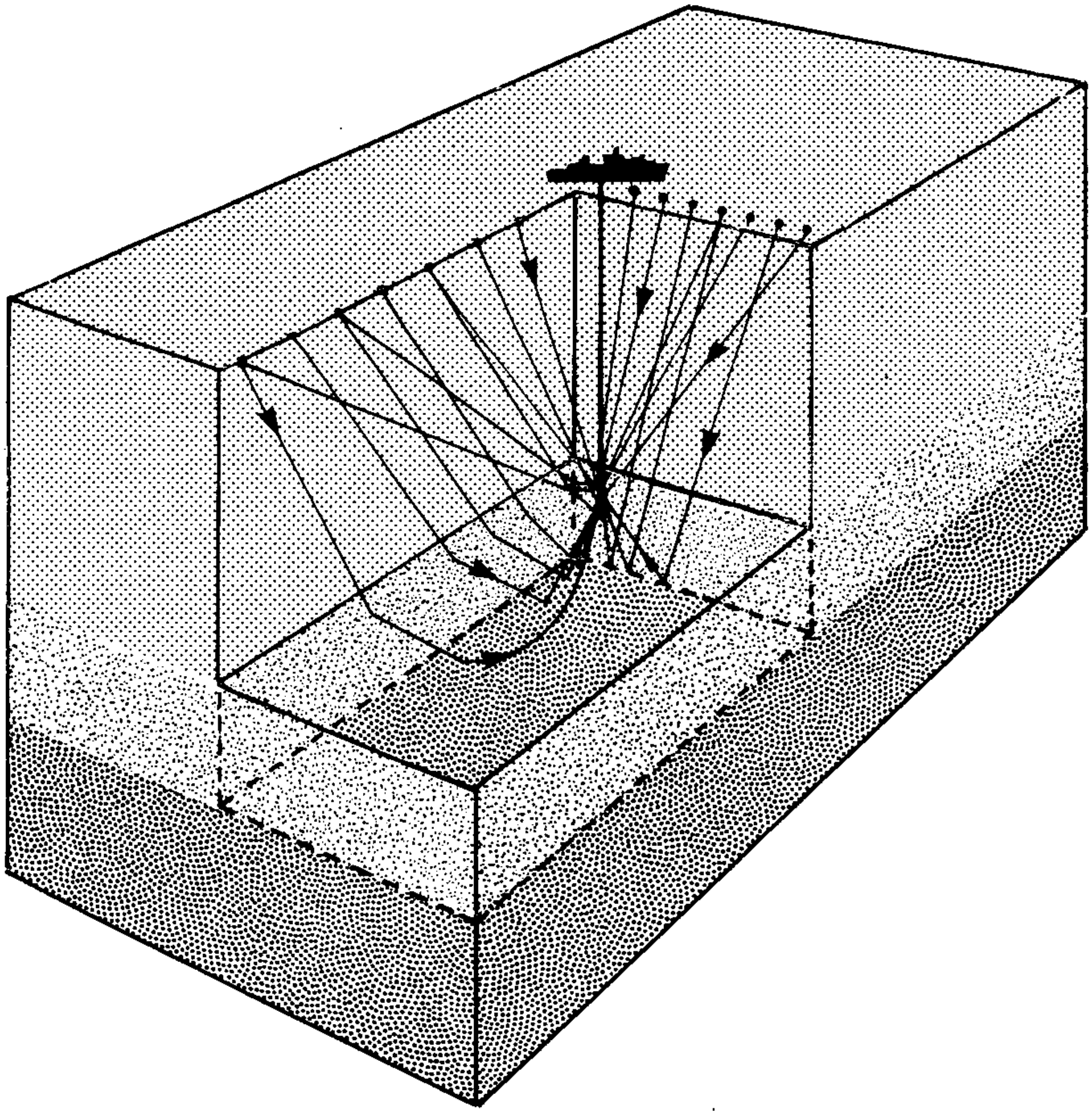

FIGURE 3 SCHEMATIC ILLUSTRATION OF AN OFFSET VSP EXPERIMENT. IN THIS CASE, SHOTS ARE FIRED AT A DISTANCE AWAY FROM THE DRILLSHIP AND RECORDINGS MADE IN THE BOREHOLE. THIS PROVIDES UNIQUE INFORMATION THAT ALLOWS THE AREA AROUND THE BOREHOLE TO BE INVESTIGATED.

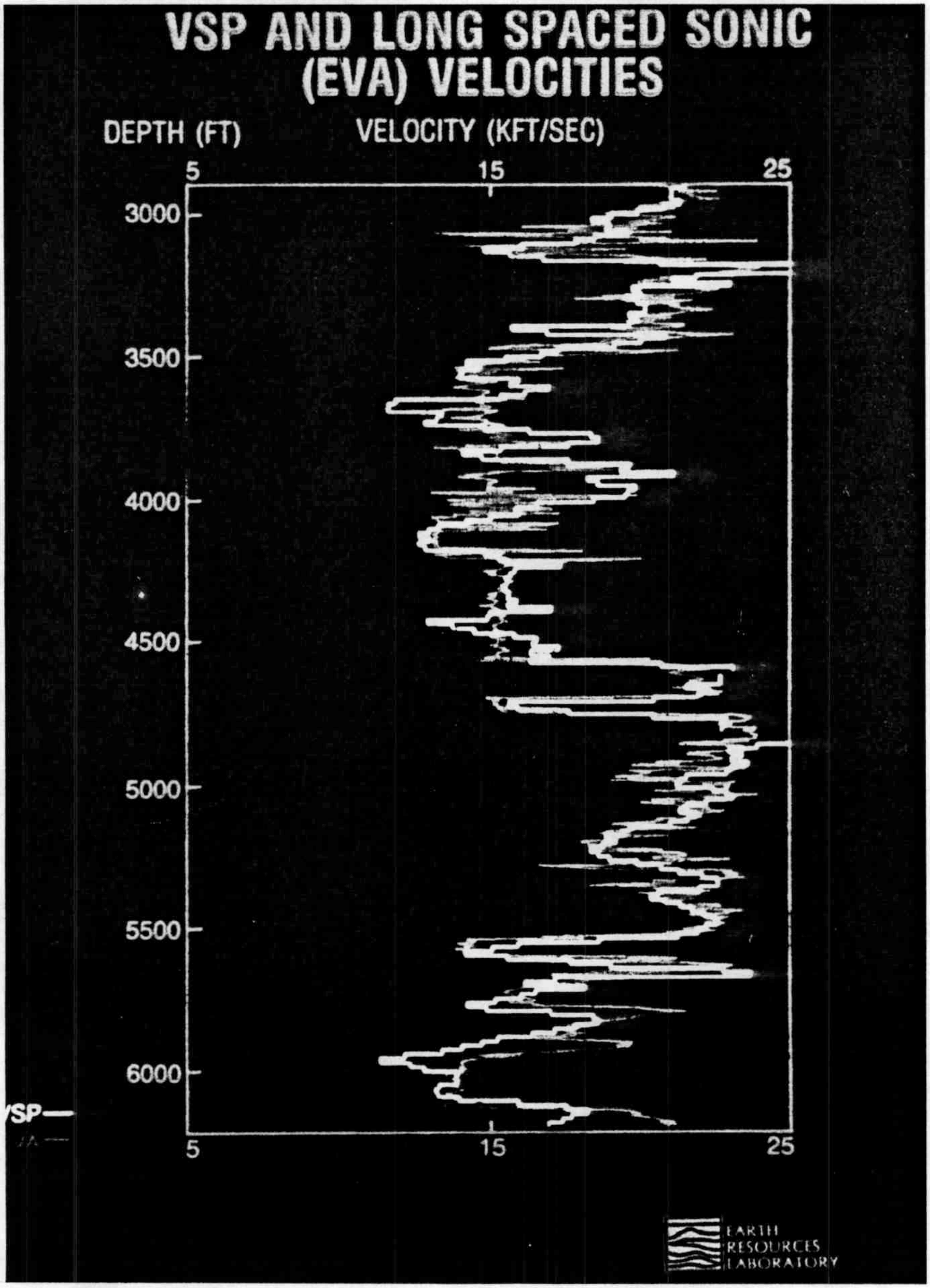

FIGURE 4 COMPARISON OF VELOCITIES DERIVED FROM VSP MEASUREMENTS WITH ACOUSTIC LOGGING VELOCITIES. THE MAJOR DIFFERENCE SEEN FROM APPROXIMATELY 3,750 FT. TO 4,100 FT. IS REAL AND CAUSED BY INTENSE FRACTURING DURING THE DRILLING PROCESS.

pulses are transmitted and received. This means that structure only very near the borehole is examined. The region may be damaged in some way during the drilling process, and hence the medium there is no longer representative of the entire structure. Figure 4 shows that over most of the figure, the VSP velocities and acoustic logging velocities (purple line) agree very well. However, in the region between approximately 3,750 and 4,100 ft., the VSP velocities are higher than the logging velocities. This is a real and important observation. In that region a limestone unit occurs that is always fractured in the drilling process. The logging technique is given a velocity that is too low, or the false impression that the entire medium is fractured. Because the VSP velocities are derived from relatively long wavelength energy, they are not greatly affected by the local imperfections right around the borehole. The velocities derived are indicative of the medium as seen by the reflection method.

The Tie between Well Logs and the Reflection Section

It is clear from the field technique alone that VSP has some of the attributes of acoustic logging and some of the features of surface seismic work. Some of the benefits that fall from this "half-way position" include the following.

Before the advent of VSP, it was a common practice to take the acoustic log from a borehole and calculate a synthetic seismogram that should be observed if a reflection line were shot through the well. Figures 5 show two situations where this procedure (tie) fails.

In Figure 5 (upper panel), we see a structure (possibly a stream channel) that the well bore penetrates, and the logs clearly pinpoint its position in depth. However, the structure is on the order of a wavelength in lateral dimension and thus it is not seen on the reflection line. A synthetic (coincident source and receiver) derived from the acoustic log indicates that a strong reflection should be seen. The confusion is removed when a ZERO-OFFSET VSP is shot in the hole and still no reflection is seen. Without the VSP, one tries to "adjust" the synthetic to fit the reflection data under the assumption that the velocities are wrong. This results, as one knows, in chaos with the other reflection events.

Figure 5 (lower panel) demonstrates the opposite source of confusion. Here the reflection data shows an event, but the well logs show nothing. The figure shows this to be again a sand body, but now the wellbore has gone through a small region where the body has thinned to zero. The synthetic derived from the acoustic log indicates that no reflection is seen in the surface data because the "hole" is on the order of a wavelength in size. Again the confusion is cleared up when a VSP is shot and a clear reflection is seen at a depth where the well logs see nothing.

These two examples provide a clear demonstration that the tie between reflection data and well log data should be achieved using a VSP and not by generating a synthetic from the logs.

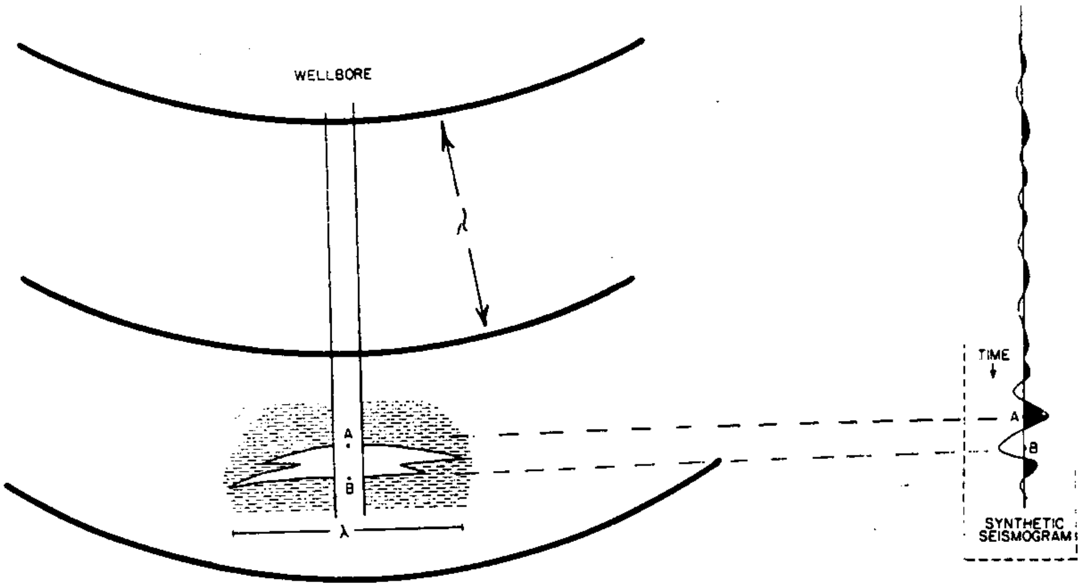

FIGURE 5 (UPPER) VSP SOLUTION TO A HYPOTHETICAL APPARENT CONFLICT BETWEEN SURFACE DATA AND WELL LOGS. REFLECTION DATA FAILS TO SEE THE SMALL (ONE WAVE LENGTH) SAND BODY BUT THE WELL LOGS INDICATE ITS PRESENCE AND PRODUCE A SYNTHETIC (RIGHT) THAT CAN NOT BE FOUND IN THE SURFACE DATA. WHEN THE VSP TOOL OCCUPIES POINTS A AND B AND MANY POINTS ABOVE, AND YET SEES NO REFLECTION THEN ONE CONCLUDES THAT THE SAND BODY IS TOO SMALL TO BE SEEN ON REFLECTION DATA.

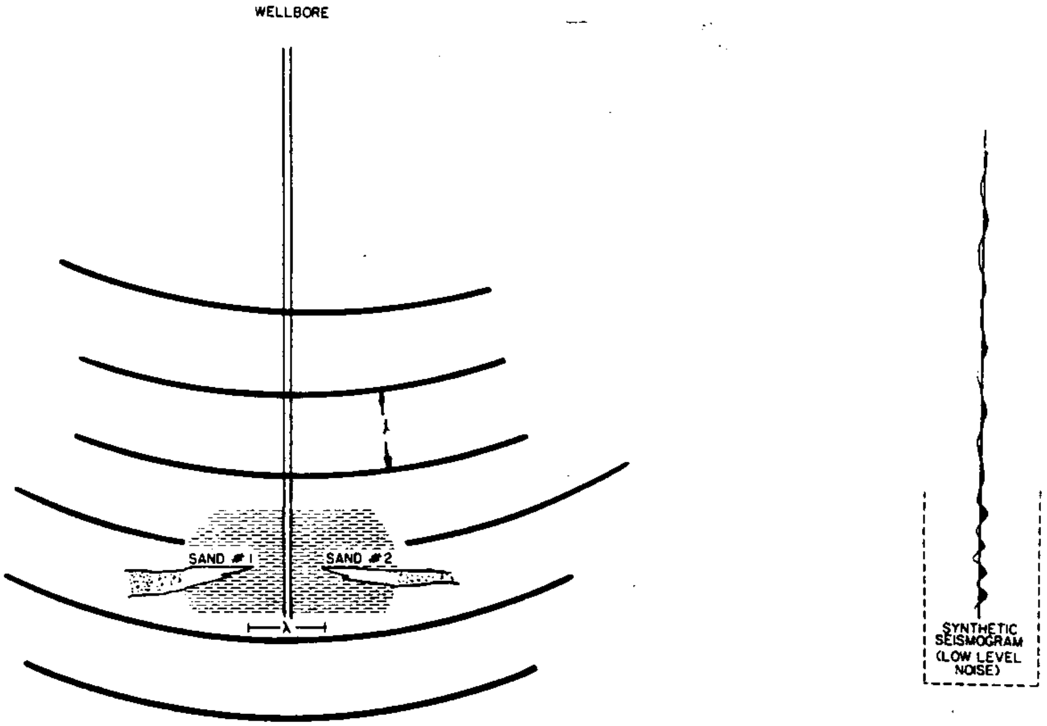

FIGURE 5 (LOWER) ANOTHER HYPOTHETICAL EXAMPLE OF APPARENT CONFLICT BETWEEN REFLECTION DATA AND WELL LOGS. HERE THE SURFACE DATA SEES THE SAND LAYER BUT THE WELL LOGS DO NOT. HERE A VSP WILL SEE A STRONG REFLECTION FROM THE LEVEL OF THE SANDS AND ONE CONCLUDES THAT THE SAND HAS THINNED TO ZERO AT THE BOREHOLE.

Deconvolution Operator

It is generally accepted that in reflection work a deconvolution operator must be used to remove the false images of layers caused by near surface multiples and/or airgun bubble pulses. This is especially true of marine reflection data. The real question is how the deconvolution operator should be derived; what data portion should be used as a clear model of the "ringy wavelet". We noted above that a VSP allows one to "see a reflection being created". This then is the time and place to observe the nature of the wavelet that impinges on the interface and creates the "spiking operator" from the observation. Figure 6 shows that the VSP faithfully contains the required downgoing primary and the unwanted multiples. Furthermore, the time delays of the multiples as they trail the primary are the same as those seen in the reflection data. Thus a deconvolution operator derived from the downgoing VSP data just above the interface in Figure 6 will be the correct operator to be used on the upgoing reflection data. We can see further that a different operator should be generated for every interface in question. Although one may not do this because of the computational expense involved, it is clear that the VSP contains the data from which it could be done.

Seeing ahead of the Bit

If a borehole is of a very important or dangerous nature it may be prudent to stop the drilling a few times and conduct VSPs. Reflections coming from interfaces below the current depth of the drill bit will be seen more clearly in the VSP than in the surface reflection data. Furthermore, estimates of the depth of those reflectors are better in the VSP because the velocities of the drilled section have been obtained from VSP analysis. Velocities ahead of the hole also can be determined from OFFSET VSP to a single downhole receiver.

Elastic Inversion and the Gyroscope

The imaging process, i.e., the inversion of the data, can now be done with algorithms that accommodate the elastic nature of the data. This means that now all of the wave types, compressional and shear, can be used in one imaging process to form the subsurface picture. Using the horizontal geophones in 3-component seismometer and a gyroscope attached to the tool, these images now take on an even better directional nature. Offset VSPs can therefore generate high resolution images around a borehole, and because of the gyroscope those images can be formed into a correct three-dimensional image.

On land, questions of anisotropy can be solved with the use of shear wave sources and a gyroscope attached or incorporated into the VSP tool. In marine studies, converted SV waves can be used with the gyroscope. In Figure 7, we see the transverse geophone portion of such a gyroscopic VSP. Here the source was a shear wave source aligned such that it generated SV waves. The exciting observation in Figure 7 is the large S-wave signal seen on the transverse geophone. Only the VSP technique can record the transmitted S waves, thus making the interpretation unique. In land reflection data, one has to interpret two S-wave passes through the anisotropic layer under study, and an unknown reflection coefficient somewhere beneath the layer. This procedure is fraught with interpretational difficulties. Offshore, the situation is worse - the reflection data are only pressure recordings and thus gyroscopic VSP data are the only data where one can study the effects of anisotropy on the particle motion of any arrivals.

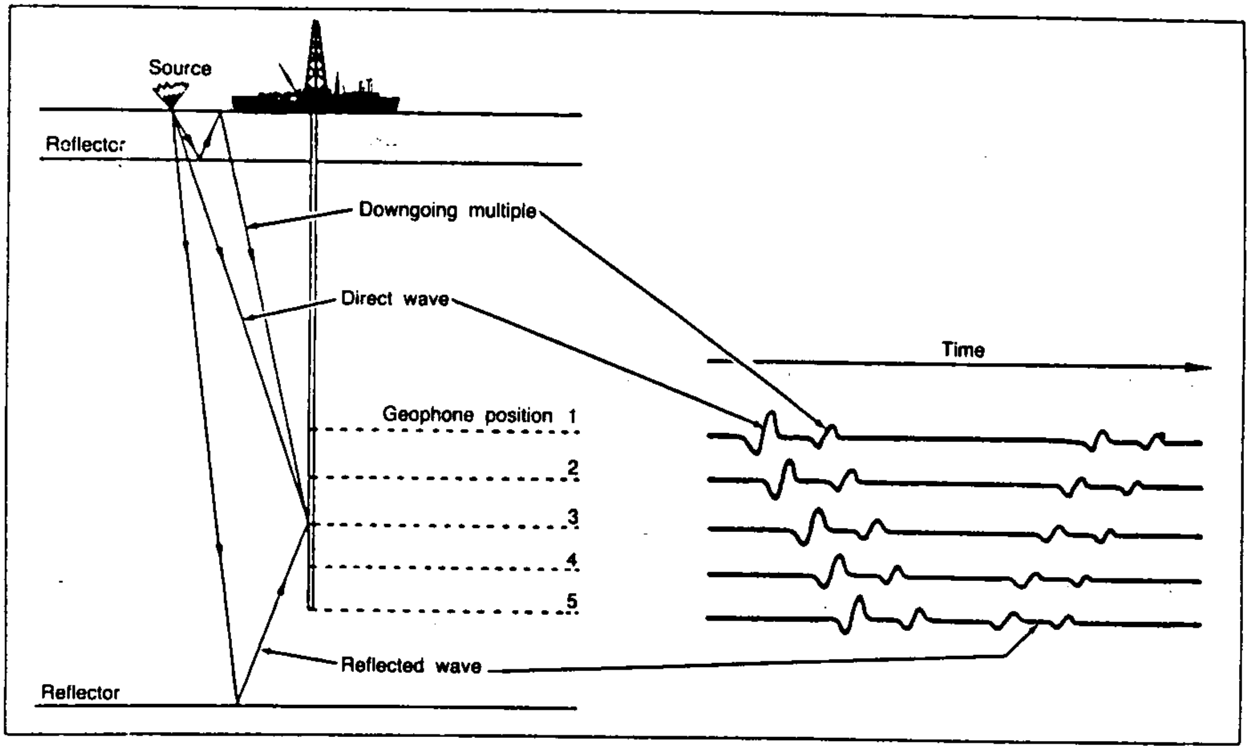

FIGURE 6 FUNDAMENTALS UNDERLYING THE USE OF VSP AS THE SOURCE OF THE CORRECT DECONVOLUTION OPERATOR FOR SURFACE DATA. HERE ONE GETS TO SEE THE UNWANTED RINGY WAVELET (PRIMARY AND TRAILING MULTIPLES) AS THEY IMPINGE ON THE REFLECTOR. WE WANT TO IMAGE THAT REFLECTOR AS SHARPLY AS THE GEOPHYSICS OF THE SITUATION WILL ALLOW. THUS THE CORRECT DECONVOLUTION OPERATOR SHOULD BE DERIVED FROM THE VSP DATA JUST ABOVE THE INTERFACE.

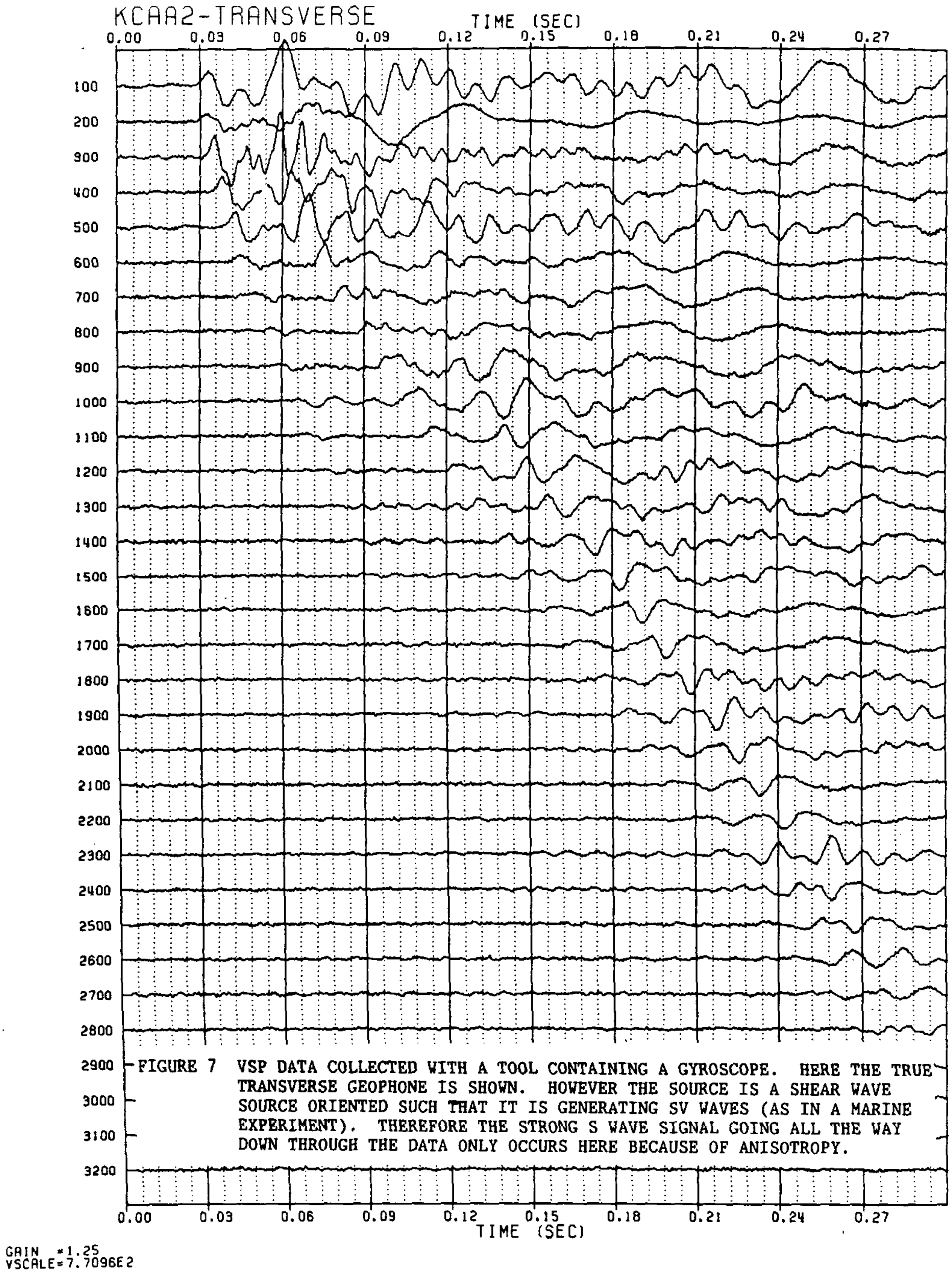

FIGURE 7 VSP DATA COLLECTED WITH A TOOL CONTAINING A GYROSCOPE. HERE THE TRUE TRANSVERSE GEOPHONE IS SHOWN. HOWEVER THE SOURCE IS A SHEAR WAVE SOURCE ORIENTED SUCH THAT IT IS GENERATING SV WAVES (AS IN A MARINE EXPERIMENT). THEREFORE THE STRONG S WAVE SIGNAL GOING ALL THE WAY DOWN THROUGH THE DATA ONLY OCCURS HERE BECAUSE OF ANISOTROPY.

Imaging Structure adjacent to the Hole

VSP integrates extremely well into an overall research program as a complement to reflection data and well logs. Images of the subsurface can, however, be generated from the VSPs alone. Since only the downgoing energy must propagate through the low velocity near surface material, it is generally found that VSP data contains about double the frequency content compared with surface reflection data. Thus the images around the borehole out to about 1 km have about twice the resolution of those derived from surface data.

In any geological study the ultimate proof of any conjecture is to drill into the structure in question. Without using OFFSET VSPs (Figures 3 and 8) it is possible that we will not know, even after drilling, whether or not the drill bit actually hit the target. The subsurface image can be incorrect in three major ways: wrong depth, wrong lateral position, and poor resolution. Thus, the borehole positioned by these data can easily be in a sub-optimal position. When this occurs the cores that are considered to be samples of a target structure may, in fact, not be from that structure, but (and this is the worst part) will still be attributed to that structure. While it is certainly understandable that the drillbit may miss the target, we perpetuate the confusion by assigning the cores (or logs) to the wrong feature. By using OFFSET VSP we can determine the location of the borehole with respect to the target (or the location of the target), and then properly assign all of the information that comes from the borehole to the correct structure.

An actual case history illustrates the problems and solution. In Figure 9 we see the map view of a portion of the Northern Michigan Reef Trend. The position of several 2-D reflection lines are shown. The target for all of these 2-D lines was a pinnacle reef at a depth of about 4500 to 5000 ft. The north-south reflection line on the map (WBE-831, F2414R-20A) is also shown in Figure 9. The event at a time of about 0.75 sec is a reflection from the base of the B Salt and the top of the A2 Carbonate. Although this impedance contrast is very strong, the reflected event is made even stronger by a second thin salt layer under the A2 Carbonate. This "tuned" event is destroyed when a reef is present because the thin salt layer disappears on top of a reef. In Figure 9 we see that the reflection become "ragged," an indication that a reef may exist just below the interface.

For this particular exploration project it was critical to know whether the reef was directly beneath the 2-D reflection line. Given only this 2-D data it is not possible to know whether the structure of interest exists in the plane of the survey. A hole was drilled (near Shotpoint #150) based on this reflection data and found to be dry. A 3-D seismic survey was then run in the area, a time slice from which is shown in Figure 10. The time slice is again taken at a time of about 0.75 sec which shows a circular object with the producing well near its center. We also see that the dry hole is clearly not within the circular object. Thus, the danger of only 2-D seismic reflection lines is evident. This liability of 2-D reflection lines is well known, and 3-D surveys are extremely time consuming and expensive. A relatively simple OFFSET VSP can be used to solve some of these interpretational conflicts.

Several OFFSET VSPs were shot along with the 3-D survey (Figures 11, 12 and 13; F, J. and L; see Figure 9 for shotpoint locations). The corridor stacks (crude migration of the data) displayed in these figures clearly show

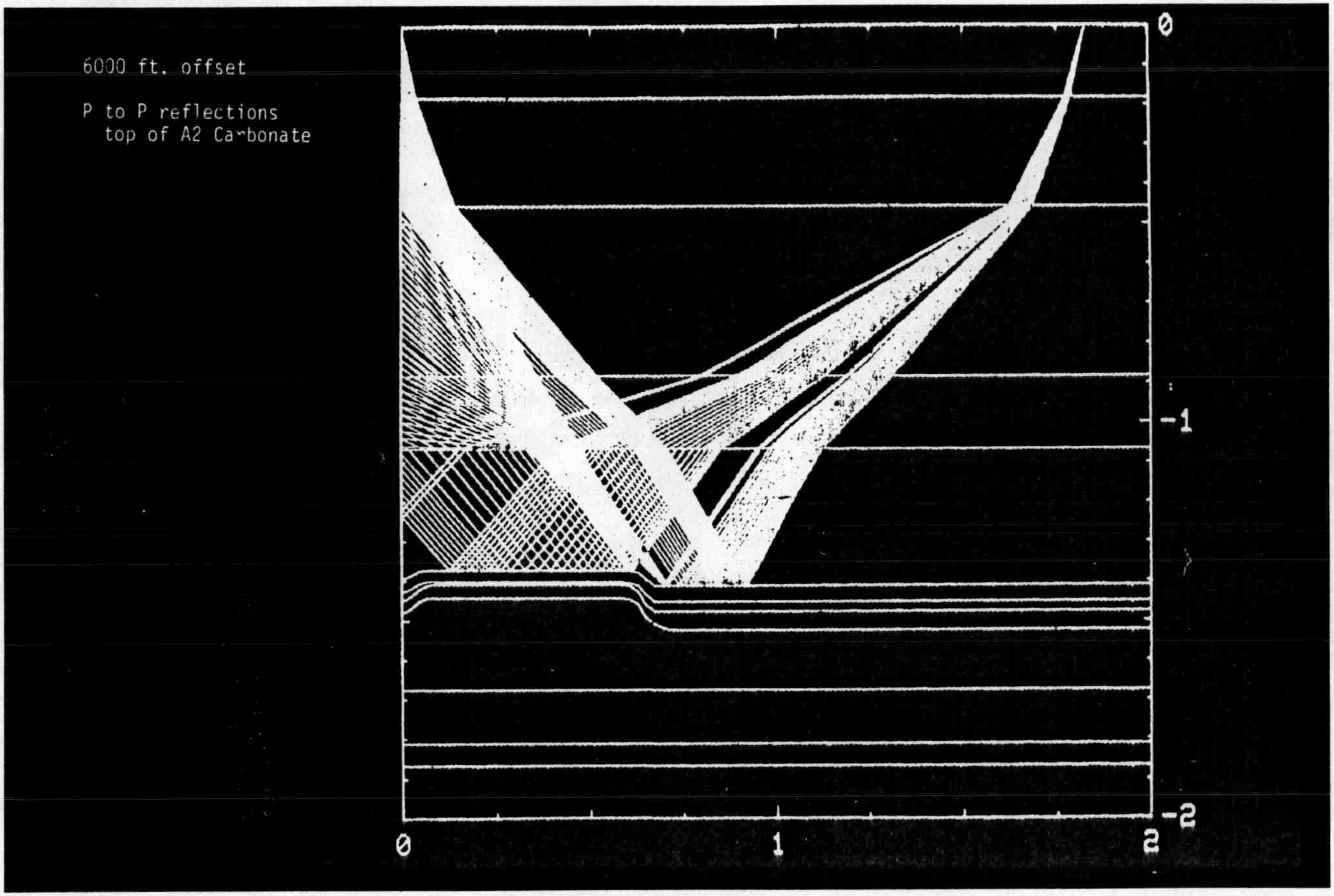

FIGURE 8 RAY TRACING FROM A SHOT AT AN OFFSET OF 6,000 FT. FROM THE BOREHOLE SHOWING REFLECTIONS FROM AN INTERFACE OF INTEREST, WHICH INCLUDES STRUCTURE ADJACENT TO THE BOREHOLE.

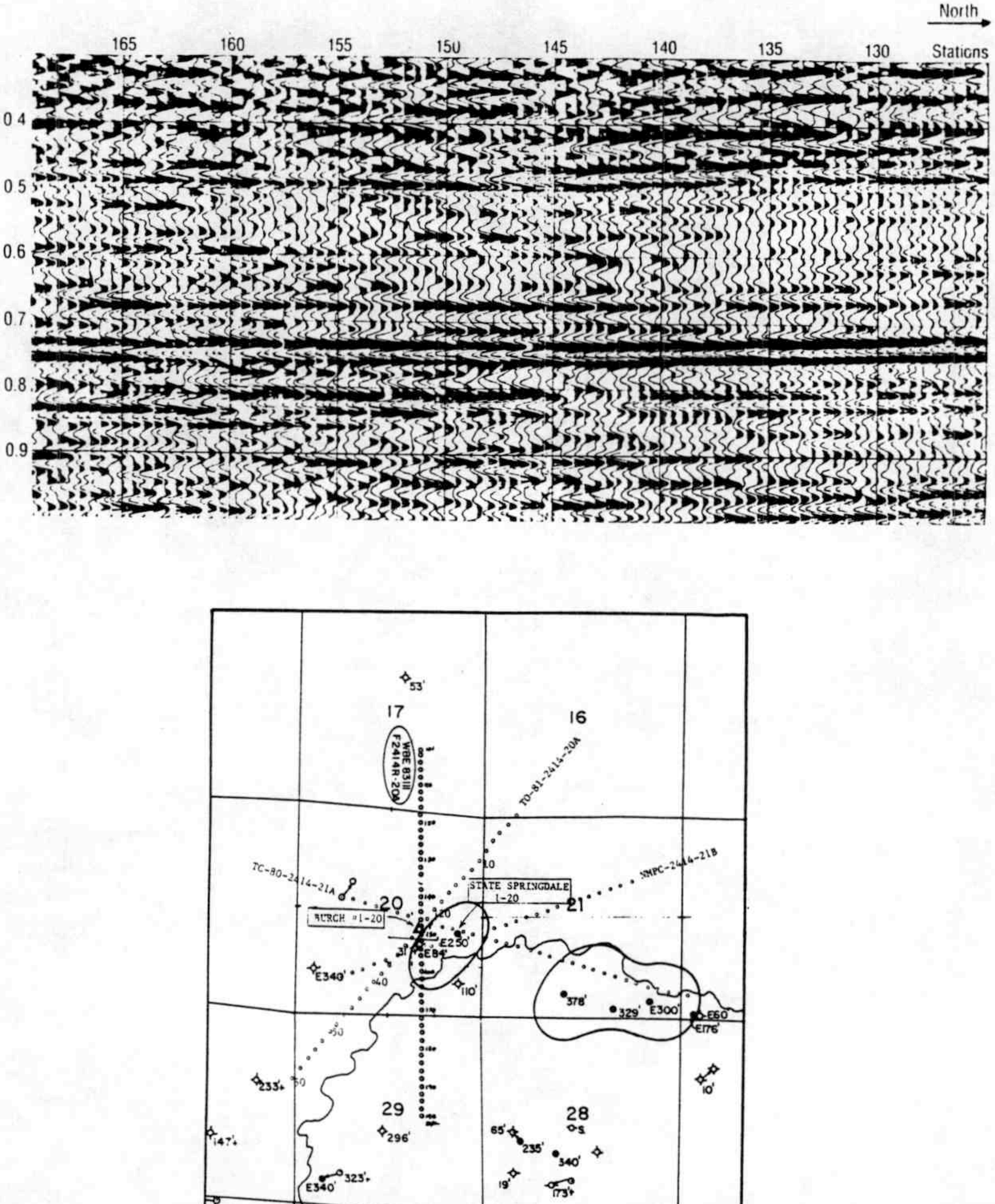

FIGURE 9 REFLECTION PROFILING DATA USED TO INVESTIGATE STRUCTURE OF THE MICHIGAN REEF TREND (UPPER PANEL) WITH SEISMIC AND BOREHOLE DATA DISTRIBUTION IN THE REGION (LOWER PANEL).

3-D SEISMIC SURVEY

740 MILLISECOND TIME SLICE

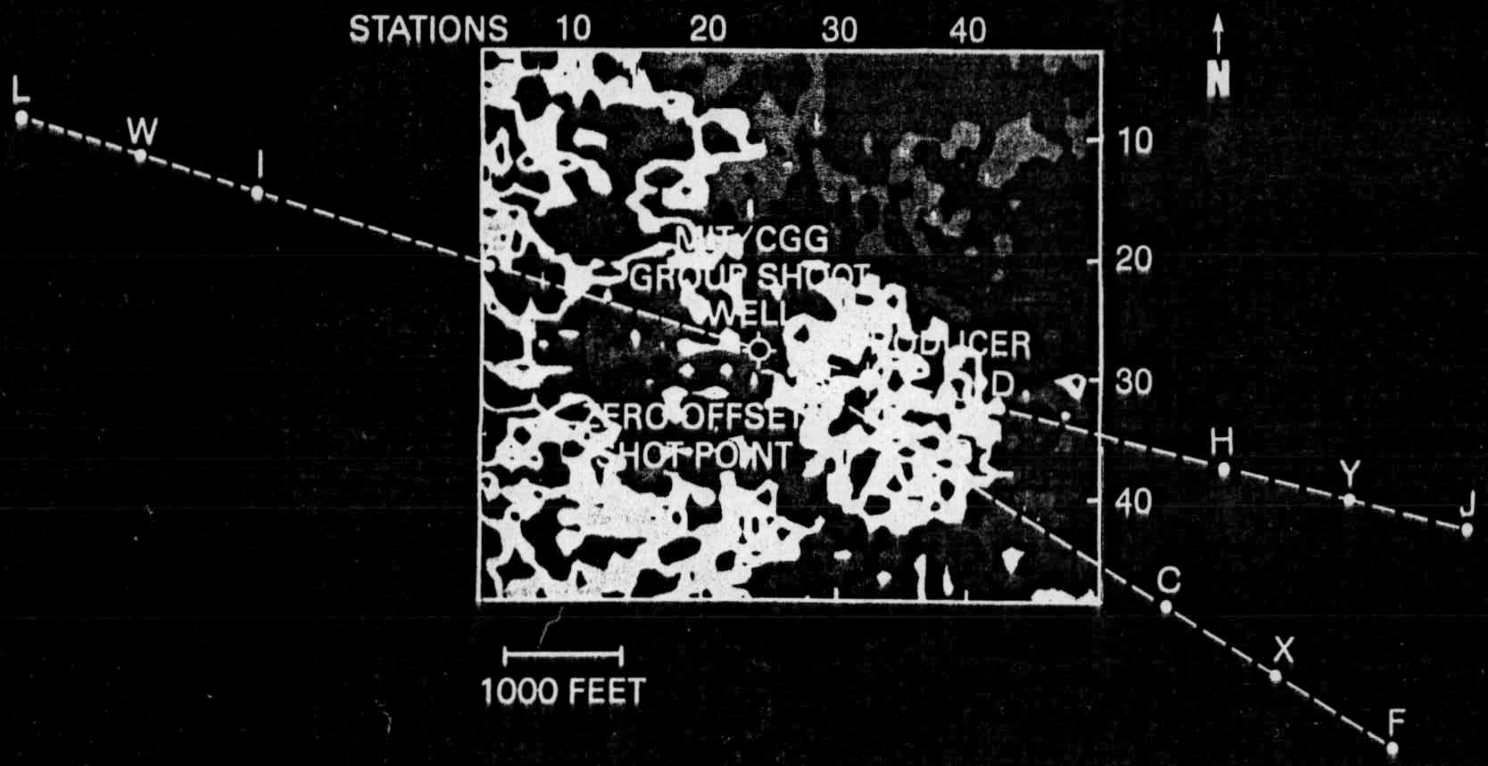

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FIGURE 10 TIME SLICE THROUGH A 3-D SEISMIC IMAGE OF THE REEF USED IN AN EFFORT TO RECONCILE DRILLING AND 2-D SEISMIC DATA SETS.

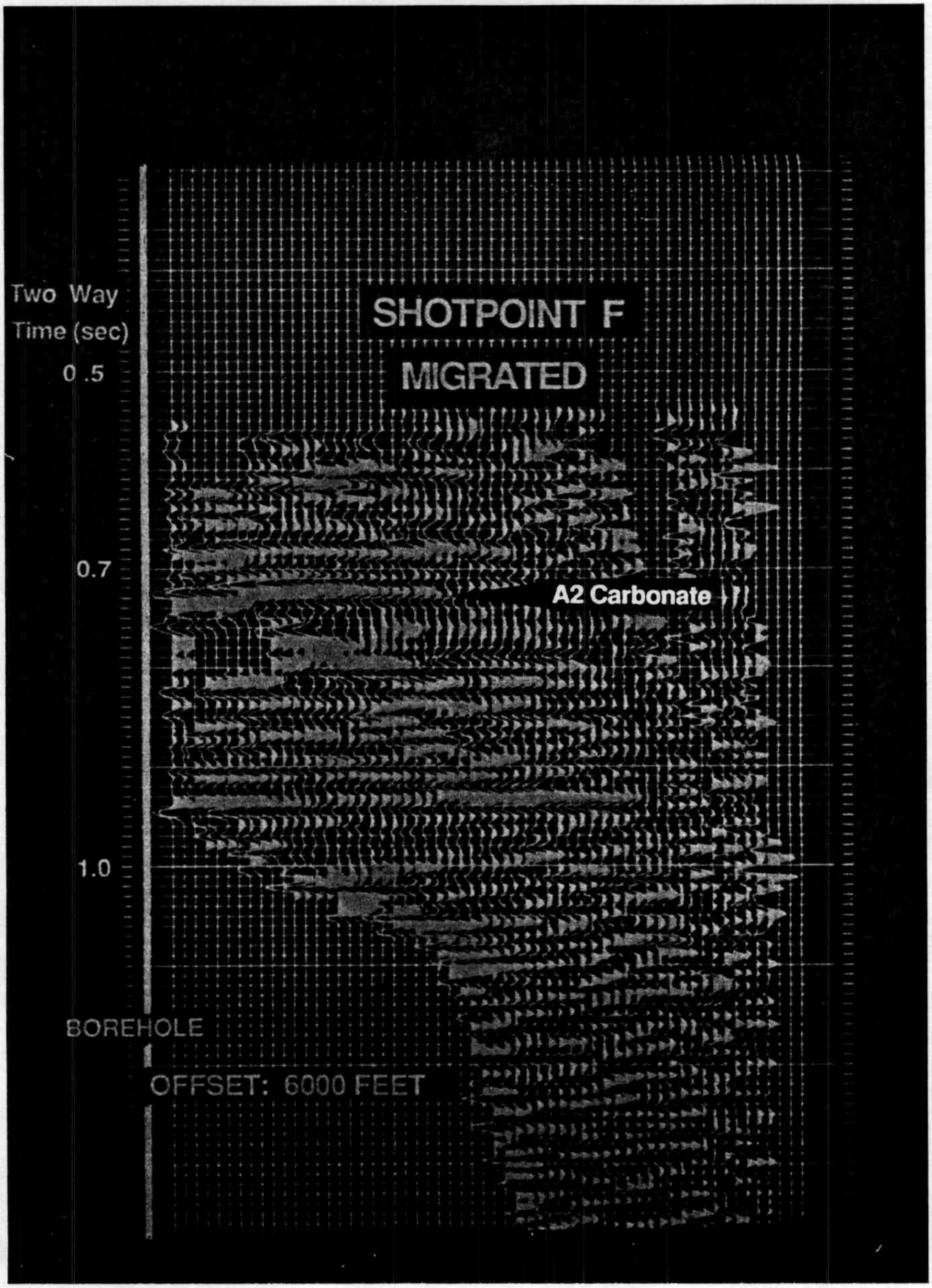
SHOTPOINT F
MIGRATED
Two Way
Time (sec)
0.5
0.7
1.0
A2 Carbonate
BOREHOLE
OFFSET: 6000 FEET

FIGURE 11

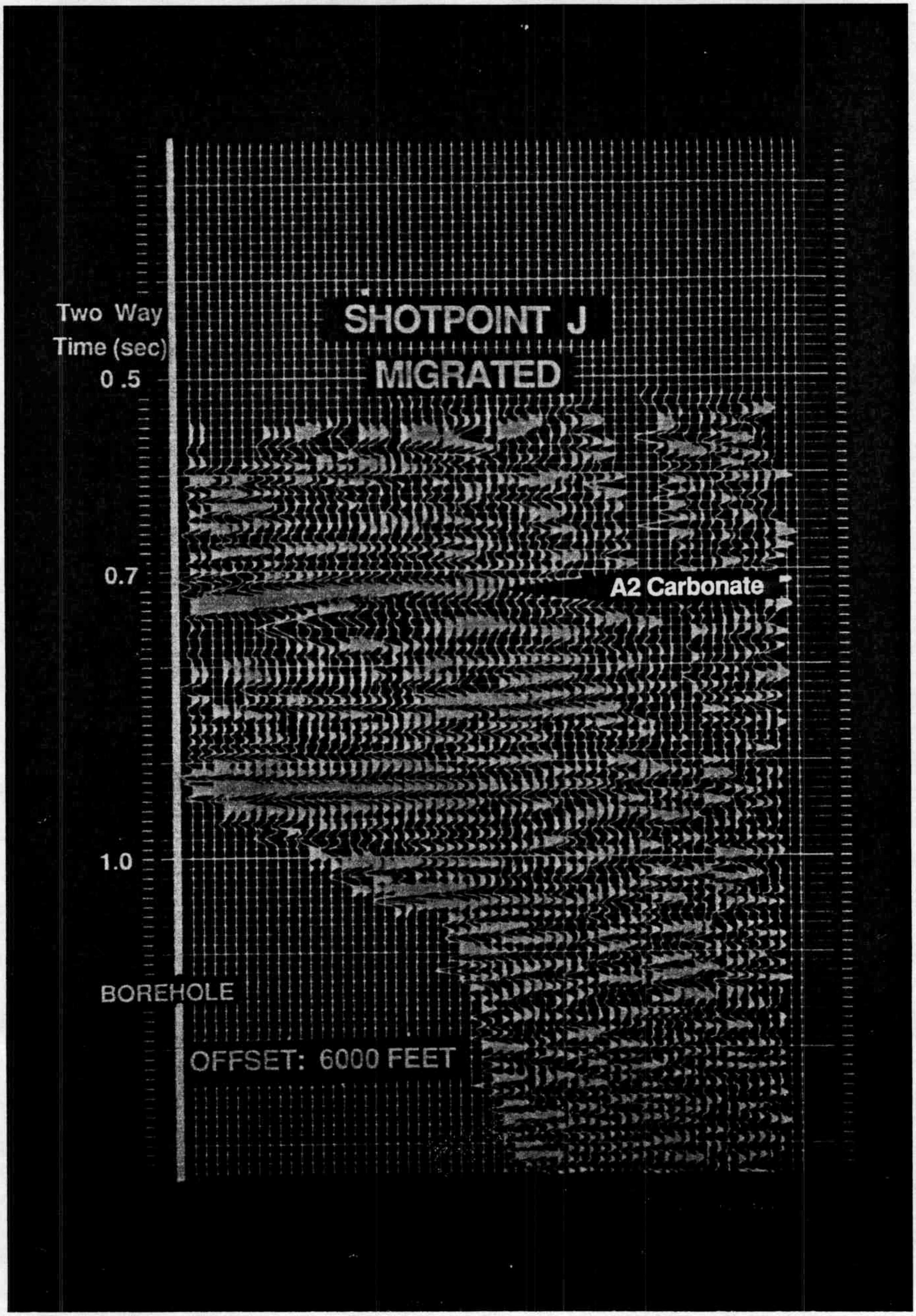
SHOTPOINT J
MIGRATED
Two Way Time (sec)
0 .5
0.7
A2 Carbonate
1.0
BOREHOLE
OFFSET: 6000 FEET

FIGURE 12

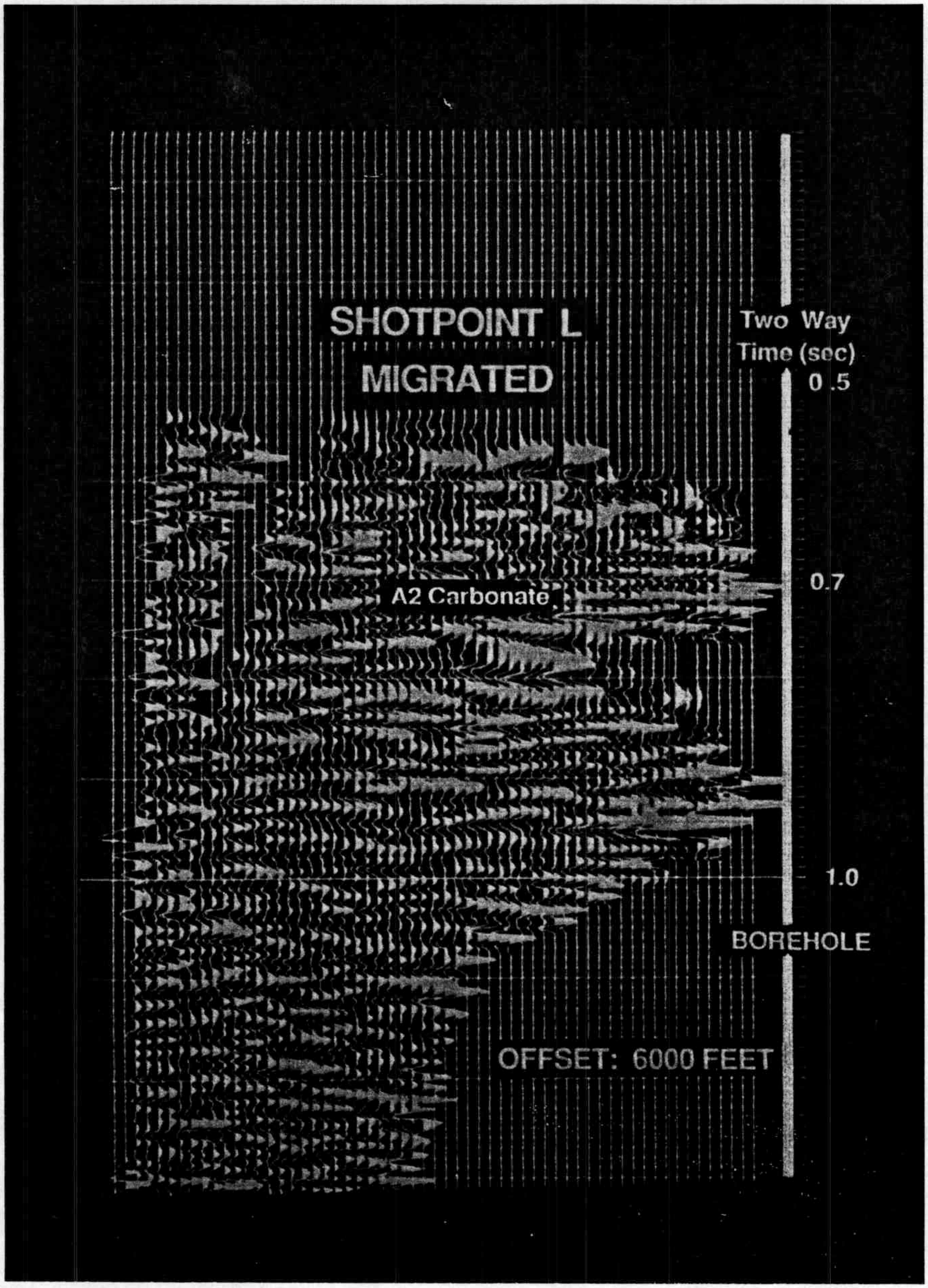
SHOTPOINT L
MIGRATED
Two Way
Time (sec)
0 .5
0.7
A2 Carbonate
1.0
BOREHOLE
OFFSET: 6000 FEET

FIGURE 13

that the event at 0.75 sec (approximately 4700 ft. in depth) is flat in the direction of shotpoint L, but has a "hump" in it in the direction of both F and J. Thus, these three OFFSET VSPs alone would have shown us that the borehole had missed the reef on the west side. In addition the OFFSET VSPs gave the correct depth. Thus the second major problem with surface seismic data, unknown depth scale, can be corrected with OFFSET VSPs.

The OFFSET VSP data also improved image resolution. The 2-D seismic section provided a very poor image of the reef. In fact, the 2-D line and the 3-D image were not of the reef at all, but rather of the interface (the B Salt/A2 Carbonate interface) above the reef. The round object in the 3-D image is a "bump" in that interface, and is related to the existence of the reef and not of the actual reservoir. So, the issue of resolution of the reservoir is moot at this time. Figure 14 is an image of one-half of the reservoir obtained by elastic migration of the P wave VSP from Shotpoint H. It shows not only an event that is the "top" of the reef (again the B Salt/A2 Carbonate interface), but we now see an event internal to the reef. The top of the reef does roll downward as one proceeds towards our well, again indicating that the MIT/Burch 1-20A borehole is a dry hole. This confirms the images of Figures 11, 12 and 13. But now we also see the reservoir itself - a resolution of about 100 ft. in the vertical direction and about the same in the horizontal direction. Compare that with the 2-D line we started with in Figure 9.

Anisotropy and Heterogeneity in the Oceanic Crust

OFFSET VSP techniques can and have (see Section IV) been used to map upper crustal variability in the oceans to a degree of resolution that is not attainable with surface seismic experiments. The particular experimental layout used has been termed an Oblique Seismic Experiment (OSE), but is simply one type of OFFSET VSP experimental layout (Figure 15), and an example of the type of result obtained is shown in Figure 16.

The original objectives of the borehole experiments were 1) to determine the lateral extent of the velocity structure intersected by the borehole, 2) to analyze the role of fissures and large cracks (greater than centimeter size) in the velocity structure of ocean crust, 3) to look for seismic anisotropy in upper oceanic crust and, 4) to obtain a measurement of attenuation. By comparing the refraction velocities from the borehole experiment to sonic log velocities and laboratory sonic measurements on recovered core material, an estimate of the large scale porosity can be made. Seismic anisotropy can be studied effectively by particle motion analysis of three component data. The observed anisotropy can be related to the preferred orientation of large scale fissures and faults. Attenuation has remained an elusive objective because of the small penetration into basement material.

The borehole seismic results have proved valuable in determining shallow basement velocity structure. The structure of the upper 500 m of basement is poorly resolved using ocean bottom or surface receivers. Traveltime inversion schemes require an estimate of the uppermost velocity in a profile. This can be measured directly at in situ conditions and seismic frequencies from borehole receiver data and the velocity-depth profile in the uppermost crust is then considerably better resolved. Amplitude analysis for borehole receivers by trial and error fitting of synthetic seismograms generated by the reflectivity and finite difference methods has also been carried out.

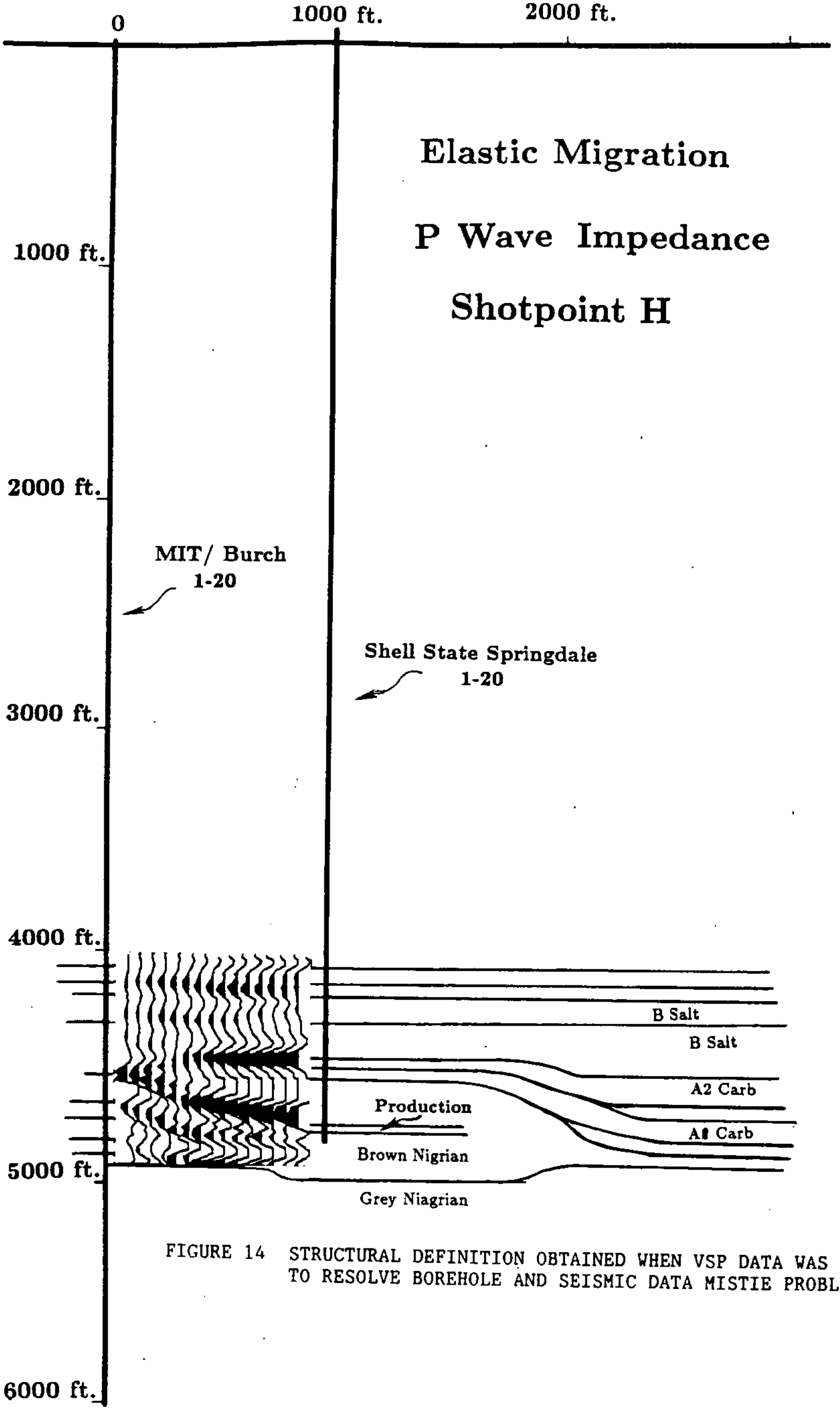

FIGURE 14 STRUCTURAL DEFINITION OBTAINED WHEN VSP DATA WAS INCLUDED TO RESOLVE BOREHOLE AND SEISMIC DATA MISTIE PROBLEMS.

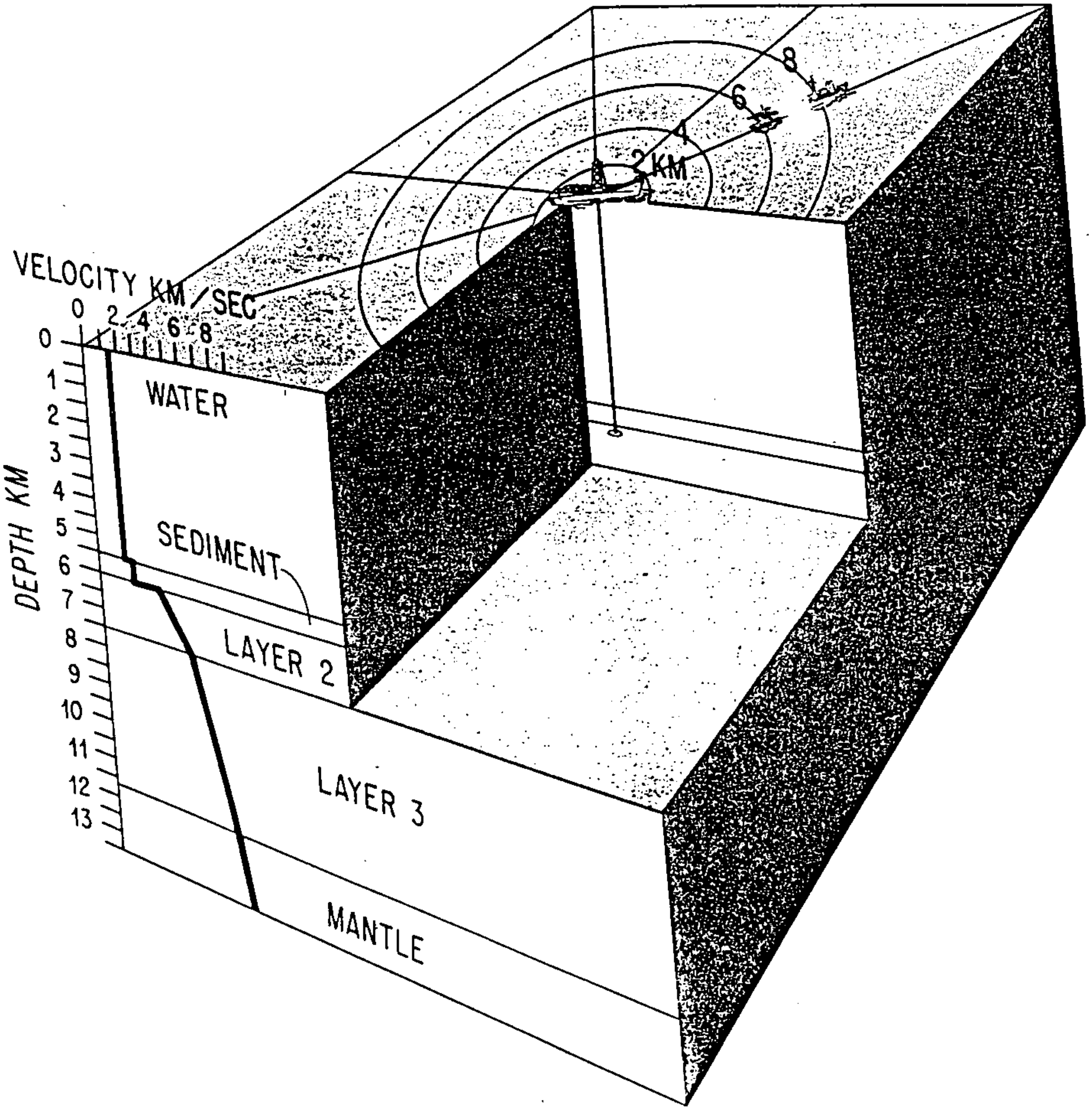

FIGURE 15 SCHEMATIC DIAGRAM OF AN OFFSET VSP (OR OBLIQUE SEISMIC EXPERIMENT). THE VELOCITY-DEPTH FUNCTION FOR A TYPICAL DEEP WATER SITE IS ALSO SHOWN.

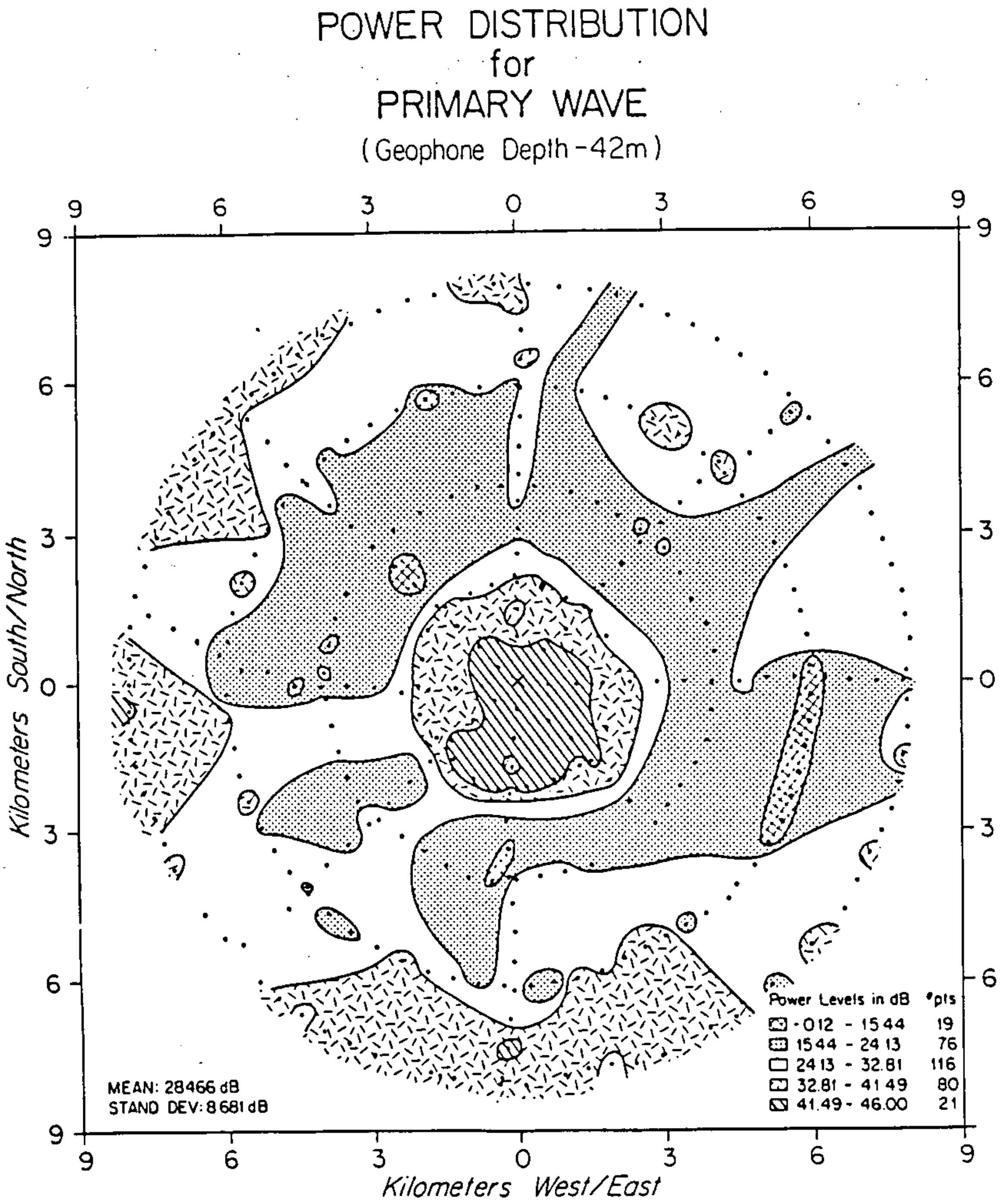

FIGURE 16 POWER DISTRIBUTION PLOT FOR PRIMARY WAVE ENERGY FROM AN OFFSET VSP EXPERIMENT AT DSDP SITE 504. THE BOREHOLE RECEIVER IS AT THE ORIGIN AND THE DOTS INDICATE SHOT LOCATIONS. IF THE SEAFLOOR WERE FLAT, ISOTROPIC AND LATERALLY HOMOGENEOUS, THIS PLOT WOULD CONSIST OF CONCENTRIC CIRCLES. DEVIATIONS FROM A CONCENTRIC PATTERN (GREATER THAN 20DB IN SOME INSTANCES) INDICATE THAT THESE FREQUENTLY MADE ASSUMPTIONS ARE INVALID AT THE SIDE. SYNTHETIC SEISMOGRAM MODELING BASED ON THE OBSERVED BATHYMETRY AT THE SITE SHOWS THAT SIGNIFICANT LATERAL HETEROGENITY (IN ADDITION TO THE BATHYMETRY) IS NECESSARY TO EXPLAIN THE ANOMALIES.

VSPs have a number of advantages over seismic refraction techniques over surface or seafloor receivers in the study of oceanic crust and include:

1. They can give velocities of material near the hole by using near normal incidence shots. By comparing traveltimes from surface shots to geophones at the top and bottom of the hole, the mean velocity of crust within about 500 m of the hole can be obtained. The velocity measured by conventional refraction experiments is an average over the range of arrivals, and the method requires ranges of 2 km or more to identify the refractor. It is inherently impossible for conventional techniques to obtain the same degree of lateral resolution as the VSP or to obtain mean vertical velocities in Layer 2.

2. The VSP does not rely on the presence of reflecting or refracting horizons in order to obtain a velocity determination. The mean velocity of the material above the receiver can be obtained from direct wave arrivals.

3. Conventional refraction experiments cannot detect low velocity zones. The VSP can detect the presence of a low-velocity zone above the receiver from the traveltimes of normal incidence direct wave arrivals to different depths in the hole. If the low-velocity zone is caused by large scale factors (e.g., large vertical fissures), logging may not detect the zone.

4. Much better Layer 2 velocities can be obtained using VSP with a receiver within Layer 2 because waves which have traveled in Layer 2 occur as first arrivals for offsets up to 10 km. This compares with distances of about 4.0 km for conventional refraction work. Also, in the presence of sediment thicker than about 100 m, shallow Layer 2 velocities are impossible to obtain from first arrival times using ocean bottom or surface receivers.

5. Traveltimes in the VSP are less sensitive to the basement topography correction than traveltimes in conventional refraction experiments because the raypaths only pass through the basement sediment interface once. Because of the high contrast in velocity between sediment (~2.2 km/sec) and basement (~5.0 km/sec) and because this interface may not be well resolved by reflection profiling, the error introduced into traveltime analysis by this correction is significant. For example, if the basement topography is not known to within 50 m, an uncertainty of 0.02 sec is introduced into the traveltimes for each time the raypath crosses the sediment-basement boundary.

6. Proper attenuation measurements in oceanic crust can be made with VSP by comparing amplitudes of arrivals at deep and shallow positions in the hole. A correction for the effect of structure between the receivers can be made when the sonic log for the hole is available. It is impossible to obtain satisfactory attenuation measurements from conventional refraction data because the effect of scattering from small-scale structure cannot be adequately determined.

7. The receiver is clamped to the rock wall of the borehole and hence has better coupling than an ocean bottom receiver which has fallen more or less randomly onto the seabed and may, for example, be sitting on a rubble zone or poorly consolidated sediment. In a VSP, if a sonic log or core description is available, solid sections in the hole can be identified in advance. In addition, one would expect the background noise for a clamped borehole geophone to be less than for a receiver sitting on the seabed which is exposed to bottom currents. One would also expect that the amplitudes of both vertical and horizontal components would be reliable and directly correlatable.

8. In VSP the receiver is well located with respect to the borehole where in situ conditions have been measured and depths are known most accurately. For free falling bottom receivers the accuracy of emplacement is at best 200 m. Since changes on this scale in basement topography and in internal structure of Layer 2 exist, detailed studies - where one is interested in crust within a few hundred meters of the borehole - are best carried out with VSP.

IV. VSPs AND BOREHOLE SEISMIC EXPERIMENTS ABOARD U.S. RESEARCH DRILLING VESSELS - A BRIEF HISTORY

Since the earliest plans to conduct scientific ocean drilling were conceived efforts have been made to incorporate the measurement of seismic information into the drilling program. The degree of success has varied considerably, from virtually complete failure to almost complete success. Table I lists the eighteen active experiments and one passive earthquake monitoring experiment that have been carried out since 1961 as part of U.S. scientific ocean drilling operations. Of these, thirteen were carried out during an eight year period of the Deep Sea Drilling Program and four during the Ocean Drilling Program's present operation; that is, something less than about two experiments per year during the life of these projects, or less than one hole in every forty drilled.

The reasons for this relatively low level of activity are probably numerous. One important consideration is that many holes drilled by DSDP and ODP had quite shallow objectives and were not tied in any way to good quality reflection profiling, either single channel or multichannel. Many relatively deep holes have been drilled for stated objectives that were primarily realized by analysis of core data, and only secondarily by ties to seismic reflection information. Furthermore the rise of routine VSP use in the U.S. exploration industry is a relatively recent phenomenon, and certainly post-dates the beginnings of DSDP. Those borehole seismic experiments conducted during DSDP were Oblique Seismic Experiments (OSEs). They employed rather different experimental configurations and had objectives that were generally somewhat different from standard industry applications. The realization that industry-type VSP experiments could be of substantial value to scientific ocean drilling really came about during the Ocean Drilling Program and is coupled to a greater appreciation of the value of down-hole logging. In parallel with this came substantial improvements in downhole geophones and clamping devices that presently allow for the routing collection of data with high signal-to-noise ratios.

The following is a brief description of borehole seismic experiments carried out to date. Table I provides a summary with appropriate reference material.

Early Experiments

The first deep ocean borehole seismic experiment was conducted in 1961 aboard the CUSS I drilling barge, developed for Project MOHOLE during the late 1950's by AMSOC; and was a complete failure. It used the oil field check-shot survey technique of the time, whereby an unclamped geophone was suspended into a fluid-filled borehole and first breaks were recorded from surface dynamite shots. Motion on the downhole geophone caused by the maneuvering drillship produced extremely high ambient noise; 200 lb. shots directly above the borehole could not be detected.

The next experiment was carried out aboard the JOIDES Project's drillship CALDRILL I in 1965. A hydrophone was suspended in JOIDES Site 2B and first breaks from small explosive charges fired at the surface were recorded at various depths down to 275 m. The shallow water of the site (46 m) combined with the moored, tautline dynamic positioning system enabled the drillship to maintain precise position over the hole, and fairly good S/N was obtained.

TABLE I

DOWNHOLE SEISMIC EXPERIMENTS AND VERTICAL SEISMIC PROFILING (VSP) ABOARD DEEP OCEAN DRILLING RESEARCH SHIPS

YEAR	Drilling Vessel/Project	Bore-Hole Sensor Emplacement Technique	Sensor Depth(s)	Environment / Location	Sound Source	Experimental Objectives	Results/Comment	Investigator(s)	References, DSDP/ODP Reports
1961	CUSS I/AMSOC-MOHOLE	Unclamped vertical component geophone suspended in drill pipe using drilling vessel (DV) well logging cable, recorded in DV.	3758 m	Deep water depth (3575 M) Basaltic basement E. Pacific off Baja CA. (Guadalupe Is.)	Large explosives (200/lbs) dropped from shooting ship	Offset Refraction Profile using shooting ship R.V. ORCA (Texas A&M Univ)	Extremely high ambient noise levels,. no useful data recorded acoustic/ radar ship dynamic positioning . Single bit hole,	G. Shor/R. Raitt (Scripps Inst.Oceano)	Bascom, W., Editor, 1961, "Experimental Drilling in Deep Water", National Academy of Sciences Pub. #914; AMSOC, American MiscellaneousSociety , 1961. "Preliminary Mohole Project Drilling Successful", GEOTIMES, Vol. V, No.8, p. 10-13; Personal Communication, George Shor.
1965	CALDRILL I/JOIDES	Unclamped hydrophone suspended in open borehole deployed through drillpipe using DV well logging cable, recorded on DV.	Various depth to 275 m	Shallow water depth (46 meters), unconsolidated sands/clay, N. Florida shelf edge Single bit hole.	Small explosives (~5 lbs) from DV	Zero offset, normal incidence/check shot-type velocity depth measurement	Adequate signal to noise (S/N) ratio to detect compressional wave 1st breaks for interval velocity estimates, tautline mooring ship dynamic positioning.	R. Gerard/J. Ewing (Lamont Geol. Observ.)	Bunce, E., et al, 1965, "Ocean Drilling on the Continental Margin", SCIENCE, VOL 150, p.709-716,, Personal Communication, John Ewing
1975	GLOMAR CHALLENGER/ DSDP Leg 45 (Site 395A)	Same as 1965 CALDRILL I Exp.	~4610 m	Deep Water (4484 m), Basaltic basement mid-Atlantic Ridge, west crest, 23° N Lat.	Small airgun (~40 in^3, 2000 psi) aboard DV	Same as 1965 CAL DRILL I Exp	Extremely high ambient noise levels. No useful data recorded, deployed in multiple bit re-entry cone hole,accoustic ship dynamic positioning.	P. Rabinowitz (Lamont Doherty Geol. Observ.)	Melson, W.G., Rabinowitz, P.D., et. al., Initial Reports of Deep Sea Drilling Project, DSDP Vol.XLV, Washington (U.S. Govt. Printing Office), p.134, 1978
1976	GLOMAR CHALLENGER/ DSDP Leg 46 (site 396B)	1) Clamped vertical component geophone suspended in open borehole deployed through drill pipe; and 2) unclamped hydrophone suspended in open hole both using DV well logging cable, both analog recorded on DV.	1) 2135 m, mid-water test of geophone in drill pipe; 2) hydrophone hung just below casing (~4665 m)	Deep water (4465 m) Basaltic Basement MAR, east crest 23° N Lat. Re-entry cone hole	1) Medium explosives (~20 lbs) from shooting ship, 2) small airgun aboard DV (~40 in^3).	Offset Refraction Profile (Oblique Seismic Experiment-OSE) using shooting ship R.V. KNORR (WHOI), 1-11 km ranges, 500 m shot interval.	1) High electrical noise over-load geophone preamplier during mid-water in-pipe test, No offset explosives shooting attempted; 2) Also High ambient noise due to pipe/cable slamming in bore hole/casing during hydrophone experiment did not allow detection of small airgun shots	D. Matthews/R. Stephen (Univ. Cambridge)	Dimitriev, L., Heirtzler, J., et al., Intial Reports of DSDP, Volume XLVI, p 47-49,1979.
1977	GLOMAR CHALLENGER/ DSDP, Leg 52 (Site 417D)	Clamped 3-component (orthogonal) geophones, suspended in open bore hole, deployed through drillpipe using DV well logging cable, analog recorded on DV.	5840 m and 6060 m	Deep water (5489 m) Basaltic Basement N.W. Atlantic (Bermuda Rise) Re-entry cone hole	Medium explosives (~20 lbs) from shooting ship.	Offset Refraction Profile (OSE) using R.V. VIRGINIA KEY (NOAA)-500 m-12 km ranges, 500 m shot interval	Adequate S/N ratio to determine velocity, depth structure using simple travel time analysis to detect azimuthal variation of P and S velocity/amplitudes around drillsite (anisotropy/lateral inhomogeneity?).	R. Stephen/K. Louden D. Matthews (Univ. Cambridge)	Donnelly, T., Francheteau, J., Bryan, W., et. al., Int. Reports of DSDP, Vol. LII, p. 675-688, 1979. Phillips, J.D. and McCowan, D.W., "Ocean Bottom Seismometers for Nuclear Monitoring and Research: A reassessment", *Mass. Institute Technology*, Lincoln Laboratory Technical Report, 1978-40, 53 pages, 1978.
1979	GLOMAR CHALLENGER/ DSDP Leg 65 (Site 482C)	Clamped 3-component (orthogonal) geophones, suspended in open bore-hole deployed through drillpipe using DV well logging cable, drill-pipe recovered (stripped) leaving logging cable connected to analog remote recorder left on seafloor for later retrieval. Complete isolation of ship/ drill pipe/cable motion from bore hole geophone sensors.	3082 m	Deep water (2998 m) Basaltic Basement E. Pacific Rise Crest - Gulf of California	None	Long-term earthquake monitoring, drill pipe stripped over severed logging cable at rigfloor, cable then paid out on seafloor with remote data recorder and tether which were retrieved by acoustic recall	Satisfactory geophone operation reported but no data obtained due to electrical/mechanical instrument problems in both shipboard and seafloor recording modes. Single bit hole.	F. Duennebier G. Blackinton (Hawaii Inst. Geophysics-HIG)	Lewis, B.R.T., Robinson, P., et al.,Initial Reports of DSDP, Volume LXV, p. 53-62 and p. 357-59, 1983.

1979	GLOMAR CHALLENGER/ DSDP, Leg 65 (Site 485D)	Clamped vertical component geophone, suspended in open borehole deployed through drillpipe using DV well logging cable, analog recorded on DV	3215 m	Deep water (2991 m) Basaltic Basement E. Pacific Rise crest-Gulf of Cal.	Medium Explosives (≈ 20 lbs) from shooting ship	Offset Refraction Profile (OSE) using R.V. KANA KEOKI 500 m - 12 km range, 500 m shot interval.	S/N ratio only adequate for travel time analysis, azimuthal variation of velocity near site observed. Single bit.	R. Stephen (WHOI) S. Johnson (OSU) B. Lewis (Wash.)	Lewis, B.R.T., Robinson, P., et al., Initial Reports of DSDP Volume LXV, p. 319-327, 1983.
1979	GLORMA CHALLENGER/ Leg 67 (Site 494A)	same as Leg 65 (Site 482c)	5826 m	Deep water (5529 m) mud stones, mid-America Trench, E. Pacific	Explosives	Same as Leg 65, also explosive offset refraction shooting by R.V. KANA KEOKI	Excellent quality explosion refraction profiles and earthquake events reported but no details given. Sgl. bit.	F. Duennebier (HIG)	Aubouin, J., Von Huene, R., et al., Initial Reports of DSDP VOLUME LXVII, p. 41-43, 1982.
1979	GLOMAR CHALLENGER/ DSDP Leg 70 (Site 504B)	same as Leg 65 (Site 485D)	3800 m 4290 m	Deep water (3473 m) Basaltic Basement Costa Rica Rift South flank, E. Pacific, re-entry cone hole.	Explosives (3-12 lbs)	Offset Refraction Experiment (OSE) using R.V. GILLIS (Univ. Miami) 500 m-12 km range, 500 m-shot interval	High downhole temperatures (>120°C) caused geophone preamplifier malfunction; however, adequate S/N level allowed travel time analysis to determine velocity-depth function, no azimuthal anisotropy no amplitude or waveform synthetic modeling possible.	R. Stephen (WHOI)	Cann, J.R., Langseth, M. G., Honnorez, J., et. al., Initial Reports of DSDP, VOLUME LXIX, p. 301-308, 1983 Honnorez, J., Von Herzen, R.P., et. al., Initial Reports of the DSDP, VOLUME LXX, p. 12,13, 1983.
1981	GLOMAR CHALLENGER/ Leg 78A (Site 543A)	Same as Leg 65 (Site 482C)	5659 m	Deep water (5637 m) Unconsolidated muds/ooze W. Atlantic, Lea. Antilles Trench	Explosives	Passive, long-term earthquake monitoring, also offset refraction profile using R.V. NORTH STAR shooting ship.	Down hole tool failed before seafloor recorder deployed, geophones recovered, no data acquired. Single bit hole.	F. Duennebier (HIG)	Biju-Duval, B., Moore, J.C., et. al., Initial Reports of DSDP VOLUME LXXVIIIA p. 227, 231, 1984.
1981	GLOMAR CHALLENGER/ DSDP Leg 78B (Site 395A)	Clamped 3- component geophone/ accelerometers and hydrophones, emplaced in open bore on special wire deployed through "stinger" attached to end of drillpipe ,which inserted downhole instrument into re-entry cone. After pipe recovered wire paid out on seafloor to isolate ship/cable motion from bore hole sensor Data was digitized downhole for first time.	5093 m	Deep water (4484 m) Basaltic Basement N.W. Atlantic basin, adjacent Site 417D Leg 52)	Explosives 1-256 lbs.	Same as Leg 65 (Site 482C) also offset refraction shooting by USNS LYNCH, 0-70 km range, 1 km shot interval, large diameter downhole tools deployed on special wire along outside side of drill pipe.	High S/N ratio levels observed compared to adjacent OBS (>30db), Travel time analysis of refraction arrivals determined velocity-depth structure of crust. Re-entry hole.	A. Ballard(NORDA) C. Mulcahy (Teledyne/ GEOTECH) R. Wallerstedt & E. Kiser (Global Marine Dev.) R. Jacobson (SIO)	Hyndman, R., Salisbuey, M.H., Ballard, A., et. al., Initial Reports of DSDP, VOLUME LXXVIIIB, p. 743-792, 1984.
1982	GLOMAR CHALLENGER/ DSDP Leg 88 (Site 581A, 581B)	Same as Leg 78B except data also recorded by seafloor digital recorder which can be retrieved.	not deployed	Deep water (5467 m) Basaltic basement N.W. Pacific (seaward side Kuriles Trench) re-entry hole.	Explosives 1-256 lb Large airgun (2000 in^3)	Same as Leg 78B also Offset Refraction Profiles using USNS DESTEIGUER (explosives) and R.V. DIMITRI MENDELEEV (airgun).	Mechanical problems in the drilling equipment did not allow installation of re-entry cone necessary for deployment of the darpa downhole instruments. No data acquired.	A. Ballard (NORDA)	Duennebier, F.K., Stephen, R., Gettrust, J.F., et. al., Initial Reports of DSDP, VOLUME LXXXVIII, p. 57, 1987.
1982	GLOMAR CHALLENGER/ DSDP Leg 88 (Site 581C)	Same as Leg 65 (Site 482C)	5845 m	Same as Leg 88 (Site 581A,B) except single bit hole.	Same as Leg 88 (Site 581A,B)	Same as Leg 88 (Site 581A,B)	High S/N ratio levels observed. Regional and teleseismic earthquakes recorded, showed S/N equivalent to land/nearby OBS stations, also refraction arrivals used in travel time analysis, to determine velocity depth structure.	D. Byrne, D. Harris F. Duennebier (HIG) et al.	Duennebier, F.K., Stephen, R., Gettrust, J.F., et. al., Initial Reports of DSDP, VOLUME LXXXVIII, p. 65-160, 1987.
1983	GLOMAR CHALLENGER/ DSDP, Leg 91 (site 595B)	Same as Leg 88 (Site 581A,B), Digital borehole data recorded on remote seafloor recorder package for 1st time	5754 m	Deep water (5630 m) Basaltic basement S.W. Pacific (seaward side Tonga Trench) Re-entry cone hole.	Explosives 1-240 lbs	Same as Leg 78B also offset refraction profiles using R.V. MELVILLE (SIO)	High S/N ratio levels observed but only 10-15 db above vertical component of OBS stations for both explosion and earthquake data; however, horizontal components show much higher S/N than OBS. Travel time analysis provided velocity depth structure	M. Harris/J. Ballard (NORDA) J. Orcutt/R. Shearer R. Adair, et al. (SIO).	Menard, H.W., Natland, J., Jordan, T.H., et. al., Initial Reports of DSDP, VOLUME XCI, p. 207-244; p. 307-346; p. 437-444, 1987.

1983	GLOMAR CHALLENGER/ DSDP Leg 92 (Site 504B)	Same as Leg 70, except 3- component geophones	3780m 4010 m 4190 m 4405 m	Deep water (3473 m) Basaltic basement Costa Rica Rift South Flank, E. Pacific..	Moderate explosive charges (≈15 lbs)	Offset Refraction Profile (OSE) using R. V. ELLEN B. SCRIPPS	High S/N ratio bserved, adequate to determine azimuthal P and S wave velocity structure variations around borehole using travel time, amplitude modeling particle and motion analyses. Re-entry cone hole	S. Little/R. Stephen (WHOI)	Leinen, M., Rea, D.K., et al., Initial Reports of DSDP, Volume XCII, p. 190-192, 1986; Anderson, R.N., Honnorez, J. Becker, K., et al. Initial Reports of DSDP, Volume LXXXIII p. 517-528, 1985; "Seismic Anisotropy in Oceanic Crust", Stephen R., *Journ Geophys. Res.*, Vol. 90, , 1985.
1985	JOIDES RESOLUTION/ODP Leg 101 (Site 627B/634)	Clamped vertical component geophone, suspended in open borehole from DV well logging cable, use DV heave compensator to reduce pipe/cable motion in borehole, Downhole data to be digitally recorded on DV.		Deep water (1035 and 2867 m) semi-consolidated carbonate sand	Large airgun (300 in ^{3}) and watergun (400 in^3) and reef rubble	Zero offset, vertical seismic profile (VSP) using large sound sources tethered on boom from DV crane. Geophone to be clamped at 10 meters intervals over entire hole depth (≈50 positions each hole).	Unstable hole conditions did not allow geophone tool deployment at either site. Abandoned both sites, also sealed Site 627B after entire nuclear logging tool string lost. Single bit hole.	J.D. Phillips (Univ. of Texas Institute for Geophysics - UTIG)	Austin, J.A., Schlager, W., Palmer, A.A., et. al., Proceedings of Ocean Drilling Program ODP Volume 101, Part A, p. 115, 486, 1986.
1985	JOIDES RESOLUTION/ODP Leg 102 (Site 418A)	Same as Leg 101 except 3-component geophone tool used. Downhole data digitally recorded on RESOLUTION	5876 m 5916 m 6065 m 6165 m 6265 m	Deep water (5520 m) Basaltic basement N.W. Atlantic Basin-Bermuda Rise, (Adjacent Site 417D Leg 52) Re-entry cone hole.	Very large airgun array (4000 in^3) Explosives 15-120 lbs	Offset Refraction experiment (OSE) using R.V. FRED MOORE (Univ. of Texas) 1-40 km range 150 m shot interval (airgun) 500 m shot interval (explosives)	Very high S/N ratio observed. Consistent airgun source allowed summing of constant range shot records . Test showed heave compensator reduced pipe/cable slamming noise in borehole. Azimuthal radial shooting pattern used but no results reported to date.	R. Stephen/H. Hoskins (WHOI) K. Griffiths/M. Weiderspahn (UTIG)	Salisbury, M.H., Scott, J.H., Aureaux, C., et al., Proceedings of ODP, Volume 102, Part A, p. 122-124, 1986.
1985	JOIDES RESOLUTION/ODP Leg 104 (Site 642E)	Same as Leg 101 except 3-component geophone tool used also drillpipe locked in re-entry cone to further reduce ship motion-induced downhole noise.	1740 m to 2400 m (15 m geophone clamping interval)	Deep water (1289 m) Basaltic Basement Norwegian Sea Voring Plateau Re-entry cone hole.	Single large airgun (1250 in^3)	Zero Offset, vertical seismic profile (VSP) using large airgun sound source tethered from DV port crane, geophone clamped at nominal 15 meters depth interval, 44 positions.	Very high S/N ratio observed, summed shot records exceed 40-50 db. Reflection seismogram shows direct correlation of borehole reflectors with well lithology/sonic logging interfaces and surface MCS profile; verified borehole penetrating of reflector "K".	J.D. Phillips/H. Winkler (UTIG)	Eldholm, O., Thiede, J., Taylor, B., et al., Proceedings of ODP, Volume 104, Part A, p. 198-209, 1987.
1986	JOIDES RESOLUTION/ODP Leg 111 (Site 504B)	Same as Leg 101/104 except vertical component geophone also DV heading adjusted to reduce ship's roll motions	3649 m to 5009 m (10 m geophone clamping interval)	Deep Water (34733 m) Basaltic basement Costa Rica Rift-South Flank, E. Pacific. Re-entry cone hole.	Single large airgun (1000 in^3) and watergun (400 in^3/80 in^3)	Zero offset, vertical seismic profile (VSP) using 1)large airgun and, 2) watergun sources, same as Leg 104 except nominal 10 meter geophone depth clamping interval, 128 positions total.	1) Airgun data showed similar high S/N level as Leg 104 results; reflection seismogram correlated with well lithology/sonic logging interfaces, depth predicted ahead of bit to Layer 2/3 boundary?; 2) 400 in^3 watergun failed before VSP began , 80 in^3 showed very low (inadequate?) S/N to allow useful wavefield separation.	J.D. Phillips (UTIG)	Becker, K., Sakai, H., Merrill, R., et al.,Proceedings of ODP, Volume 111, Part A, in press, 1987.

Deep Sea Drilling Project

a) Lamont-Doherty Geological Observatory Experiment (1975):

The first DSDP experiment was conducted in 1975 by L-DGO scientists during the first leg of the International Phase of Ocean Drilling (IPOD) of the DSDP on Leg 45 at the Mid-Atlantic Ridge. It was made during the initial multiple bit, re-entry drilling at Site 395A, in a water depth of 4500 m with the dynamically positioned GLOMAR CHALLENGER. The experiment was not successful; apparently, the large maneuvering circle required to maintain position in deep water caused the drillpipe and logging cable to slam against the borehole wall and re-entry core casing. The small 40 in^3 airgun sound source proved inadequate to overcome the high ambient noise levels on the unclamped hydrophone. This slamming-induced acoustic noise, coupled with the drillship's heaving motions which tug on the logging cable and downhole sensor, were early recognized as major sources of borehole noise.

b) Cambridge Experiments (1976-77):

In 1976-77, University of Cambridge (England) scientists attempted to overcome the S/N problems by rigidly fixing a geophone against the borehole wall (which by then had become common practice in oil field borehole surveys) and moderately large explosive charges (about 20 pounds) were deployed from a nearby ship. This offered the opportunity to conduct offset source seismic profile experiments to obtain wide angle arrivals (Oblique Seismic Experiments - OSE). For the Cambridge experiments a conventional, mechanically actuated clamping arm provided the rigid coupling of the geophone against the borehole wall. Unfortunately, the first experiment (1976) during Leg 46 at DSDP Site 396B failed due to electrical noise problems encountered in the downhole preamplifier circuitry while the geophone was test clamped in the drillpipe well above the sea floor.

In the second (1977) Cambridge experiment, a conventional 3-component orthogonal geophone tool was successfully clamped against the borehole wall after the drilling of Site 417D (Leg 52) on the mid-Atlantic Ridge 23°N) in 5489 m water depth. Twenty pound explosive charges were dropped from a shooting ship and recorded at two geophone clamping positions in oceanic Layer 2 (5840 and 6060 m depth). An adequate signal-to-noise (S/N) ratio was observed which allowed traveltime and particle motion analyses of the horizontal and vertical component waveforms to determine azimuthal variation of the P- and S-waves' velocity structure of the oceanic crust around the drillsite. The data were of sufficient quality that synthetic seismogram modeling was employed to analyze the observed seismic waveforms.

c) Woods Hole Oceanographic Institution (WHOI) Experiments (1979-83):

A group of WHOI, University of Washington, and Oregon State University (OSU) scientists conducted an OSE on Leg 65 at Site 485D on the E. Pacific Rise crest (Gulf of California) using a vertical component geophone. The geophone was clamped in basalt at a subbottom depth of 224 m. Data quality was sufficient to allow traveltime and amplitude analyses.

A second OSE was attempted during Leg 70 at Site 504B on the Costa Rica Rift. For this experiment a 3-component geophone was clamped at 327 and 817 m subbottom depths. Explosive charges were varied as a function of offset from 15 to 60 pounds. Unfortunately, high down-hole temperatures (>120°C) caused the geophone preamplifiers to malfunction so that only vertical component, traveltime analysis of the P-wave arrivals were possible.

The most successful offset refraction experiment was conducted during Leg 92, again at Site 504B and repeated the largely unsuccessful experiment attempted on Leg 70. For this experiment, a "temperature hardened", 3-component geophone was clamped at four depths: 3780, 4010, 4190, and 4405 m below sea level or 307, 537, 717 and 932 m below sea floor. Nearly 1000 explosive shots, 15 pounds each, were fired out to ranges of 7 km (Figure 15). The high S/N ratio data obtained allowed traveltime, synthetic seismogram and particle motion analyses of both the P and S waves. Detailed studies of the azimuthal variation of velocity structure around the drillsite (Figure 16) verified the crustal velocity anisotropy suspected for the earlier Leg 52 (Site 417D) results (Stephen, 1985).

d) Earthquake Monitoring Experiments:

1) Hawaii Institute of Geophysics' Experiments (1979-82)

Four experiments aimed at assessing the usefulness of ocean borehole seismometer stations for long-term, passive monitoring of seismic activity on ocean ridges and trenches were conducted. The first of these experiments was attempted during DSDP Leg 65 at Site 482C on the East Pacific rise crest (2998 m water depth) in the Gulf of California. For this experiment a 3-component geophone tool was deployed through the drillpipe and clamped in Layer 2. While satisfactory geophone operation was reported when the geophone signals were observed on the drillship, no data were obtained due to electrical/mechanical data recording problems.

A second HIG experiment was performed during DSDP Leg 67 (Site 494A) in the Middle American Trench (5529 m water depth). A shooting ship was also used to conduct offset refraction profiles using explosives. Excellent quality seismic refraction profile and earthquake data were obtained.

The third (Leg 78A - Antilles Trench W. Atlantic Site 543A) and fourth (Leg 88 - Kuriles Trench W. Pacific, Site 581C) seismic monitoring experiments also employed a shooting ship to conduct offset refraction profiles. The first was aborted due to failure of the geophones. The Leg 88 experiment resulted in high quality earthquake data as well as seismic refraction profile data being recorded on both 3-component borehole unit clamped at 328 beneath the sea floor in basalt, and on nearby ocean bottom seismometers (OBS). Comparison of both regional teleseismic events on both seismometer types showed that the S/N ratio of the vertical component of the borehole units to be only slightly higher than the OBS; however, the horizontal component borehole S/N ratio was considerably higher (20-30 dB) than the OBS horizontal components. Similarly the S/N ratio of the borehole units for recording of refraction arrivals was much improved over OBS'.

2) Naval Oceanographic Research and Development Activity (NORDA) Experiments (1981-1983)

Under Defense Advanced Research Project Agency (DARPA) sponsorship, NORDA carried out several experiments aboard the GLOMAR CHALLENGER to determine the feasibility of using borehole seismometers for long term monitoring of seismic activity. The first DARPA experiment was conducted in 1981 during DSDP Leg 78B which re-entered Site 395A. This was primarily an equipment feasibility experiment. A DARPA experiment planned for Leg 88 was cancelled due to equipment problems aboard the drillship.

During Leg 91 DARPA conducted a successful experiment at Site 595 near the Tonga Trench that was essentially the same as the Leg 78A HIG experiment except that a broader band digital seismometer was placed at a shallower subbottom depth (109 m vs. 609 m), and a remote seismic data recorder with tether line was left on the sea floor for recovery after a 40-day deployment. Only 1-1/2 days data were acquired due to a failure in the seafloor recorder, but considerable high S/N ratio data was also recorded while the downhole geophones were still connected to the drilling ship. S/N ratio of the vertical component data of the borehole sensors was 10-15 dB better than the adjacent OBS observation. Horizontal component data again showed markedly higher S/N ratios than the horizontal component OBS data (20-30 dB), as observed in the HIG Leg 88 experiments.

Ocean Drilling Program (1985-present)

Leg 101:

The first downhole seismic study of the ODP was attempted by UTIG (University of Texas Institute for Geophysics) scientists during the first leg of the JOIDES RESOLUTION. This was intended to be a conventional, ZERO-OFFSET vertical component VSP experiment. Downhole seismic noise was to be reduced by withdrawing the drillpipe up the borehole to within a few tens of meters of the sea floor and engaging the RESOLUTION's drillpipe heave compensator: Alternate shooting cycles of a large air gun and water gun suspended from the ship's crane were to be used to obtain two separate VSP records. Unfortunately, highly unstable borehole conditions were encountered in the carbonate reef rubble materials drilled on Leg 101. Despite two attempts for a VSP experiment at Sites 627B and 634, the borehole collapsed before the geophones could be deployed.

Leg 102:

The most extensive OSE conducted so far during ODP was done by WHOI and UTIG during Leg 102 at Site 418. For this experiment, a WHOI 3-component geophone was clamped at five positions in the oceanic basement. The downhole seismic data, as well as the shot timing/and radar navigation data for the UTIG shooting ship R/V FRED H. MOORE, were digitally recorded and processed using the UTIG-designed MASSCOMP and VAX computer systems aboard the drillship, respectively. The MOORE's airgun array (4000 in^3) was used for shooting a radial-patterned offset experiment for ranges out to 12 km, while 15-120 pounds of explosives were fired along four, 40 km long profiles. Airgun shots were fired every 150 m along each line. No ZERO-OFFSET VSP shooting was attempted from the drillship during Leg 102.

Leg 104:

A ZERO-OFFSET VSP was performed by UTIG at Site 642 on the Vøring Plateau off Norway using a prototype, triaxial geophone seismometer developed by Phillips Petroleum to obtain 3-component seismic data. The data were digitally recorded using the RESOLUTION's MASSCOMP seismic data acquisition system. The geophone was clamped at 15 m intervals through a sequence of dipping volcanic layers, 1740-2400 m below sea level. Typically 12 airgun shots (1250 in^3) were summed in real time at each clamping depth to obtain a very high S/N ratio, 44-depth trace VSP section. The downhole noise was markedly reduced by engaging the drillpipe heave compensator, as on Legs 101/102 and by locking the drillpipe into the re-entry cone using a special casing/landing tool assembly.

Real time multiple shot summing, f-k velocity filtering to separate the upgoing and downgoing wavefields, source deconvolution using the downgoing waves, and VSP trace stacking to generate the final VSP reflection seismogram were performed on this data. The resulting VSP reflecting seismogram was used to correlate the borehole lithology and logging information obtained through the basalt sequence with the surface multichannel seismic (MCS) profile across Site 642 (Figure 17).

Leg 111:

A commercially contracted, vertical component geophone (Schlumberger) was used to acquire a ZERO-OFFSET VSP at Site 504B (Costa Rica Rift). A large airgun (1000 in^3) and a small watergun (80 in^3) source were fired alternately providing two VSP record sections; 128 airgun shots and 45 watergun shots for geophone depth positions, spaced 10 m apart, were recorded. Typically only 5 airgun shots were required to obtain a very high S/N ratio summed record (>>40 dB). The VSP experiment spanned nearly the entire subbottom depth interval, 3809-5009 m, and required only about 40 hours to execute.

Computer processing was done onboard the RESOLUTION. This "quasi-real time" shipboard processing made it possible to correlate the seismic section directly with the observed borehole lithology and seismic interfaces defined by well-logging and to extrapolate beyond the drillbit to predict the depth to the next major reflection interface in the crust (Figures 18).

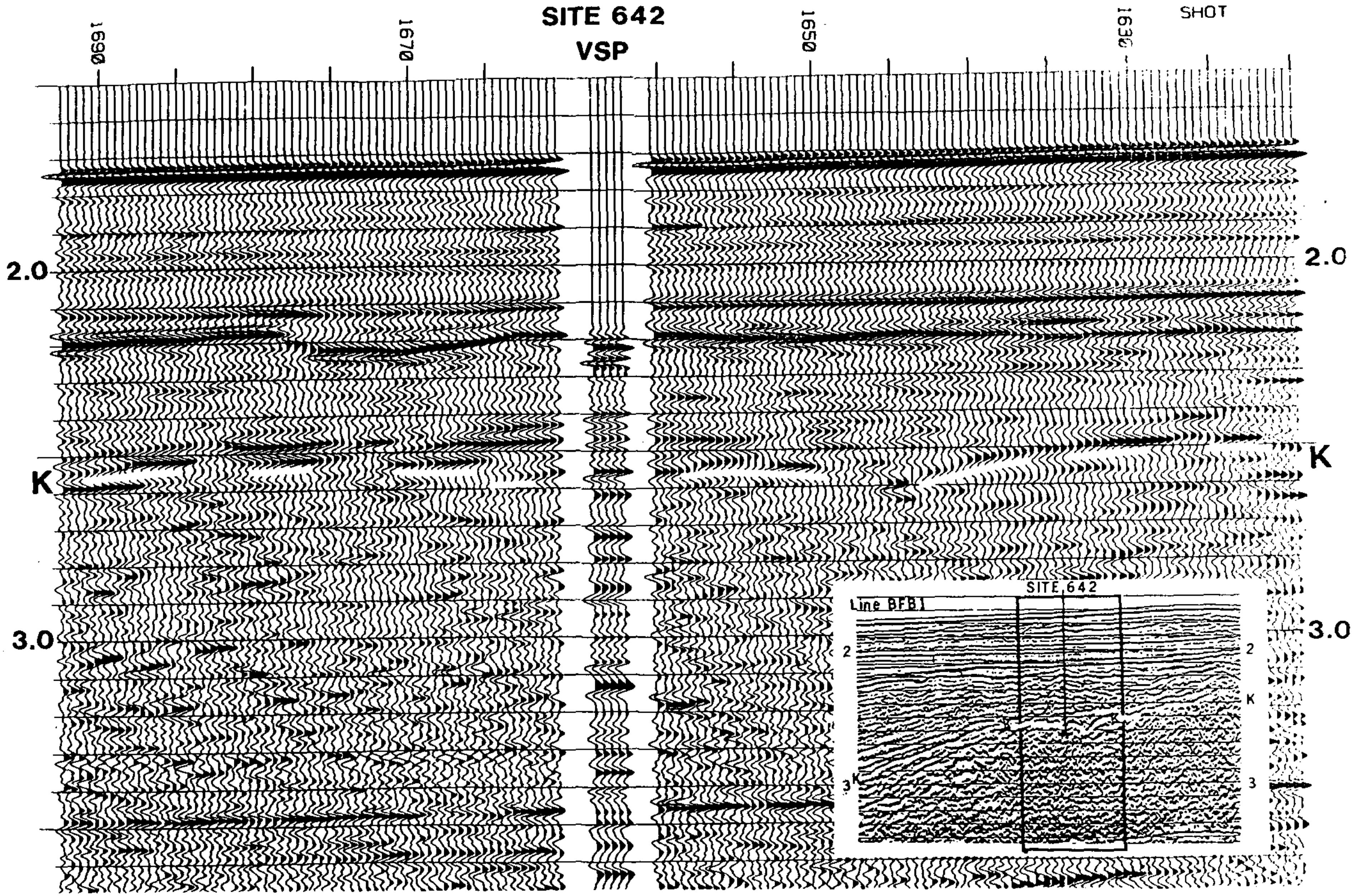

FIGURE 17 COMPARISON OF VSP SEISMOGRAMS OBTAINED BY UTIG AT ODP SITE 642 (VØRING PLATEAU, NORWEGIAN SEA) WITH MULTICHANNEL REFLECTION PROFILING OBTAINED BY BGR (BUNDESANSTALT FUR GEOWISSENSCHAFTEN UND ROHSTOFFE, HANNOVER, FRG). THE BOREHOLE PENETRATED TO A DEPTH EQUIVALENT TO 2.63 SEC.; THE VSP PROVIDES INFORMATION TO ALMOST TWICE THAT DEPTH.

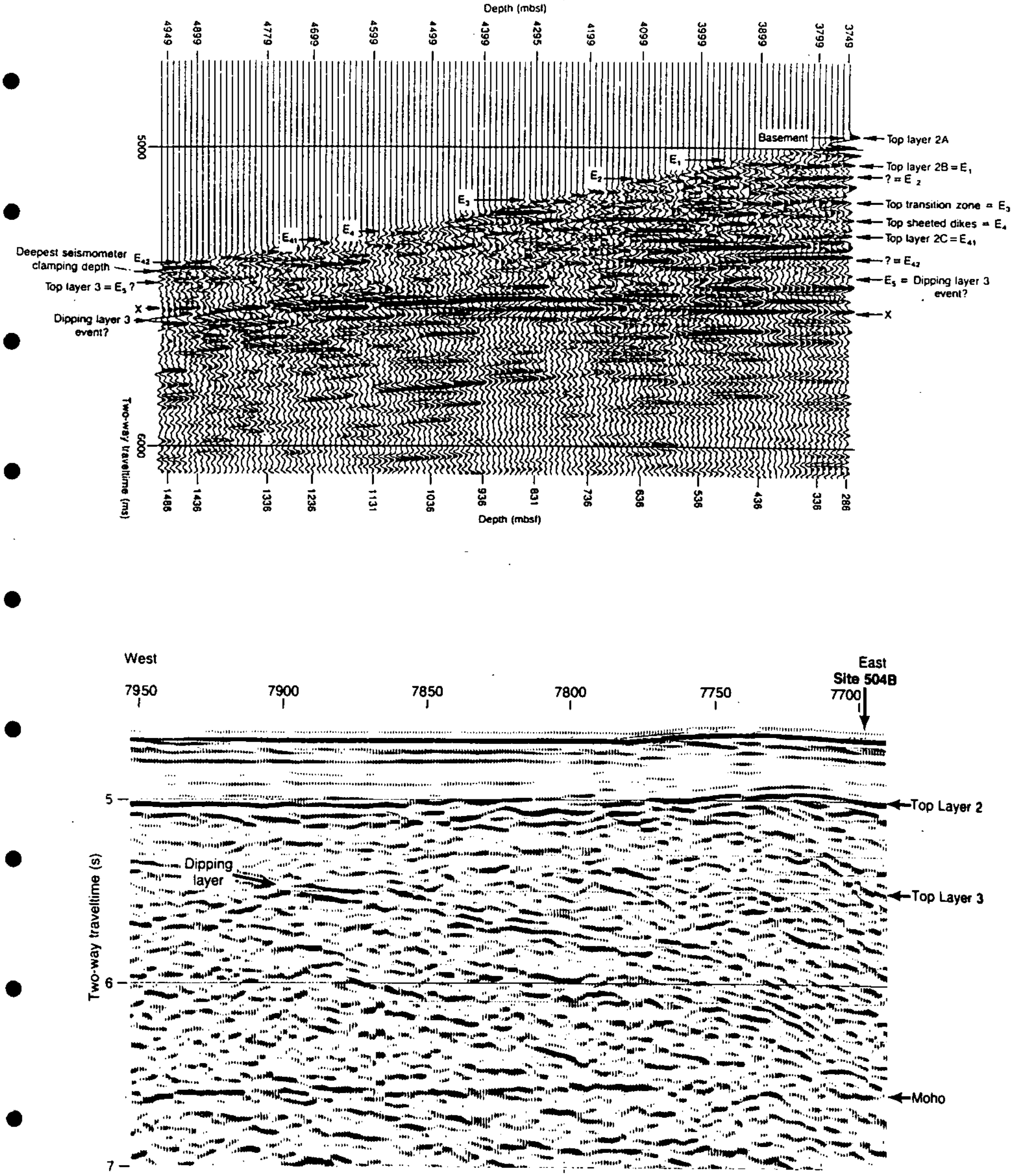

FIGURE 18 VSP RESULTS FROM ODP LEG 111 SHOWING INTERPRETATION OF SEVERAL INTRACRUSTAL EVENTS IN THE OCEANIC CRUST AT SITE 504B (UPPER PANEL). THE LOWER PANEL SHOWS A MULTICHANNEL SEISMIC REFLECTION PROFILE OBTAINED AT THE SITE BY LAMONT-DOHERTY.

V. POTENTIAL ROLE OF VSPs IN THE OCEAN DRILLING PROGRAM

Drilling is the only technique that exists in the marine earth sciences for the absolute ground truthing of structural and stratigraphic interpretations based on geophysical observations. The drillship is, however, an expensive and limited resource. It is extremely important that we have reliable techniques to relate drilling results to surface geophysical observations and to exploit the unique geometry of the borehole to investigate the physical properties of the surrounding crust. The VSP technique and related borehole seismic experiments described in Sections III and IV can, and have, played a crucial role in this because, along with logging results, they provide a bridge between the small-scale observations provided by the core samples themselves and regional surface seismic reflection/refraction data. They can thus help extend our direct observations of sub-surface geology in the borehole over lateral scales of tens of kilometers or more.

Although the VSP technique is widely used in the exploration industry, it has seen only limited application thus far within DSDP or ODP (Section IV). While this may be due to the very different objectives that scientific drilling has when compared to commercial drilling, the workshop participants were in unanimous agreement that the technique has been underutilized and that an expanded, systematic program of borehole seismic experiments within ODP could increase the value of scientific ocean drilling, and make a significant contribution toward its fundamental objectives. The following briefly summarizes some of the potential contributions of an expanded VSP program.

Time-to-Depth Conversion of Borehole Sonic Logs and Correlation with Surface Seismics

One of the most straightforward and potentially important applications of VSP experiments is to relate reflectors seen on surface seismic reflection profiles to lithologic and physical property variations found within boreholes. In general, this cannot be done unambiguously using only borehole sonic logs, since they are acquired using a much different source-receiver geometry and with much higher frequencies than surface seismic reflection data. As described in Section III, ZERO-OFFSET VSPs can provide this critical traveltime and interval velocity information (including the existence of low velocity zones), and because they are acquired using a similar, low frequency source, the observed waveforms can be more easily correlated with surface seismic reflection profiles (Figure 17). While it is generally important to "tie" every ODP drill hole to surface seismics, there are two ocean drilling applications where ZERO-OFFSET VSP experiments can be particularly valuable: deep stratigraphic tests (DSTs) and deep sampling of the oceanic crust.

Deep Stratigraphic Tests (DSTs): There is great interest within the paleoceanographic community for obtaining complete stratigraphic sections through thick (>1 km) sedimentary sequences in major marine depocenters in order to investigate global climate and sealevel changes. Another important objective is to relate biostratigraphic and lithologic variations observed within sedimentary sequences to regionally correlative seismic horizons. This would permit the results from a DST to be extrapolated regionally within a sedimentary basin, significantly extending the scientific value of each hole. As the ZERO-OFFSET VSP is the best technique for making the tie between the drilled section and regionally mapable seismic horizons, such VSP's should be conducted at every DST, in conjunction with the acquisition of the standard suite of Schlumberger borehole logs.

Oceanic Crust: Recent advances in multichannel seismic reflection (MCS) techniques have revealed the first evidence for reflections within the igneous oceanic crust. These include relatively flat-lying, often discontinuous reflectors in the shallow crust and steeply dipping, diffracting events in the lower crust, as well as a usually prominent Moho reflection at or near the base of the crust (Figures 18). The origin and geological significance of these events remain controversial and can only be unequivocally established by deep crustal drillholes. The ZERO-OFFSET VSP technique and other borehole seismic experiments will play a critical role in understanding the nature of these reflectors, since they offer the only way of carrying out seismic experiments in the drillhole with the bandwidth necessary to span the gap between individual drilling samples, logging results and surface reflection/refraction data. With the technical difficulty and expense of crustal drilling, surface seismic experiments (MCS, ocean bottom refraction, tomography, etc.) will remain, in the foreseeable future, the only practical method for determining oceanic crustal structure on a regional scale. VSPs will allow the geological ground-truth of the borehole to be applied directly to the interpretation of these seismic results, potentially making it feasible to map the structure and stratigraphy of the igneous crust in a manner analogous to what is currently done in sedimentary basins.

Recommendations of at least two Working Groups at the COSOD II meeting in Strasbourg, July, 1987, made clear statements concerning deep drilling as primary science objectives in the coming drilling program. Working Group 4 (Stress and Deformation of the Lithosphere) stated: "A basic premise of future margin drilling should be based on deep holes with thicker crustal records...". They considered 6 km to be a future target depth. Working Group 2 (Mantle/Crust Interactions) stated: "The single most important contribution would be drill holes through the entire thickness of the ocean crust." Considerable attention was given to outlining the technological advances needed to achieve these deep objectives. The extent to which COSOD II recommendations will be acted upon is difficult to judge, but it is clear that there is considerable momentum behind deep drilling, and its incorporation into ODP planning in some form seems certain.

Prediction ahead of the Bit

One potentially very valuable use of VSP experiments is to image the seismic structure below the total depth of the drillhole. In general, it is possible to resolve structures to a depth equivalent to two or three borehole lengths beneath the bottom of the hole. One instance where this has already been done with some success is at DSDP Site 504B (Figures 18). The major objective of drilling at this site has been to reach the dyke/gabbro (layer 2/3) boundary. A VSP conducted at the end of ODP Leg 111 revealed reflectors 125 and 900 m below the bottom hole that may be the layer 2/3 boundary (reflectors E5 and X, Figures 18). If this interpretation is substantiated by subsequent analysis, it will give scientists and engineers target depths to plan for in any future drilling at this site.

Another potential application of this kind is in imaging decollement zones at accretionary margins. These zones are frequently overpressured and potentially dangerous if unexpectedly encountered during drilling. A VSP carried out during the early stages of drilling a hole in this setting could accurately predict the depth to the decollement zone and thereby provide drilling engineers and shipboard scientists with precise information on which to plan safe drilling operations.

A variety of other situations can be envisaged in which the ability to "see ahead" could be of critical importance. The RESOLUTION is, for instance, not equipped to drill in oil or gas-prone areas, yet scientific objectives require that we penetrate near to reservoir rocks. The tilted fault blocks of passive continental margins are just one obvious example. In many cases the gas-prone units have been well mapped from exploration work. Thus a VSP conducted as part of a drilling strategy would allow the onboard scientists to judge how near the dangerous units were to the currently drilled depth, and continue only if safe. Somewhat simpler, but equally important, may be the requirement to judge the depth to basement or some other important geological horizon in order to devise or modify drilling objectives. ZERO-OFFSET VSPs requiring less than 24 hours of ship time can answer these questions.

Seismic Anisotropy, Attenuation Measurements and Lateral Variability

OFFSET VSP's can be used to provide in situ measurements of both seismic anisotropy and attenuation within the upper oceanic crust or sedimentary column (see description in Section III). Seismic anisotropy can be observed from azimuthally dependent traveltime anomalies, and compressional and shear-wave particle motion analyses of three-component borehole geophone data. The importance of the VSP technique in these kinds of studies is illustrated by the fact that three of the four reported observations of seismic anisotropy in the upper 2 km of oceanic crust in the past ten years have been based on OFFSET VSP data (OSE configuration). The most probable cause of anisotropy in the upper oceanic crust is the preferred orientation of large scale fractures created during the crustal generation process.

In other tectonic settings (e.g., in plate interiors or at convergent plate margins), fracture-induced anisotropy may be present in the crust or the overlying sediments that reflects the local stress regime. In sedimentary environments, anisotropy can also arise from depositional mineral fabrics or diagenesis, although very little is known about this kind of anisotropy in deep-sea marine sediments. The main difficulty in anisotropy studies is separating the effects of anisotropy from lateral heterogeneity and scattering effects. More theoretical work is needed in this area, but it is clear that the VSP technique is one of the best methods for making in situ anisotropy measurements in the upper oceanic crust and in marine sediments.

In surface seismic data, it is difficult to separate "intrinsic" attenuation caused by anelastic behavior of the medium in which seismic waves are propagating from "apparent" attenuation caused by energy partitioning in a layered medium. VSP experiments record both upcoming and downgoing reflections and include, if variable offsets are run, both compressional and coverted S-wave energy. These data, which can be precisely correlated with the borehole sonic and density logs, can potentially allow accurate determination of reflection coefficients and more reliable measurements of intrinsic attenuation. The coincident information on P- and S-wave velocities, densities, reflection coefficients and attenuation available from borehole VSP experiments should improve predictions of lithologic relationships from surface seismic data, especially in sedimentary environments.

Imaging Structure around ODP Drillsites in Complex Settings

The case history presented in Section III (Figures 9-14) demonstrated the effectiveness of the OFFSET VSP in determining the structural configuration of targets around a commercial drillsite. While the motivation for scientific ocean drilling may be quite different from that of the exploration industry, the technology and operational techniques are almost identical. The production-oriented question is answered by intersecting a "target" geologic horizon; the science-oriented question is answered in an identical manner. In both cases multichannel seismic data is used to guide the location of the borehole. The exploration industry frequently base their exploration plans on dense grids of reflection data, including 3-D seismic data. Such coverage is rarely available in advance for siting scientific boreholes, and the cost of its acquisition is substantilly in excess of what is presently available to support site-related geophysics. With a relatively sparse grid of MCS lines in a structurally complex region, the likelihood of mislocating the borehole and/or assigning cores and logs to the wrong formation is extremely high. The resultant interpretational uncertainties would substantially attenuate the value of scientific drilling, even if the drilling itself was technically "successful".

The ODP has shown no reluctance to site boreholes in structurally complex regions using sparse seismic data. Figures 17-21 illustrate examples from ODP legs 104, 111, 103, 107, and 110, respectively, where the geologic setting ranges from accretionary prism to passive margin fault blocks and volcanic complex. True 3-D control was not available at any site, much of the 2-D seismic coverage is of moderate quality, not all has been migrated, and no data have any 3-D effects included in their processing. Velocity control is typically available only from analysis of CDP gathers using well-known approximations to the true traveltime behavior of seismic arrivals. It is extremely unlikely that adequate ties of the drilled section to the local geology have been made in these places. The inclusion of an OFFSET VSP experiment as a component of drilling in these structurally complex regions is the most appropriate way in which this crucial tie can be achieved.

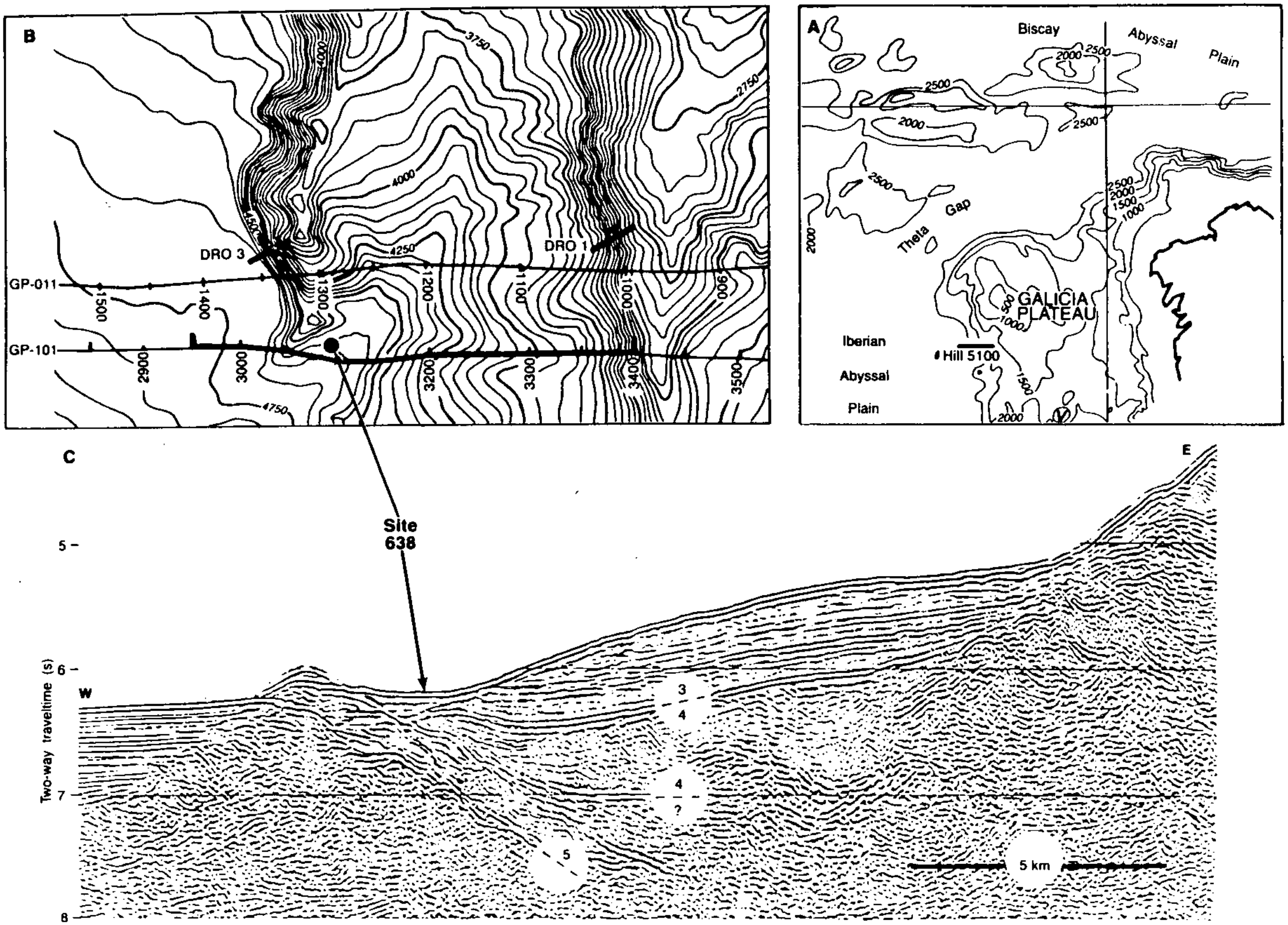

FIGURE 19 A SERIES OF ODP SITES, INCLUDING THE ONE SHOWN WERE LOCATED IN ROTATED FAULT BLOCKS OFF THE GALICIA PLATEAU (BOILLOT, WINTERER, ET AL., 1987; ODP LEG 103 PART A REPORT).

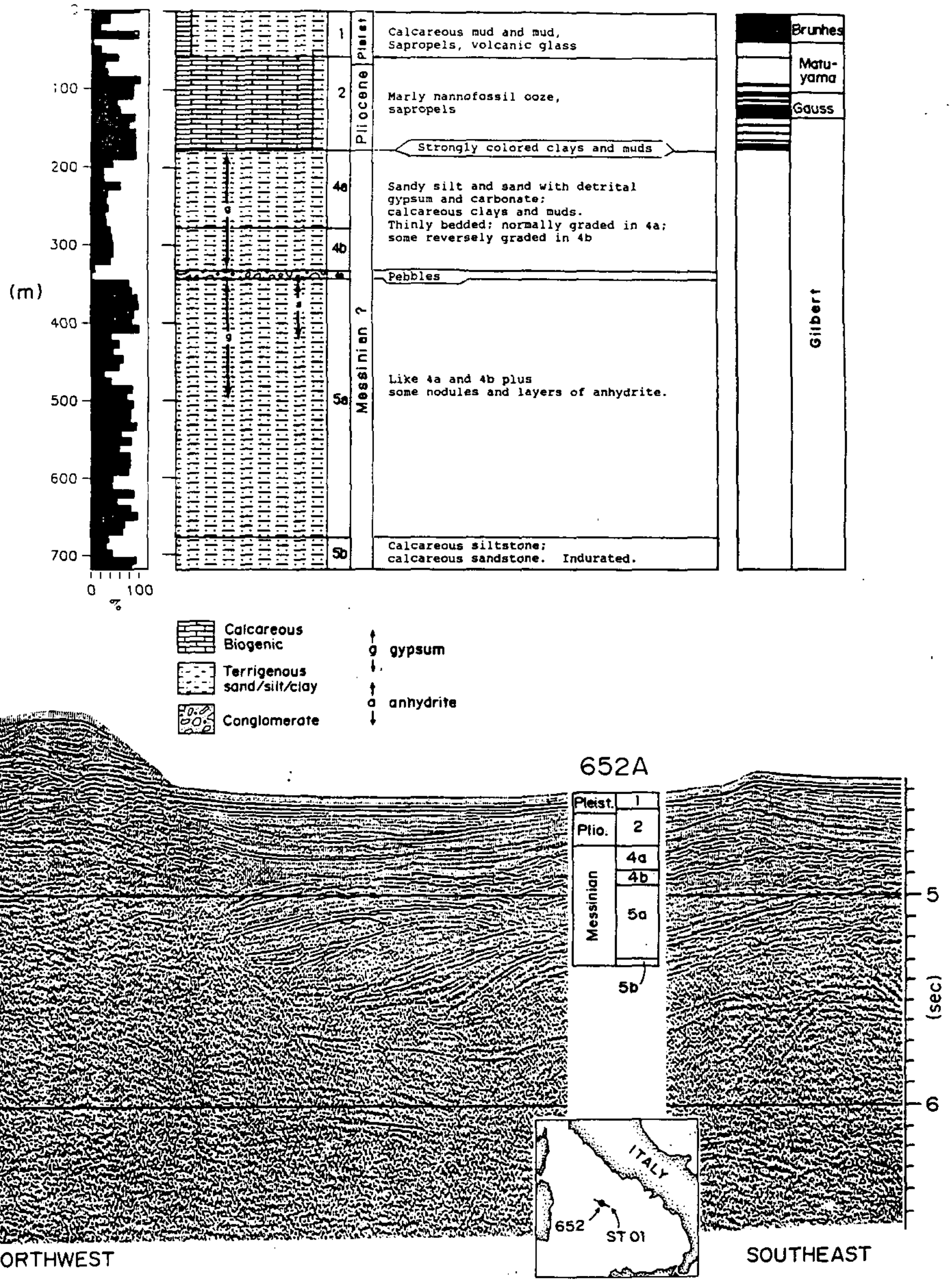

FIGURE 20 DRILLING RESULT FROM ODP LEG 107 IN THE TYRRHENIAN SEA (UPPER PANEL) AND A SIMPLIFIED DRILLED SECTION COMPARED WITH A MULTICHANNEL REFLECTION PROFILE (LOWER PANEL). NOTE THE COMPLEX SEDIMENTARY STRUCTURE THAT WILL GREATLY INHIBIT THE POSSIBILITY OF OBTAINING A SATISFACTORY TIE OF GEOLOGIC DATUM TO THE DRILLED SECTION.

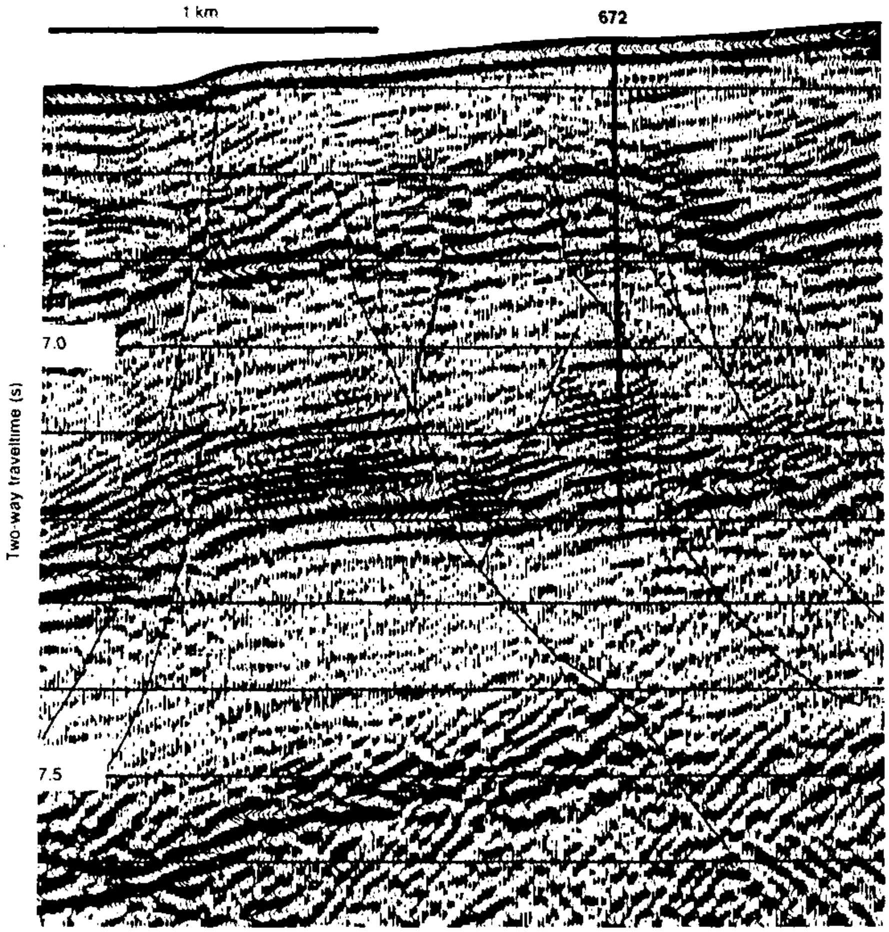

FIGURE 21 COMPARISON OF DRILLSITE LOCATION AND MULTICHANNEL SEISMIC PROFILE AT ODP SITE 672, SEAWARD OF THE BARBADOS ACCRETIONARY PRISM. NOTE THE OBVIOUS STRUCTURAL COMPLEXITY. THE DEPTH TO BASEMENT AT AROUND 7.5 SEC COULD BE ACCURATELY DETERMINED FROM A ZERO-OFFSET VSP HERE.

VI. ESSENTIAL ELEMENTS OF A VSP PROGRAM FOR ODP

The consensus of our Workshop was that a strengthened and rationalized VSP program can considerably improve the scientific return of ocean drilling. We recommend that VSP data acquisition become an integral component of ODP operations. VSPs should be acquired at a suite of ODP sites with certain hole characteristics, geological environments and drilling objectives. The present system of somewhat ad-hoc VSP experimentation "added on" to drilling legs is not likely to ensure the realization of the potential role of VSPs. At present VSP experiments "compete for time" with what is generally considered the primary purpose of drilling - the recovery of rocks. If, however, this sample-based knowledge is to prove of value to understanding major geologic processes such as oceanic crustal formation, the development of sedimentary sequences and basin evolution, it _must_ be properly linked to regionally extensive surface geophysical measurements and correctly located within the local structural environment. To achieve this fundamental objective we believe that VSPs should become an integral part of ODP operations, much as downhole logging. The elements of our suggested plan for VSP acquisition are noted in points 2-5 of the Executive Summary. We expand upon them in the following.

ZERO-OFFSET VSP

Because the establishment of an accurate tie between the drilled section and regionally extensive seismic coverage is essential to achieving the scientific objectives at many ODP sties, we consider that a systematic program of ZERO-OFFSET VSP acquisition ought to be included in the ODP. Experiments using this technique have been conducted at several ODP sites (see Section IV), and the Downhole Measurements Panel (DMP) has recommended ZERO-OFFSET VSPs at many upcoming sites. All sites in relatively simple structural settings which have been drilled to more than 400 m, and have within their suite of objectives the recovery of a stratigraphic record (either sedimentary or igneous), should have a ZERO-OFFSET VSP conducted along with standard logs and sonic logging. We therefore envisage this VSP application as an enhancement to the routine Downhole Measurements program already in place. The decision as to which holes should have ZERO OFFSET VSPs could be made through DMP and the Site Survey Panel if the present ODP panel structure was employed. Input from the Site Survey Panel would be required to assess if the regional seismic coverage is adequate to justify the experiment. There is little justification for a borehole seismic experiment designed to provide an accurate tie of the drilled section to reflection profiling if the surface seismic data are poor or sparsely distributed. In general, a regional grid of good quality multichannel seismic profiling should be available, or planned in the immediate future.

OFFSET VSP

THE OFFSET VSP, by nature of the experiment itself, is substantially more time consuming to execute and logistically demanding than ZERO OFFSET VSPs. The offsets needed for the experiment require that a source be carried on a separate floating platform, as a crane or boom-mounted structure cannot provide sufficient lateral separation from the drilling vessel. This requires either that the experiment be conducted with another vessel brought to the site of drilling operations, or that a specialized platform be deployed from the drilling vessel itself.

Shooting operations only are performed from the separated platform, so that a fairly modest vessel is required. Nevertheless, the operational requirements are quite a bit higher than for ZERO-OFFSET VSP work. While the OFFSET VSP can provide a wealth of information on the geologic environment around a borehole in any setting, we believe that they will be most valuably employed in settings of complex structure and/or strongly laterally varying physical properties. While such environments are often drilled by ODP, they represent a small proportion of total sites drilled; much less than those drilled in fairly simple settings. We, therefore, envisage a natural restriction of these more time-consuming VSP experiments to a relatively few sites.

We emphasize, however, that this should not be considered to imply that OFFSET VSPs are somehow unique or extraordinary experiments, and hence treated as aberrations to "normal" operations. The OFFSET VSP technique is virtually standard in industry use because exploration targets frequently occur in structurally complex environments. Their application in ODP would be less common because this type of environment is not encountered as frequently as in industry work. The VSP technique in ODP and industry applications would differ little, if any; it is the rationale for their use that may differ substantially.

The OFFSET VSP applications in ODP have been outlined in the previous section under the headings "Seismic Anisotropy, Attenuation Measurements and Lateral Variability", and "Imaging Structure around ODP Sites in Complex Settings". While a fairly diverse suite of site characteristics could be embraced under these general descriptions and a wide variety of geographic/ geologic environments included, we summarize the common characteristics as follows. OFFSET VSP experiments should be performed at sites where:

1) The borehole has been located to intersect strata within a region of deformation (basement involved or sedimentary). Passive margins and accretionary wedges are obvious examples. The role of the VSP here is to ensure a correct tie of the drilled units to the object structure and/or obtain a satisfactory understanding of the structural environment of the borehole.

2) The borehole is located in a region where strong lateral and horizontal changes in the crust's physical properties are expected, and are of importance to understanding the geology of the region. The oceanic crust is the obvious example here. The role of VSP is to derive estimates of physical properties such as attenuation that are difficult to measure from surface measurements and to map lateral variations.

Details of the experimental design would vary depending upon the individual objective and, particularly for 1) above, a dense coverage of geophysical data around the site is an important requirement.

Tools and Analysis Requirements

To carry out recommended VSP experimentation as an integral part of ODP science will require that a suite of equipment be routinely available aboard the RESOLUTION, and be coupled to an adequate shore-based facility for data analysis. We believe that the following represents a facilities complement that would match our goals.

1. Shipboard Requirements

   a. Tools

   The standard tool of choice is a 3-component down-hole seismometer. Since tool development is currently in a state of flux, with improved models constantly coming on line, it would be self defeating to buy tools for specialized VSP experiments. Instead, we recommend that these should be leased from a contractor. Desirable enhancements include Gyroscope orientation, added hydrophone, internal calibration via vibrators, and multi-element tools. Four- and eight-level tools are currently available and/or under development. Use of such tools would greatly reduce the time required to acquire VSP data but are unlikely to be deployed in uncased holes. Future possibilities include tools with up to 16 levels and down-hole multichannel hydrophone arrays which might increase the feasibility of 3-D multi-offset, walk-away surveys.

   b. Seismic sources

      i ZERO OFFSET VSPs

      The sources currently in use are single air guns and water guns. The frequency content of these sources would be greatly improved if it were possible to deploy larger numbers of guns. Since the technical aspects of this are constrained by equipment-safety considerations of the drilling ship, continuing negotiations with SEDCO personnel will be necessary.

      Due to SEDCO-imposed limitations on the permissible amplitude of source-induced pressure fronts on the Dynamic Positioning system seals, the largest air gun used to date was about 1200 cubic inches. A tuned four-gun array with this total volume would be more efficient and would have a superior signal character. It is possible that some spatial beam-forming could be accomplished with a larger number of guns with larger total volume, resulting in minimization of the peak pressure felt at the ship.

      Water guns have an intrinsically large spectral bandwidth. Two contaminating features of this signal are the low frequency precursor and the free surface ghost. These can be minimized by forming an array of three or more water guns, each suspended at a different depth. This results in variations between the precursor-primary and the primary-ghost times that enhance the primary pulse and diminish the contaminating features. This source should be superior for VSPs in the sedimentary columns. Equipment for monitoring the near-field and far-field signatures, and for synchronizing the guns must be available.

ii OFFSET VSPs

Several possibilities exist for offset sound sources. Conventional airgun arrays can be deployed from multichannel seismic ships or placed on ships of opportunity. The latter case would require an investment in equipment; compressors, air guns and deployment gear. If an ODP support vessel were to be obtained, such a system could be designed as a portable unit.

A smaller airgun array, such as that outlined above for ZERO-OFFSET VSP's, could be deployed from a small (40 ft) multi-purpose ship that could be carried aboard the drilling ship and launched by crane. This source would only be adequate for limited offsets and/or depths. Explosives could be used for larger scale refraction work. This satellite vessel would have to be equipped with ranging, timing, navigation and telemetry gear.

c. Recording Equipment

Conventional gear, possibly provided by a contractor, would be sufficient. Necessary specifications include:

1) at least 96 channels

2) record lengths between 5 (zero offset) and 20 (offset) seconds at sampling rates of .25 msec

3) recording delay of up to 10 seconds

4) demultiplex to SEG-Y format aboard ship

5) Dual tape transports

6) "real-time" quality control capability, both of source monitors and recorded data.

Data logging capability for other geophysical parameters, clocks, two-ship ranging equipment, dynamic ship positioning parameters, etc.

The advent of down-hole and surface marine vibrating sources would eventually require that the acquisition system be capable of correlating long (up to 99 seconds) sweeps.

d. Shipboard Processing and Modeling

The basic requirement is for "standard" processing capabilities, such as those afforded by any one of a number of commercially available packages or, perhaps, academic institutions. The field inputs and shipboard outputs should be standard, i.e., SEG-Y tape format, so that data will be immediately accessible. The existing shipboard system has many of the desirable aspects required and provides a viable basis on which to develop a wholly satisfactory system.

The planning and flexibility of VSP acquisition can be greatly enhanced by the availability of onboard VSP modeling. This may be available as a commercial software package, or an academic home brew program, running on the processing computer. This software should include elastic and anisotropic modeling.

2. Shore-Based Facilities

It is desirable that a group of workers and a shore-based facility be nominated to coordinate the VSP acquisition and processing. This group would provide liaison between contractors and scientists, where necessary, and would support the basic processing and modeling facilities on the ship. Duplicate or compatible computers and software must therefore be available at this site. Facilities should also be available to onshore VSP processing by interested P.I.'s.

This group would also be responsible for processing interpretations and dissemination of "standard" VSP data.

Interpretation methods are always being developed and improved, but all of the "standard" tools should be available at this location.

3. Time Considerations

The few ZERO-OFFSET VSPs that have been acquired to date in the ODP have taken 24-36 hours each. It is certain that this time will be improved, on average, when VSP acquisitions become a routine procedure.

The utilization of multi-level tools, better source characteristics, and improved clamping/calibration procedures would also shorten the time required. The use of down-hole vibrating sources and the acquisition of multi-offset, multi-depth profiles could lengthen the time. Estimations for ZERO-OFFSET VSP profiles may be based on the following menu:

Transit from surface to sea floor:	
Inside drill string	3000-5000 meters/hour
Transit and clamp, each station	4-7 minutes
No. of pops per station	5-15
Pop repetition rate	20-30 sec
Time back up hole to sea floor	1000 meters/hour

U.S. National VSP Management

The workshop participants recommended that a U.S. National VSP Laboratory should be established:

1. to carry out routine ZERO and OFFSET VSPs as required by U.S. scientists in the drilling program,

2. to carry out research and development into VSP technology both in hardware and in data acquisition, reduction, analysis and interpretation,

3. to interface with other groups working on wireline re-entry technology and long term earthquake monitoring (these two categories are the subjects of other USSAC sponsored workshops),

4. to interface with the JOIDES Logging Contractor and the JOIDES Drilling Contractor in shipboard operations. The laboratory should be a 'center of excellence' with personnel and equipment available to carry out innovative VSP projects. It would provide support to U.S. scientists who are interested in various aspects of a VSP program but who lack the facilities to carry out an independent effort.

The U.S. National VSP laboratory would be funded through the USSAC Program and would report to the USSAC Committee. Liaisons to the JOIDES Downhole Measurements Panel (and perhaps the Planning Committee) should be established.

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APPENDIX I

AUTHORS AND TITLES OF PRESENTED PAPERS

James A. Austin (UTIG, Austin):
The Ocean Drilling Program: Its Scope and Objectives

David Goldberg (Lamont-Doherty, Borehole Research Group):
ODP's Logging Program

Joseph D. Phillips (UTIG, Austin):
ODP's VSP Program to date

Ralph Stephen (WHOI):
Oblique Seismic Experiments at Boreholes

Roger Turpening (MIT):
Innovative uses of the VSP Experiment

Dale Pennington (Schlumberger):
Use of Borehole Seismics in the Petroleum Industry Today

Doug Foster (ARCO):
Elastic Wave Separation of OFFSET VSP Data

Bruce Shapiro (Western-Atlas):
Receiver Design and Response and Observation of Anisotropy in VSP Processing

Richard Verm (Geophysical Development Corp.):
VSPs: Fact, Fiction and Conjecture

Gerald T. Schuster (Univ. of Utah):
Traveltime Tomography applied to VSP Data

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APPENDIX III

ODP LOGGING PROGRAM

Lamont-Doherty Geological Observatory, as the prime logging contractor for the Ocean Drilling Project, is contracted to supply a full suite of geophysical and geochemical services which involve the acquisition, processing, and presentation of in situ logging measurements to JOIDES scientists. Our charge is to provide state-of-the-art logging services customized to scientific needs, plus certain specialty logs which, though not generally available, are of particular usefulness to scientific logging. We also provide interpretation and dissemination services so that JOIDES scientists can use logs to help solve their particular scientific problems.

To direct us in these duties, the Downhole Measurements Panel helps to plan long-term equipment and services development, to assist in the identification of new technology, to recruit scientific logging scientists to participate in each ODP leg, and to coordinate and integrate the L-DGO logging services with third-party downhole measurements programs.

The Logging Services for ODP consist of three major components: A subcontract to Schlumberger Offshore Services for basic logging data acquisition. Schlumberger, the industry leader, supplies their state-of-the-art commercial logging services on every leg of the ODP. Second, specialty logging services which are not available through Schlumberger at the present time, including acoustic borehole televiewer and multichannal sonic tools, are run by Lamont-Doherty Borehole Research designated personnel. Third, a log analysis center at Lamont-Doherty has computer processing, log analysis and interpretation services ready for the ODP scientist's use after leaving the ship. This center is designed to provide the JOIDES scientist with the interpretive skills and tools necessary to solve his geological problems using logs. To carry out the program at sea, there are three logging personnel on each ODP leg: a logging scientist from the JOIDES scientific community, a Schlumberger field engineer to operate their tools, and a L-DGO logging staff scientist to assist the co-chiefs and logging scientist in the design, implementation and subsequent interpretation of the logging program on each leg.

DATA ACQUISITION OVERVIEW

Geophysical log data are recorded using probes which are lowered on the end of a wireline through the drillpipe and into a previously drilled borehole. The logs most commonly run in the ODP wells are Schlumberger logs. The Schlumberger logging tools, run by the Schlumberger engineer, are combined into multiple-tool strings for efficient operation. We presently operate three standard tool combinations: the seismic stratigraphic, the litho-porosity, and the geochemical combinations. Some overlap exists between these combinations, and the data are synergistic in the sense that some of the more sophisticated post-processing and analysis cannot be accomplished without data from all three lowerings. Some measurements are also common to all lowerings in order to provide a correlation point such as the sediment/basement contact or the bottom of the drillpipe to relate the log depth to the drilling depth.

In general, all ODP logging tools are less than 3.675" in diameter in order to fit through the ODP drillpipe and are temperature rated to 350 °F. Additional tools, run by the L-DGO Logging representative or the JOIDES logging scientist, include the acoustic borehole televiewer and multichannel sonic tools. Related L-DGO logging equipment on the JOIDES RESOLUTION includes log analysis computational software, a wireline heave compensator, and a digital depth decoder. The L-DGO and Schlumberger logging tools, equipment, and their applications are summarized below. Acronyms are given in parentheses for reference.

Seismic Stratigraphic Combination:

The seismic stratigraphic combination includes the long spacing sonic (LSS), dual induction (DIL), gamma ray (GR), and caliper (MCD) tools. Its value to seismic stratigraphy is that it directly measures compressional wave sound velocity and indirectly measures the two variables that most often affect velocity: porosity and clay mineral percentage.

Litho-porosity Combination:

The litho-porosity combination includes natural gamma spectrometry (NGT), lithodensity (LDT), and compensated neutron (CNT-G) tools. This combination provides measurements of formation porosity and density as well as an estimate of the proportions of the primary radioactive elements (U, K, and Th).

Geochemical Combination:

The geochemical combination includes natural gamma spectrometry (NGT), induced gamma ray spectrometry (GST), and the aluminum clay tool (ACT; a second NGT paired with a Californium-source CNT-G neutron tool). Its value to geochemistry comes from its ability to measure relative concentrations of 11 elements: silicon, calcium, iron, sulphur, aluminum, manganese, hydrogen, chlorine, potassium, thorium, and uranium.

Dual Laterolog:

Induction logging probes do not produce reliable results in highly resistive formations such as oceanic basalts. The Schlumberger Dual Laterolog (DLL) provides the deeper measurement of resistivity into the rock with high precision at high resistivities.

Borehole Televiewer:

Borehole acoustic televiewers are employed to detect and evaluate fractures and bedding intersecting the borehole wall. An acoustic beam scans horizontally around the circumference of the borehole wall as the tool is moved vertically. Televiewers are very sensitive and can outline quite small features such as fractures, vugs or other large size porosity and bedding planes. The dip and orientation of fractures or bedding planes in the formation can frequently be determined. Measurement of the travel-time of the reflected pulse yields a 360 degree caliper log which can be used to detect spalled zones in the wellbore related to horizontal stresses.

Magnetometer/Hole Orientation:

An additional measurement cartridge (the GPIT) can be included in the string of the litho-porosity or geochemical combination, to determine hole azimuth and deviation and the vector components of the magnetic field. Although this device is not oriented gyroscopically, magnetic field inclination can be measured accurately. The device also monitors vertical and horizontal accelerations applied to the logging probe and thus can be used to determine the effects of ship heave on the logging run.

Heave Compensation:

Experience during DSDP demonstrated that ship heave can seriously degrade the quality of logging measurements. Although the relationship between ship motion and the motion of a downhole instrument is not simple, a significant amount of heave was being transmitted to the logging probe. Therefore, L-DGO asked Schlumberger to design a heave motion compensator for the logging cable.

The depth at which the measurements are made is determined primarily by measuring the length of cable run into the hole, and data are typically recorded at half-foot (0.1524 m) intervals in the borehole. During logging operations the logging cable is run through a piston-mounted sheave on the heave compensator and back again to the rig floor. As the piston extends, the length of cable between the winch drum and the rig floor is reduced by twice the amount of extension. Ship's heave is sensed by an accelerometer mounted near the rig floor, and the signal is transmitted to a computer which computes the effective motion. The piston-mounted sheave is then driven in or out to compensate for vertical motions of the drilling vessel. Tests of this system on ODP Legs 105 and 109 and 118 indicated that in operation the heave compensator improved log quality and reduced the primary components of ship's heave.

SONIC LOGGING

Sonic tools are designed to measure the elastic compressional-wave velocity of the formation surrounding the borehole. In essence the sonic tool can be thought of as a miniature seismic refraction experiment carried out within the cylindrical borehole. A sonic tool is usually centered in the hole by means of bowsprings, and contains one or more sources and receivers. A source fires acoustic energy which is transmitted into the borehole fluid. When the wavefront impinges on the borehole wall, a refracted compressional wave is generated. If formation shear velocity is higher than the acoustic velocity of the fluid, a refracted shear wave will also be generated. The refracted waves travel along the borehole wall, re-radiating energy into the fluid. Energy arrives at receivers on the logging tool at a time which is linearly proportional to their offset from the source. Thus formation elastic-wave velocities can be determined by differencing the arrival times at two receivers a known distance apart. Additional guided modes are typically produced in the borehole environment, and their propagation is controlled by the properties of both the formation and the fluid-filled borehole.

Principal Applications:

Compressional sonic velocity is one of the primary elastic properties measured during logging. The product of velocity and density (impedance) is useful in computing synthetic seismograms for time-depth ties of seismic reflectors. If a refracted shear arrival is present, its velocity can be computed from the full waveforms, and the frequency content and energy of both compressional and shear arrivals can also be determined. Variations in energy and frequency content are indicative of changes in fracture density, porosity, and in the material filling the pores. In some cases compressional-wave attenuation can also be computed from the full waveforms.

Long-Spaced Sonic Tool:

The Schlumberger Long Spacing Sonic (LSS) sonde uses two acoustic transmitters spaced 2 feet apart and two receivers also spaced 2 feet apart and located 8 feet above the transmitters. This provides 4 source-receivers offsets of 8, 10, 10, and 12 feet. Compensation for borehole irregularities and inclination of the tool to the hole axis is achieved by memorizing the first transit time reading and averaging it with a second reading obtained after the sonde has been pulled up by a fixed distance along the borehole. The symmetry of the sources and receivers allows 4 travel-time measurements across each two-foot interval using 8 combinations of sources and receivers. The upper centralizing spring also measures caliper using a linear potentiometer to measure bowspring extension.

The LSS tool records the full waveform for each source-receiver pair, in addition to its automatic determination of arrival time. The sonde can be run in two modes to either correct downhole gains for variations in amplitude or to maintain a fixed gain. As arrival-time is determined automatically using a threshold detector, the variable gain mode often produces better travel-time logs, although absolute amplitude logs will no longer be possible.

DT and DTL logs are presented as interval travel-times in microseconds per foot for the near and far receiver pairs, respectively. Care must be taken to ensure that the value of sonic transit time is reasonable. Cycle skips (where the first arrival is missed) can be a problem, and washouts and wall roughness complicate the velocity measurement. In very slow formations DTL provides the only valid measurement, as the refracted wave is not seen at the near receivers. The sonic waveforms can also be displayed alongside the travel-time curves, and the individual travel-time measurements in microseconds are also available. Pips on the log plot indicate integrated travel-time to depth for crude seismic correlations.

Multi-Channel Sonic Tool:

The multi-channel sonic log (MCS) is a multi-receiver single-source sonic logging tool which records 12 sonic waveforms at each source depth. The MCS tool is configured with the source above the receiver string, separated by a variable-length spacer assembly. The receivers are spaced 15 cm apart, resulting in a 1.65 m receiver array. The MCS geometrty is therefore similar to the geometry of a surface refraction survey. During the log, the MCS tool is centered in the borehole by means of bowspring centralizers.

A MASSCOMP computer controls the tool during logging, allowing the operator to select the depth increment between recorded suites as well as the number of receivers to be used. The data are digitized by the MASSCOMP and recorded on magnetic tape during the logging run. The MCS log is obtained while logging uphole at a rate which depends on the depth increment and number of receivers selected. For a 0.3-m depth increment and 12 receivers per source depth, typical logging rates are at present about 3 meters per minute.

The MCS waveforms can be analyzed to yield compressional, shear and Stoneley velocities across the receiver spread using a modified Semblance calculation. In addition, variations in frequency content and amplitude of the individual modes can be determined. Although the standard Schlumberger sonic logs can provide accurate compressional velocities, the additional information provided by the MCS tool allows the complete characterization of the elastic properties of the formation. The final output can be displayed either in log format or in full waveform format on a Versatec plotter. The MCS data are presently used for lithologic determination and porosity estimation from compressional velocities, fracture location, structural analysis in basaltic rocks, and estimation of pore aspect ratio from Vp/Vs.

Array Sonic Tool:

The Schlumberger Digital Array Sonic tool (SDT) is the newest addition to ODP logging equiptment and is scheduled for routine operation in 1988. The tool uses 2 transmitters and 10 receiver spaced so that the 8, 10, 10, 12 foot geometry of the LSS tool is preserved, and a linear array of 8 receivers spanning 3.5 feet from 10 to 13.5 feet from one transmitter. The tool can be run in LSS-type borehole compensation mode, linear-array mode recording a suite of 8 full waveforms, or high-resolution mode enabling 6-inch depth resolution of velocity between receiver pairs in the array. The SDT waveform data is digitized downhole and telemetered to the surface computer for recording.

The major advantages of the SDT is that the array geometry provides high-resolution velocities that were available previously only using the MCS tool, but now may replace the LSS tool in the seis-strat combination. All the elastic wave modes can then the measured without requiring an additional logging run. In addition, the SDT downhole digitizer has greater dynamic range than existing uphole systems yielding more accurate waveform amplitudes. The SDT data are displayed and analyzed similarly to MCS waveforms, and the improved velocity and amplitude measurements also have the same applications.

DATA ANALYSIS

The computer on the Schlumberger recording sled (designated CSU) is designed primarily for data acquisition and display of the primary log curves. However, it can run a few analyses to obtain a "quick look" at computed values. In general, however, the CSU is used only for data acquisition and to produce clean data tapes and log playbacks for the shipboard party.

The MASSCOMP logging computer onboard the JOIDES RESOLUTION runs a log analysis package called Terralog, which can do log cross-plots, lithologic analyses and corrections as well as displaying the new analyses in standard log format. Once data tapes have been copied for use on the L-DGO system, scientists perform these analyses in the course of preparing the logging chapter of the shipboard report.

All logging data are archived at L-DGO, and three independent log analysis systems are available for use by JOIDES scientists: a Schlumberger Elite system, an Energy Systems system, and the Terralog package on the L-DGO MASSCOMP computer. Data can be analyzed at L-DGO Borehole Research Laboratory using these systems or translated into several possible formats for use on different systems. All logging data is available to the JOIDES scientific community one year after the termination date of each ODP leg.

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