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PRELIMINARY RESULTS OF SEISMIC AND MAGNETIC SURVEYS OFF DELAWARE'S COAST

BY

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PURPOSE

The nature and occurrence of subsurface resources, whether ground water, minerals, or petroleum, are controlled by the geologic history and framework of any particular area. Several years ago the staff of the Delaware Geological Survey began an informal assessment of the potential resources of southern Delaware and demonstrated the lack of basic data on the deep subsurface in this area. This assessment was later summarized by Benson (1976) with particular emphasis on the possibilities for petroleum occurrence.

The purpose of this project was to map the top of the "basement" surface beneath the rocks of the Coastal Plain sediments in southern Delaware. In this case "basement" rocks were defined as crystalline rocks of igneous or metamorphic origin, similar to the types which crop out in the Piedmont Province of northern Delaware. They were thought to underlie the Coastal Plain sediments at depths of about 7,000 to 10,000 feet (2100 to 3000 meters) below sea level in the area of study. Near Lewes, in the northern part of the study area, Marine and Rasmussen (1955) had placed basement at a depth of about 6,000 feet (1800 meters) below sea level. The configuration and depth of the basement surface in southern Delaware has taken on increased significance because of the possibility of offshore petroleum occurrences.

As the study progressed it became necessary to distinguish between "geologic basement" or the crystalline basement described above and "acoustic basement." Acoustic basement for the purpose of this study is the first horizon below identifiable unconsolidated Coastal Plain sediments that can be distinguished by either a strong reflection on the seismic record or by a change in the general character of the reflected sound waves. Such a horizon may or may not correspond to the crystalline basement surface. For example, consolidated sedimentary rocks lying beneath Coastal Plain sediments but above crystalline basement might give a noticeable reflection.

METHODS AND AREA OF STUDY

Geophysical methods were chosen over exploration drilling because of the cost of drilling to the depths expected. Several geophysical techniques were considered: (1) marine seismic reflection, (2) land seismic reflection, (3) land seismic refraction, (4) magnetic surveys, and (5) gravity surveys.

It was felt that the most suitable technique for the purpose outlined above was that of seismic reflection. Initially, it was planned to confine the work to the onshore portion of the State and to include in the study area portions of all three counties where well control to basement is available. These plans were prompted by the existence of seismic equipment at other institutions and the possibility of arranging a cooperative study. However, it became apparent soon after the project starting date that such equipment could not be made available in time for scheduled completion of the project.

In the meantime, the DGS staff had been collecting and interpreting offshore seismic reflection data as part of another project supported by the Delaware Office of Management, Budget and Planning (Contract 04-6-158-44014/1506/1) and had generally become familiar with the quality of data obtainable. Also, the price of offshore seismic surveys was less than half the cost of comparable land surveys. As a result the emphasis of the program shifted to a marine survey to be run as close to the Delaware shoreline as possible. This would still accomplish most of the original objectives of the land program. A contract was signed with Digicon Geophysical Corporation to run a "high resolution" seismic reflection profile over an approximately 21-mile course from about the Delaware-Maryland boundary north of Ocean City to a point just inside the mouth of Delaware Bay (see Figure 1). The area was selected because of (1) deep well control at Ocean City and Cape May, (2) the availability of other seismic profiles farther offshore which could be tied into this profile and (3) the potential importance of the adjacent coastal area in any future resource development. The "high resolution" profile, with proper interpretation, can give exceptional detail on the geology by means of the seismic record.

These plans generated further outside interest and both private companies and other agencies indicated a willingness to participate. Subsequently, the Water Resources

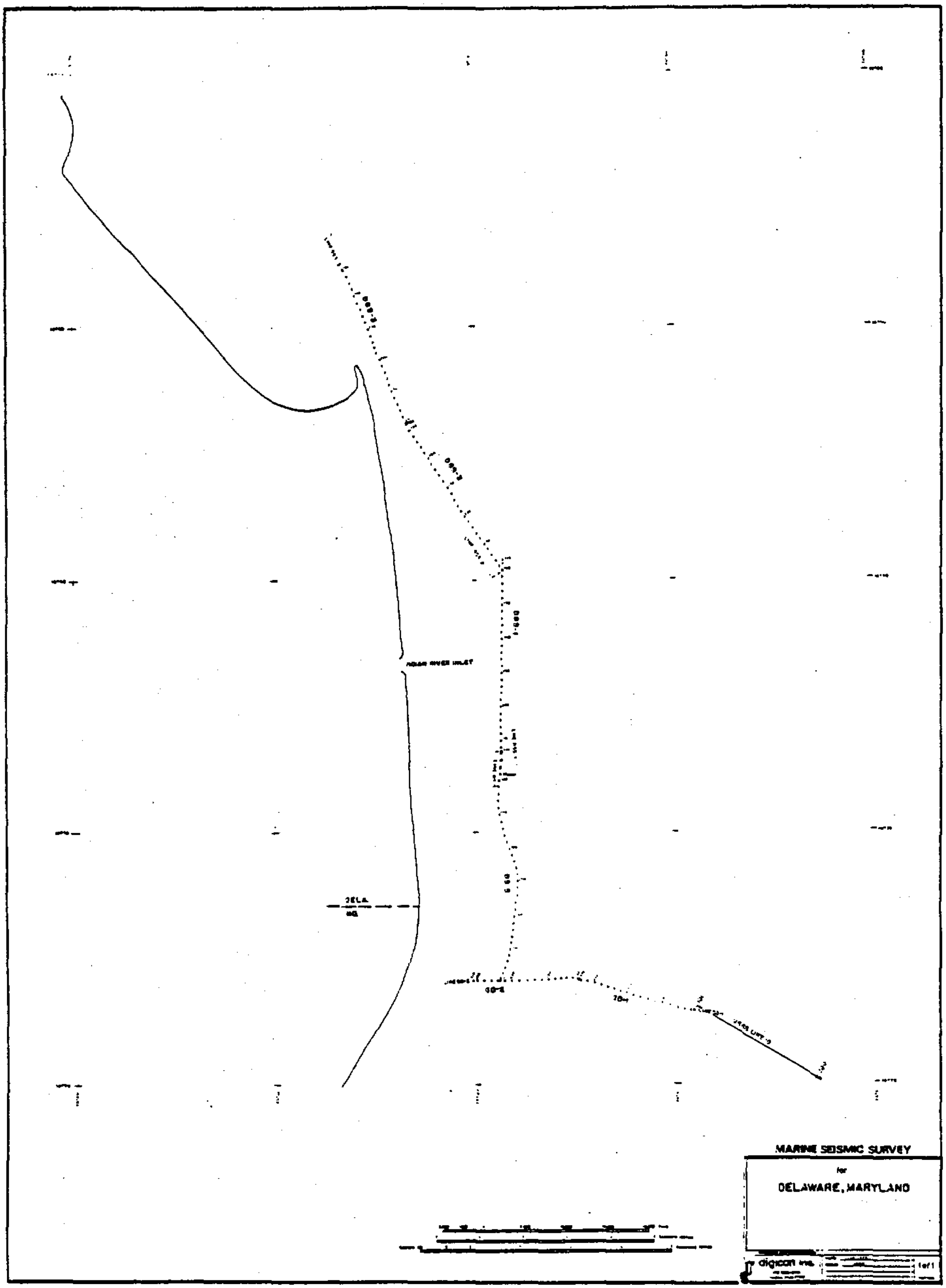


FIGURE 1. Profile and shot-point locations.

Division of the U. S. Geological Survey (Maryland-Delaware District) purchased additional mileage on the same survey. This extended the southern end of the DGS line south from Delaware to a point opposite Ocean City, Maryland. Grant support from the U. S. Geological Survey, Office of Marine Studies, Atlantic-Gulf of Mexico Branch provided a tie from this point east to the western end of USGS Line 10 (see Figures 1 and 2.) Total mileage contracted with Digicon was about 41 statute miles. Copies of all data went to all participating parties.

The 41-mile course was broken into six segments labeled DGS-1, DGS-2, DGS-3, DS-5, GD-1, and GD-2 (Figure 1). All lines were run on May 17, 1976 and data were processed by June 3, 1976 at the facilities of Digicon in Houston. The technical information and original profiles are on file at the Delaware Geological Survey. Most of the pertinent data of interest to geophysicists in studying the records are on the individual profile sheets. Two-way travel time of sound waves was recorded for a total time period of three seconds, which, based on other information, was initially judged to be long enough to record crystalline basement reflections.

Alternative geophysical methods were considered as an independent check on the seismic data within the constraints of the budget. It was found that a great deal of recent magnetic data already existed in the form of aeromagnetic quadrangle maps published by the U. S. Geological Survey. However, the map that included Delaware (Aeromagnetic Map of Atlantic Continental Margin Quadrangle N38-W74) was incomplete along the Maryland-Delaware coast. The technical difficulties leading to the omission of the Maryland-Delaware area were discussed with the original contractor, LKB Resources. It was determined that the Delaware portion of the map could be completed with data already existing in the files of LKB Resources. Consequently LKB was contracted by DGS to complete the map and also to provide (by subcontract) an interpretation showing depth of magnetic basement based on the magnetic data. These results will be discussed in a later section of this report.

RESULTS OF SEISMIC SURVEY

Correlation of Reflectors

It became apparent after initial study of the seismic reflection profiles that crystalline basement was not well

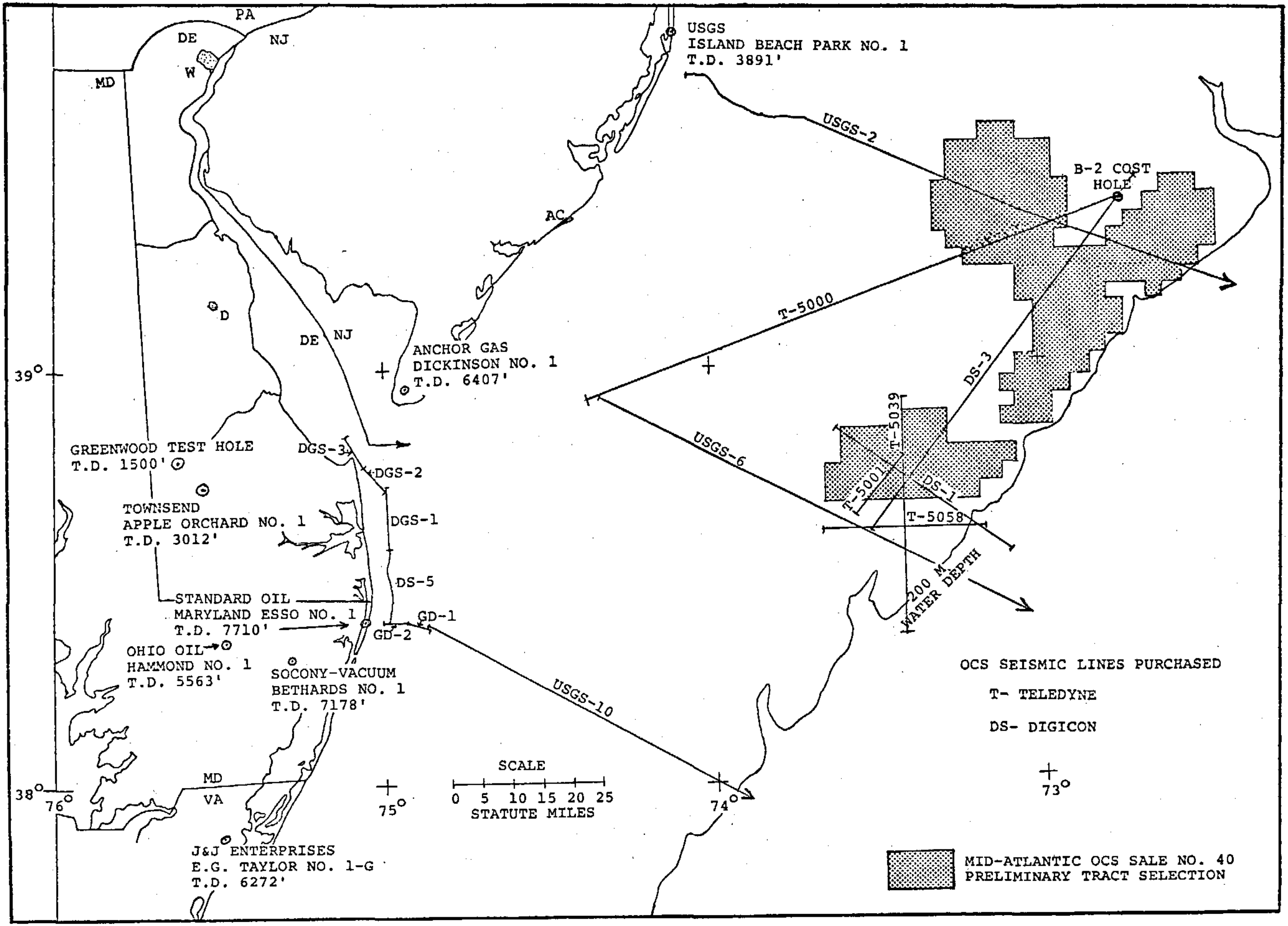


FIGURE 2. Sketch map showing location of seismic profiles and well control used in this study.

defined in most cases. However, weak and discontinuous reflections on what was defined as "acoustic basement" could be seen in most instances. The upper half of the profiles (about 1.5 seconds of two-way travel time or approximately four thousand feet in depth) showed excellent resolution and detail, particularly for ground-water use planning purposes. Under the assumption that crystalline basement was indeed present within the three seconds of record, DGS continued discussions with Digicon in an attempt to devise additional processing techniques that might enhance reflections from crystalline basement. Little success was had in these attempts and it was concluded at that time that part of the problem was loss of energy due to absorption in Coastal Plain sediments and possibly by gas within the sediments.

In the final interpretation however, it appears that at least in most cases, crystalline basement is considerably deeper than expected and is below depths that would give reflections within the three seconds of record. Figure 3 is a reduction of the original data for line GD-1 and is included as an example of the type of data obtained. The entire set of original data is on file at the Delaware Geological Survey. The cross-sections in Figures 4, 5, and 6 were constructed from the original data and summarize the interpretation of the results. These were constructed with considerable vertical exaggeration in order to show detail. Another set of sections was constructed with no vertical exaggeration (not shown) in order to show true perspective. The depths to the various reflectors were calculated by use of velocity analyses supplied by the contractor.

Three major units can generally be identified on each line or profile by character of the record alone. These units and their interpretations are as follows:

1. from the top of the record to approximately 0.5 to 0.8 seconds - characterized by continuous reflectors usually easily traced across the record; represents sediments of predominantly marine origin.

2. from about 0.8 seconds to about 2.0 seconds or deeper - characterized by broken discontinuous reflectors, traceable for short distances across the record; represents sediments of marginal marine to non-marine origin.

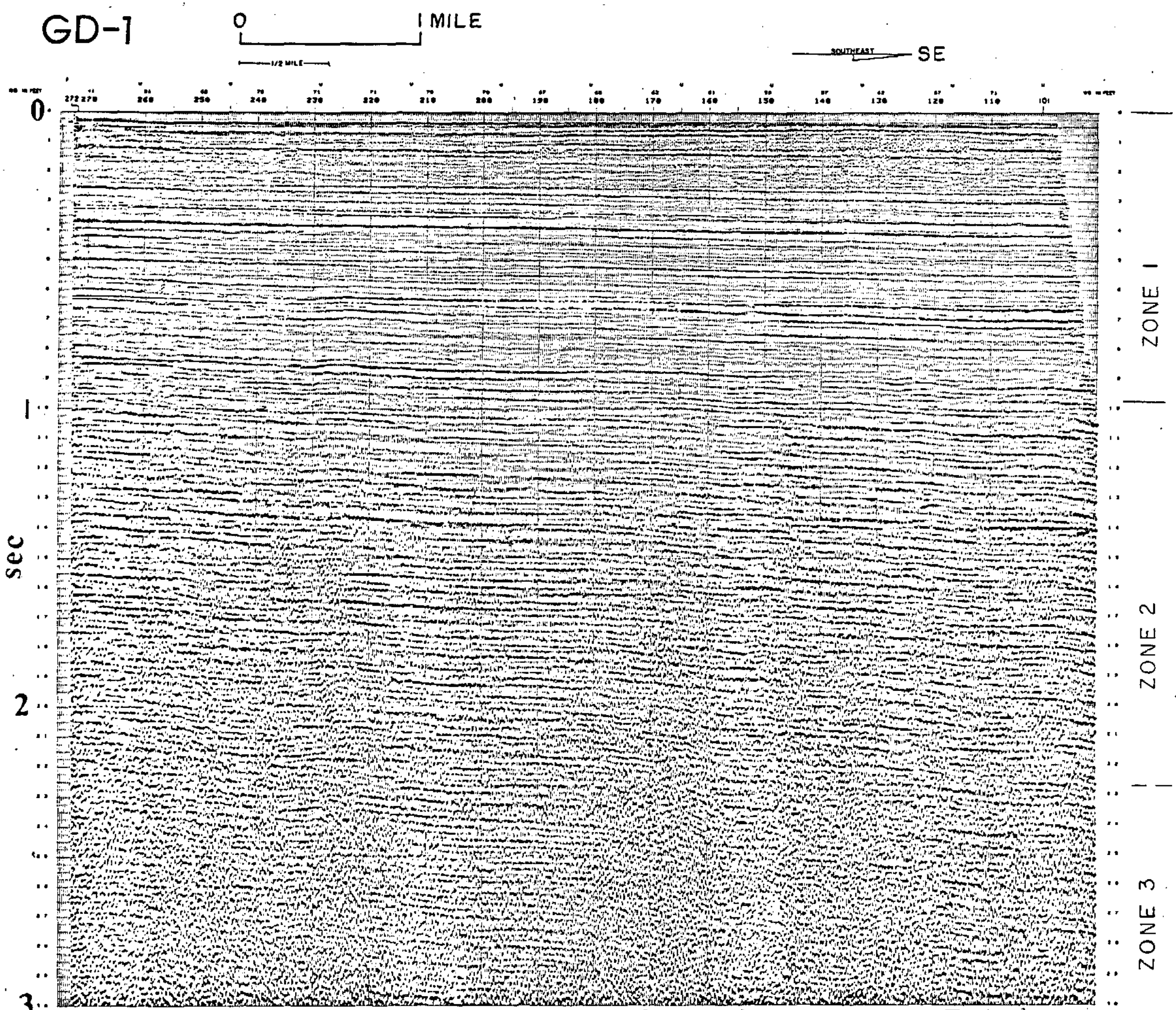


Figure 3. Line GD-1, approx. 1/3 original size.

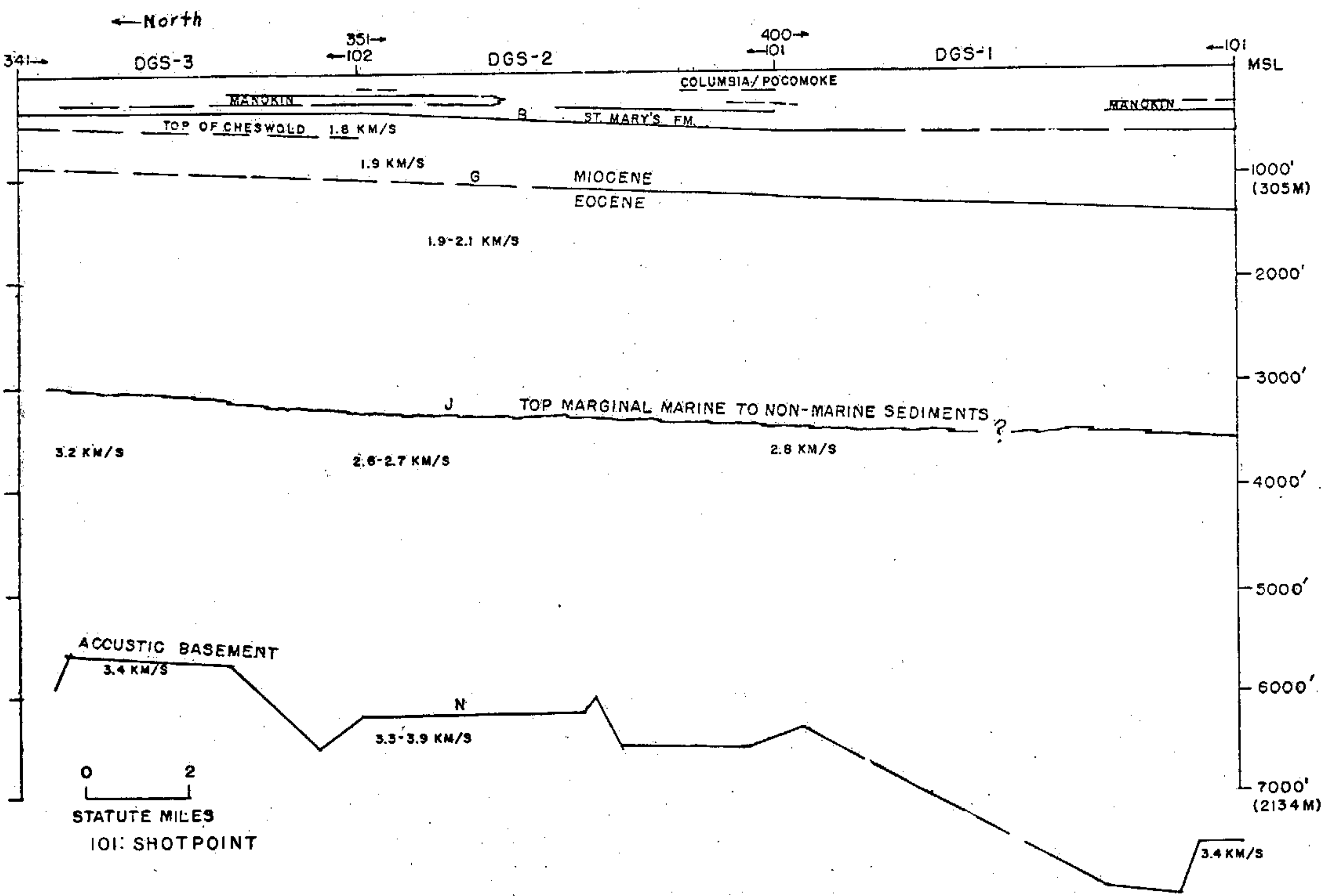
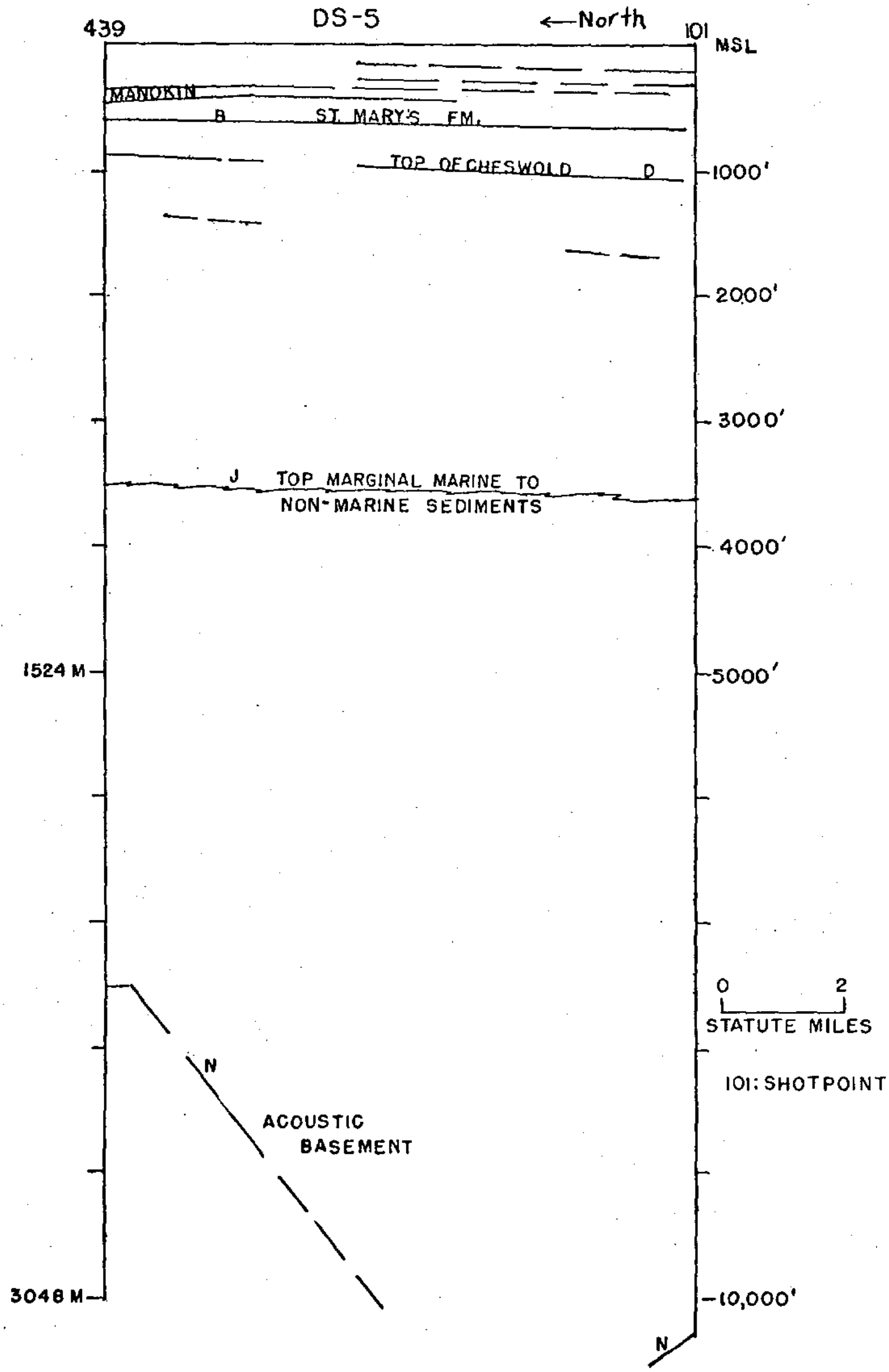


FIGURE 4. Interpretive cross-section, lines DGS-1, DGS-2, DGS-3.

FIGURE 5. Interpretive cross-section, line DS-5.



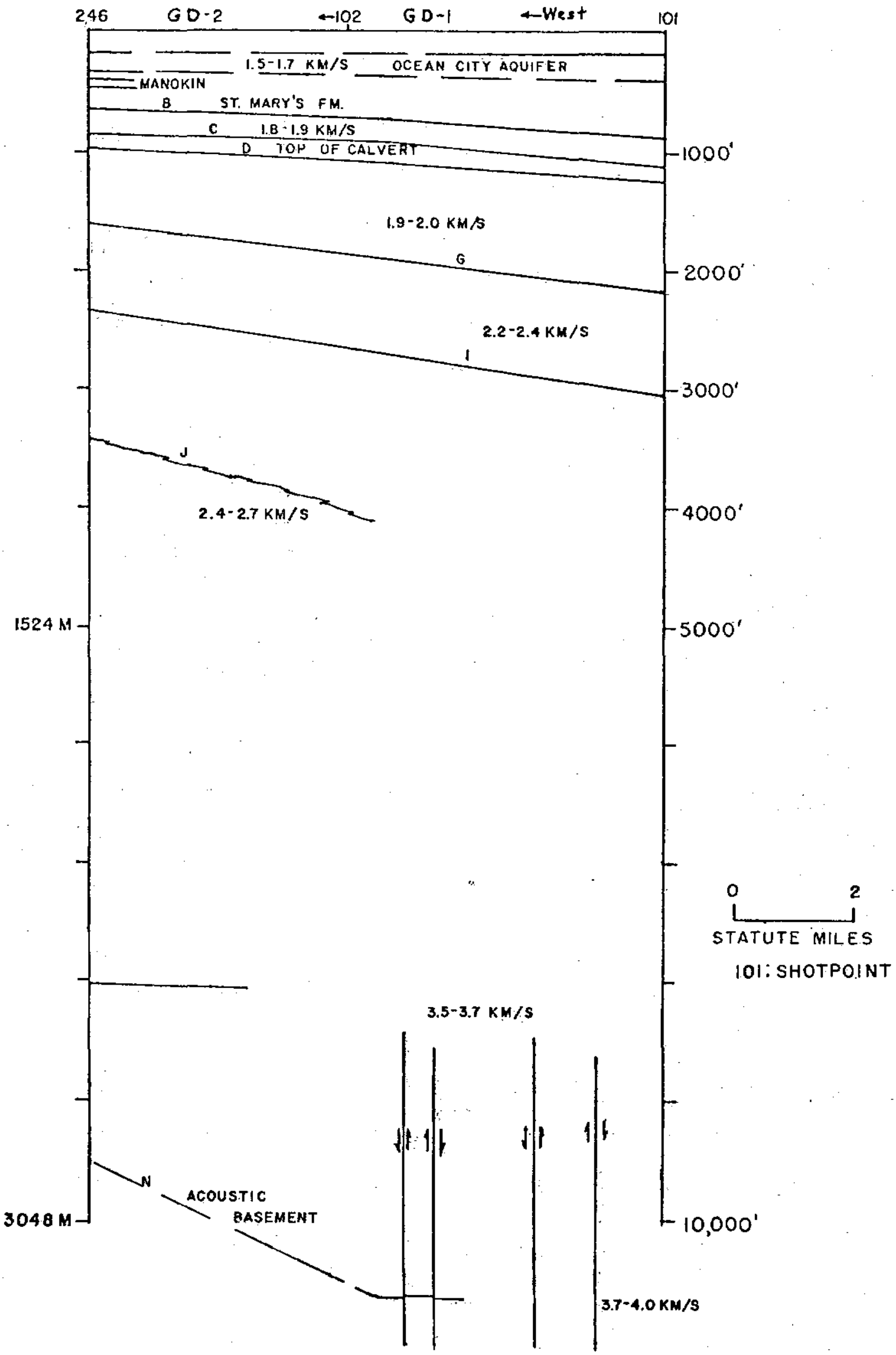


FIGURE 6. Interpretive cross-section, lines GD-1, GD-2.

3. 2.0 seconds, or deeper, to the bottom of the record - characterized by almost no obvious traceable reflectors except possibly at the top of the interval, reflectors jumbled, may represent non-marine sediments, but could also be due to noise and loss of signal.

Individual reflectors were then correlated with existing well control and were carried from section to section wherever possible. Those reflectors that could be traced across all or nearly all of the study area were given informal letter designation as follows:

B - bottom of St. Mary's Formation (Weigle, 1974) a fairly persistent confining layer beneath shallow aquifers of Miocene age.

D - top of Calvert Formation (USGS terminology), a series of sands and clays of Miocene age.

G - break between sediments of Miocene age and older sediments of Eocene age.

I - appears to be the top of a major sandy unit within sediments of Cretaceous age. "I" seems to correspond to the top of a major aquifer that is known to be present north in Kent and New Castle Counties (Magothy Formation?).

J - marks the transition between sediments of marine origin and sediments of marginal marine to non-marine origin.

N - probably "acoustic basement" rocks in most cases. (This is not a persistent reflection but occurs sporadically throughout the study area.)

Reflectors marked as D, G, and C were traceable over less than half of the entire survey but can be correlated with reflectors seen on the western end of USGS seismic Line 10. Line 10 is the eastern tie or anchor point to this survey.

The above reflectors proved to be "key" horizons for correlation with onshore well control and with other seismic records. Data from the Esso oil test (Maryland Esso No. 1) near Ocean City, Maryland and the oil test at

Cape May, New Jersey (Anchor Gas) provided the bulk of the deep onshore control (see Figure 2). Shallow wells at Bethany Beach, Rehoboth Beach, and Lewes provided secondary control.

Velocity Analyses

Velocities of sound waves within major zones or geologic units (interval velocities) were calculated in an attempt to evaluate the general type of rock present in any given interval. Major rock types can often be defined by a range of characteristic velocities. In general, interval velocities increase with depth, reaching a maximum of about 13,400 feet per second (4.08 kilometers per second) in what was defined as acoustic basement beneath Line GD-1. The youngest sands in the geologic section give the slowest interval velocities, about 5,000 feet per second (1.52 kilometers per second). In most cases a distinct contrast in velocities between various geologic formations does not seem to exist. Instead, geologic units are characterized by overlapping ranges of velocities which would be expected in Coastal Plain sediments. However, it is believed that the velocities in basement rocks should be distinctly higher than those in the overlying sedimentary rocks. Previous work (Woodruff, 1971) indicated that velocities in unweathered crystalline rocks cropping out in the Piedmont of northern Delaware are between 15,000 feet per second and 25,000 feet per second (4.57 km per second to 7.62 km per second). However, no velocities as high as these were noted in the present survey.

These relatively low velocities imply that acoustic basement is not composed of crystalline rocks of the Piedmont type but, rather, might be semi-consolidated to consolidated shales or sandstones. A Triassic age has been suggested (Maher and Aplin, 1971) for rocks at the bottom of Bethards No. 1 well in Maryland shown on Figure 2. Sabat (1977) has suggested the presence of a Triassic Basin near Chesapeake Bay, west of the present study area. If Triassic age rocks are indeed present it is possible that there are no large differences in velocities between acoustic basement rocks and the overlying Coastal Plain sediments. An examination of downhole velocity logs from a number of deep test holes in the Atlantic Coastal Plain sediments show that velocities vary widely. Velocities near the bottom of several thousand feet of Coastal Plain sediments may be as high as those in more consolidated rocks.

Crystalline basement may thus be much deeper than originally expected and the travel time (two-way) of reflected sound waves may be greater than three seconds, the time interval during which reflections were recorded in this survey. In general, the three second reflection time would allow the recording of reflections to about 15,000 feet, depending on exact velocities.

Basement Definition and Structure

Some of the problems of defining precisely the top of the basement have been discussed in the previous section. In most cases a clear reflector indicating basement top is lacking. Acoustic basement was generally taken to be the top of Zone 3 (see Figure 3) discussed under "Correlation of Reflectors." Usually acoustic basement was picked by noting where the change occurred in the general character of the reflector pattern from Zone 2 to Zone 3. Velocities within the layer designated as acoustic basement range from about 10,100 feet per second (3.1 kilometers per second) to 13,400 feet per second (4.1 kilometers per second). These velocities, as has been suggested, are not clearly indicative of any specific rock, but are considerably lower than velocities for fresh crystalline rock. Calculated depths to the top of this surface are indicated on the cross-sections (Figures 4, 5, and 6) and range from about 5,500 feet (1,675 meters) below sea level at the northern end of the study area (Line DGS-3) to a possible depth of 11,000 feet (3,350 meters) below sea level at the western end of Line GD-1. At the eastern end of Line GD-1 no basement pick of any kind could be made and even "acoustic basement" appears to be "deeper" than the three seconds of record. This interpretation agrees with the data from the western end of USGS Line 10 which seems to place basement (crystalline?) below 3.3 seconds or at a depth of about 16,000 feet (4,877 meters).

Despite the lack of good definition of the top of crystalline basement at least two major structural features can be identified from the survey: (1) on Line DS-5 a major trough appears to be present with possible thickening of Coastal Plain sediments; (2) from the western end of Line GD-2, east to the beginning of Line GD-1, the basement surface (acoustic) drops off quite abruptly. A series of faulted blocks are proposed in order to account for this abrupt steepening. Furthermore, the proposed faults seem to extend upward into overlying Coastal Plain sediments of Cretaceous (?) age. The interpretation of these structures are consistent with the interpretations obtained from the magnetic data, as discussed in the next section of this report.

RESULTS OF AEROMAGNETIC METHODS

Magnetic intensities are due to the presence of magnetic minerals within rock masses. General rock types can often be deduced from the shape and intensity of the magnetic field and the depth of the rock body producing the field can be calculated within certain limits. The outstanding feature of the magnetic survey interpretation as submitted by Intex (subcontractor to LKB Resources) is the generally deep crystalline basement (Figure 7), which in nearly all instances is placed deeper than 16,000 feet (4,877 meters). This interpretation would agree closely with that obtained by the USGS (personal communication) for the western end of their Line 10 and with the DGS interpretation of the seismic data for the eastern end of Line GD-1.

Farther to the north, the seismic and magnetic data seem to give somewhat different interpretations of the depth to basement. The "magnetic basement" is placed at depths that would be "deeper" than three seconds in all cases. This would, however, explain the lack of crystalline basement reflections on the seismic profile if magnetic basement does indeed correspond to the crystalline basement.

A "shallow" magnetic horizon (in addition to the crystalline basement) was also interpreted by Intex at about 8,200 feet (2,500 to 3,000 meters). This horizon in some areas seems to correspond with "acoustic basement" as interpreted by DGS from the seismic records. LKB, likewise, does not believe this shallow horizon is associated with the crystalline basement directly. Even this shallow horizon is somewhat deeper than acoustic basement in most places.

The magnetic survey also shows (Figure 7) two major linear features within the study area. These appear to be major faults within crystalline basement rocks and seem to correspond with faults identified from the seismic survey. The north-south trending structure appears to be cut by the east-west trending linear.

Two basement "highs" or domes are apparent on the magnetic interpretation just to the north and to the south of the major "linear" through the study area. These domes would present distinct possibilities for further exploration both from the standpoint of petroleum exploration and as gas storage reservoirs. Both of these features are apparently cut by major faults (above) which further increases their potential attractiveness. It should be noted that the center of the northernmost dome is only about 16 miles due east of Indian River Inlet.

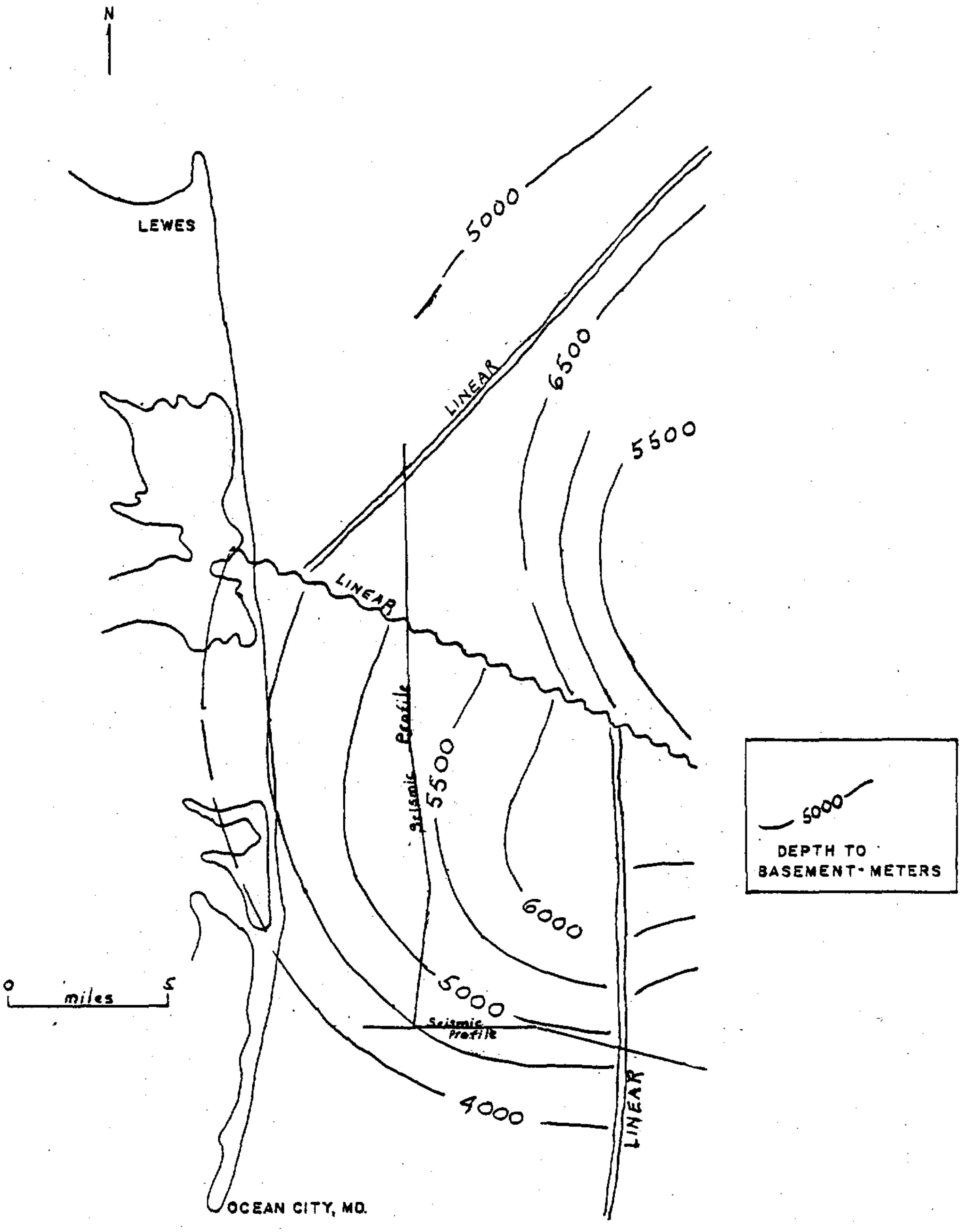


FIGURE 7. INTERPRETATION OF MAGNETIC SURVEY

APPLICATIONS

One of the results of the seismic survey was the rather good detail obtained on the extent and character of geologic units in the upper 1,000 feet (3,048 meters) of sediment. Individual aquifers from which coastal communities presently withdraw large amounts of ground water can often be readily identified on the seismic record. The bottom of a Miocene age unit, the St. Mary's Formation, seemed to provide a persistent marker bed throughout the area of investigation and also appears to form a barrier to direct vertical movement of ground water. The overlying sands and silty units which include the Manokin, Ocean City, and Pocomoke aquifers were nearly all discontinuous laterally and no individual aquifer or aquiclude could be traced throughout the entire study area.

Line DGS-1 was particularly helpful in confirming the lithology of the coastal area between about Dewey Beach and Indian River Inlet. Previous test drilling had indicated that sands normally providing relatively high yields of fresh water were thin or absent in this area. The lack of traceable reflectors on the seismic survey confirms the drilling results and seems to outline the lateral extent of this anomaly. Other locations where lateral changes in sediment type occur within a named formation or aquifer can also be identified. The possibilities for ground-water development in such areas would probably be poorer than in adjacent areas. The lack of strong reflectors could indicate the absence of tight confining beds and thus a possibility of salt-water contamination due to ground-water withdrawals. Because of these apparent lateral changes in lithology, geologists have experienced difficulties in correlating individual aquifers and confining beds along the southern Delaware Coastal area. The seismic work emphasizes the nature of the problem and indicates that in some cases the assignment of individual aquifer names may be arbitrary. More importantly, the survey results strongly suggest that the entire geologic section from the bottom of the Manokin aquifer upward could function as a single "leaky hydrologic unit" over a time period of perhaps several years. Thus pumping in one aquifer may have an eventual effect on other aquifers. The present Delaware Geological Survey Cooperative Program with the Water Resources Division of the U. S. Geological Survey includes the construction of a computer model of hydrologic conditions in the upper 500 feet of Coastal Plain sediments in southern Delaware. The data on aquifer continuity obtained from the seismic lines assisted in making basic decisions on how to treat the overall ground-water system above the St. Mary's Formation. The model in turn will assist water regulatory agencies of the State in allocating ground water and planning future withdrawals.

Both the specific agreements and discrepancies between the magnetic and seismic surveys have been pointed out. The common feature produced by both methods is the fact that "basement," both acoustic and magnetic, seems to be considerably deeper and more irregular than formerly believed. The top of "acoustic basement" seems to be a minimum depth at which basement rocks by any definition will be found. Geologic structures, (faults, domes) also seem to be present and this combination of structure and increased sediment thickness increases greatly the chances for both hydrocarbon accumulation and gas storage potential.

The possibility of a highly faulted basement just off shore also raises the question of whether or not there is still any geologic activity or movement along such faults. Little data exists at the moment. Some "felt reports" provided by local residents over the past few years indicate that there may have been small seismic events in the past but no instrumental recordings exist to confirm this. The Survey's seismograph net is presently being expanded and possibly could help answer this question.

One immediate application to State policy and planning is suggested as a result of this work. A U. S. Department of Interior position paper (June, 1975) urged States to submit nominations for offshore lease areas. Delaware may, at some time, wish to consider encouraging or discouraging exploration within or adjacent to State boundaries. Data derived from this project are, at the moment, the only known detailed data available within possible State lease areas. Such a possibility also suggests that the present State oil and gas regulations may need review. It will be important to have such geologic data as guidance so that decisions will not be made in the absence of objective facts.

CONCLUSIONS

This project has shown that (1) "acoustic basement" probably does not coincide with "crystalline basement" throughout most of the study area. Acoustic basement seems to be much shallower than the interpreted depth to the crystalline rocks and may represent rocks of a much younger age (Triassic?). This is not inconsistent with regional geology and with the informal thinking of a number of geologists (personal communications). (2) Crystalline basement rocks appear to be much deeper than expected and may be deeper than 15,000 feet (4,500 meters) beneath most of the study area. (3) Complexities in geologic structure are apparent, particularly offshore from the Maryland-Delaware boundary. An area of major faulting seems to occur near the eastern end of Line GD-1. (4) In the upper 500 feet of Coastal Plain material, individual aquifers and confining layers seem to be discontinuous laterally. (5) The potential for resource exploration close to the Delaware-Maryland coast appears to be more favorable now than before this study was undertaken.

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