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Reference No. 61-19

Seismic Reflection Study of the Geologic
Structure underlying Southern Narragansett
Bay, Rhode Island

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Seismic Reflection Study of the Geologic
Structure underlying Southern Narragansett
Bay, Rhode Island

By

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Paul M. Fye, Director

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INTRODUCTION

A subbottom reflection survey of southern Narragansett Bay, Rhode Island was made by means of a continuous seismic reflection technique (the Continuous Seismic Profiler) developed at the Woods Hole Oceanographic Institution (Knott and Hersey, 1956). The observational program was conducted in May, 1958 under contract with the Corps of Engineers, U. S. Army, and in May, 1960 under contract with the Bureau of Ships, U. S. Navy, to obtain foundation data for locating hurricane barriers (Corps of Engineers, 1957) and to develop techniques for studying the geologic structure of shallow water areas. At the Woods Hole Oceanographic Institution this work is part of a continuing, broader program directed toward describing the structures and tracing the geologic history of continental margins.

The Continuous Seismic Profiler employs a wide-band sound source the pulses from which are reflected from the bottom and from sediment and rock layers beneath the bottom. The sound pulse is synchronized with the sweep of a Precision Graphic Recorder (PGR), which records sound energy received at an underwater detector. (In 1958 the sound source was an early form of the Sparker, while in 1960 the Edgerton Thumper was the source. (These instruments are described below.) When the sound source and the detector are towed from a boat, the reflected sound energy is recorded to present a continuously correlated picture of subbottom structure.

Measurements in Narragansett Bay were made south of the Jamestown Bridge in the West Passage and between Conanicut Island and Newport Neck in the East Passage (Fig. 1A and 1B). Two additional traverses were made across the bay in areas to the north where core data are available (Fig. 2).

ACKNOWLEDGMENTS

The field work of 1958 was performed under Contract DA-19-016 CIVENG-58-65 with the U. S. Army Corps of Engineers. Fundamental studies of the technique, the field work of 1960, and scientific analysis of the data were done under Contract NObsr 72521 with the Bureau of Ships, U. S. Navy.

Mr. S. T. Knott of the Woods Hole Oceanographic Institution's staff gave advice and help with the instrumentation. The field party of 1958 included D. R. Fink, E. T. Bunce, and A. L. Carter from the Institution, and C. G. Hard, A. J. Powers, and C. A. Maillard from the Corps of Engineers. J. S. Bercaw captained the Institution's Research Vessel ASTERIAS in that survey. The field party of 1960 included E. T. Bunce, E. E. Hays, and others from this Institution, and Research Vessel BEAR with E. J. Mysona, master, was the survey ship.

The technical account of the survey was prepared by D. R. Fink with slight emendations later by the other authors to include the use of the Thumper sound source. The interpretation of the seismic reflection data was carried out by J. B. Hersey and A. H. Nalwalk. D. R. Fink and A. H. Nalwalk analyzed the velocity profiles. A. J. Nalwalk and A. H. Nalwalk inspected bedrock outcrops on shore and prepared a reconnaissance map of the areal geology (Fig. 3) and the report on the geological investigations from field data and available literature.

Grateful acknowledgment is made to C. S. Innis, Jr. for preparation of figures, to the photography laboratory of the Woods Hole Oceanographic Institution and J. W. Stimpson for reproduction services. We are indebted to H. B. Fink for assistance in the analysis of data and to E. T. Bunce, D. A. Fahlquist, and J. W. Graham for critical review of the whole survey.

METHOD OF INVESTIGATION

Instrumentation

The equipment for the first reflection survey of 1958 included a spark sound-source (Sparker), AX-58 hydrophone (Brush Development Co.), Suitcase amplifier, Spencer-Kennedy electronic filters, and Precision Graphic Recorder (PGR). These instruments are pictured on Plate 1; a functional diagram is presented in Fig. 4A. The instrumentation is discussed by Knott and Hersey (1956) and Hersey (1957). In the 1960 survey from the Institution's Research Vessel BEAR, an Edgerton Thumper (Hersey, et al, 1960) supplanted the Sparker as the sound-source, Allison Series 2 passive network filters were employed, and one experimental hydrophone and preamplifier were used during part of the survey. There was no departure, however, from the functional diagram of Fig. 4A, and except for superior performance in 1960, there should be no difference in the results from the two parts of the survey.

Characteristics of the Sound Sources

When the Sparker is used, an underwater electric discharge, actuated synchronously with the PGR sweep, takes place at the spark electrode (a platinum wire embedded in a bakelite cylinder) and a sound pulse having approximately the pulse shape shown in Fig. 4B is radiated into the water. (Note: With the equipment used for this investigation, approximately 4000 volts are developed across a 1 mfd. condenser in the spark power source, i. e., 8 watt-sec. power input, whereas the pulse shown in Fig. 4B resulted from a 400 watt-sec. spark.)

The Thumper consists of a flat spiral coil against which a flat aluminum plate is held by a spring (Plate 2). A very large transient current sent through the coil repels the plate, generating a short, intense sound pulse in the water (Fig. 4C). The power input to the coil is approximately 1000 watt-sec.

As currently developed the Sparker and Thumper radiate comparable, but not identical, transient sounds. However, the Thumper used in the 1960 survey radiated a much more intense sound pulse than the early model Sparker employed in the 1958 survey. Measurements of depth to subbottom reflectors were the same for these two sources so long as both sound pulses were strong enough to produce echoes. Many echoes were recorded from Thumper that were not detectable from the early model Sparker.

The Use of Filters

Bottom and subbottom echoes are received at the detector (hydrophone) and go through a Suitcase amplifier to a variable passive network filter. This filter has adjustable frequency high-pass and low-pass sections, each having an attenuation of about 30 db per octave beyond cut-off. Signals within the selected frequency range are then fed to the PGR for amplification and recording.

The choice of frequency band of the filter is governed by the following considerations:

- 1.) Attenuation of seismic waves per unit distance in sediment and rock increases with frequency. There is, therefore, a practical upper limit to the frequencies that will penetrate to the desired reflecting surface.
- 2.) In any practical system, water noise, towing noise, and noise radiated by the towing ship tend to mask the desired reflection. All of these noises are apt to be considerably more intense in the low frequencies than in the high. Therefore there is a practical lower limit to the frequency band.
- 3.) The response of a filter to a transient sound, such as an echo, is prolonged in inverse relationship to the bandwidth of the receiving system. Thus a narrow filter has limited ability to resolve echoes having slightly different travel times. The prolongation of the pulse is approximately the inverse of the bandwidth, so that a filter 100 cps wide will not properly resolve events 1/100 sec. apart.

Requirements 1.) and 2.) are conflicting, but 2.) imposes a practical limit for a given ship, towing arrangement, and sound source. This determines the high-pass setting of the filter, while 1.) dictates how deeply the survey can penetrate. Sometimes, because of adverse noise conditions, it is advantageous to employ a low-pass filter as well; then the ability to trace thin-bedded formations is limited by 3.). In these surveys our operations were burdensomely noise-limited, but we were able to employ bands several hundred cycles per second wide in the range 200 to 1200 cps. By comparing the results from the two surveys we were able to trace reflections with confidence to about 400 feet below sea level. We feel certain that the Thumper was capable of reaching considerably deeper reflectors in Narragansett Bay, but in 1960 no attempt was made to do so. During 1958 we frequently recorded echoes to 400 feet below sea level, but could not do so consistently anywhere in the bay.

The Precision Graphic Recorder

The recorder unit of the PGR is a helical sweep-type graphic recorder which utilizes a damp, chemical recording paper (Knott and Hersey, 1956; Knott and Witzell 1960). The recorder drive is controlled by precision power as is the scale-line generator which superimposes time-lines on the record. A selection of drum speeds, and hence writing speed is possible. Commutators attached to the recorder drum permit various sound pulse-to-drum rotation ratios to be programmed so that energy from different depth intervals can be recorded. For the 1958 survey, the writing speed having a full scale depth of 400 feet was used predominantly. This scale was chosen to provide information from the deepest reflecting horizons to which energy

penetrated, and, at the same time, adequate resolution. In a few instances, the 200-, 240-, 300 and 600- foot writing rates were used. In the 1960 survey the 600-foot scale was used throughout.

Field Procedure (1958 Survey)

For continuous reflection profiling, the water electrode of the Sparker and the hydrophone were towed behind a boat just below the water surface (Fig. 5A). The electrode and hydrophone were kept relatively close together (about a 10-foot separation) and were maintained at approximately the same depth in the water (5 feet) to avoid the need for determining true depths from oblique reflections (p. 11).

The Institution's forty-foot motor launch ASTERIAS was used because it has the maneuverability desirable for this type of investigation, and the four-foot draft makes near-shore measurements possible. There was also sufficient auxiliary generator power to satisfy the electrical requirements.

Personnel conducting the survey aboard the ASTERIAS consisted of a scientific party of two from the Institution to operate the equipment, the boat captain and a helper, and three engineers assigned by the Corps of Engineers to take navigational sights.

Measurements were made along tracks designated by the Corps of Engineers in areas where subbottom foundation data were desired. Navigational control was achieved by taking horizontal sextant angles simultaneously on shore ranges at frequent intervals. In general, every fifth "fix" along a traverse was marked on the PGR record when it was made, so that direct correspondence of navigational "fixes" could be made with the record. Cloudy weather and rough seas were difficulties encountered at times in measuring the angles.

To supplement the graphic picture of subbottom structure obtained by continuous horizontal profiling, velocity profiles were made at several locations. These profiles provide factors for correcting depth measurements and for determining the different sound propagation velocities of the sediment layers. Propagation velocity is measured by increasing gradually the spacing between the sound source and the hydrophone while maintaining the vessel at a fixed position (Fig. 5B). The travel-times to various subbottom horizons, as measured on the graphic recording, can then be plotted against the corresponding travel-time of the direct water wave between the electrode and hydrophone for increasing angles of incidence. Computations of velocity from the resulting curves are discussed below.

In practice, the gradual increase in spacing between electrode and hydrophone for velocity profiling was accomplished by paying out the hydrophone to avoid handling the high voltage wire feeding the water electrode. In addition, it was necessary to maintain a slight forward speed in order to separate the hydrophone from the sound source, so that the velocity data are taken over a small area instead of at a fixed position.

In conjunction with the recording of subbottom information, bathythermograph observations were made at frequent intervals so that the speed of sound in water could be accurately computed for correction of the records.

Field Procedure (1960 Survey)

The Thumper was towed from the forward boom of BEAR at a depth of 6 to 8 feet. An AX-58 hydrophone was towed some distance astern, the exact distance being measurable only as a travel-time from actuation of the thump to the direct water arrival. A typical separation was 200 feet. For a portion of the work a Minneapolis-Honeywell flexi-disc hydrophone was towed from a boom extended ahead of the bow. This hydrophone was much closer to the Thumper, being about 40 feet away. When the two hydrophones were in use simultaneously, as they were much of the time, one could be used to check the results from the other.

PRINCIPLES OF INTERPRETATION

General Considerations

The acoustic energy which is emitted at the sound source is propagated through the water. Both sources produce a wide spectrum of sounds; the lower frequency components, being far less attenuated than the higher ones, are able to penetrate the bottom.

For interpretation it is assumed that the sound is propagated along straight-line paths through isotropic, homogeneous media. The sound energy which is able to penetrate the bottom is reflected at velocity discontinuities in the subbottom material. The recording of bottom and subbottom echoes presents a continuously correlated graph of travel-times corresponding to the reflecting horizons as the survey ship proceeds along a given traverse.

Continuous Profiling

If the sound source and receiver are at exactly the same location, and the bottom and subbottom horizons are parallel and horizontal, the sound paths will be normal to the horizons both initially and after reflection since the angles of incidence, reflection, and transmission will be zero. Thus, the travel-times to various surfaces of velocity discontinuity can be converted directly and simply to distances from the source-receiver, if the velocities of propagation between reflecting surfaces are known ($\text{depth} = \text{velocity} \times \text{time}$).

This picture was complicated in practice by the fact that the spark electrode and the hydrophone were towed about ten feet apart. This introduced an error in depth measurement greater than one foot for water depths shallower than thirteen feet. In deeper water this error became negligible.

As mentioned above, the source-hydrophone separation was about 40 or 200 feet. Hence oblique reflection corrections had to be made for these data. This was done by assuming the reflecting surface to be plane and horizontal, and the overlying material to be of uniform velocity equal to that of water.

The first arrival of reflected energy from any particular horizon is that which follows the path of the shortest travel-time. In general the path is not vertically below the source and receiver. Where the subbottom structure is complex and contains dipping layers, serious errors may result if the records are viewed simply as geologic cross-sections. They are actually continuous time-correlation records, and determination of true depth to a subbottom layer requires not only a knowledge of propagation velocities in the media, but also consideration of offset of depth reading due to inclined least-time paths.

As a first approximation, vertical soundings were computed from the echo sequences taking oblique reflections into account and assuming a constant velocity. These soundings were plotted as though they were structural profiles. For depths less than 200 feet in the southern Narragansett Bay region, such a section, corrected for true water velocity, requires little correction for differences between velocity in water and in sediment, since velocity measurements indicate that the sediments overlying bedrock have sound propagation velocities close to that of water. In the area where the highest velocity was found ($V_n / V_w = 1.15$), a maximum correction of +15 feet per 100 feet of thickness would be required (Fig. 6).

Plate 3 is a sample record showing many features characteristic of recordings in the bay. It is noted that reflections from the individual discontinuities consist of a band of closely-spaced traces. The first trace of such a group provides a measure of the least-time path reflection. The bubble pulse from the spark discharge and reflections from the surface near both hydrophone and source further prolong the wave train from a single bottom reflection. The exact wave form is further altered by the response of the filter. The time-scale superimposed on the records from the Sparker survey represents ten-foot intervals based on water-wave travel-time of 4800 ft/sec; the time-scale on the Thumper records represents thirty-foot intervals based on the same water-wave travel-time.

Multiple reflections involving both the bottom and subbottom horizons are not unusual. Care must be exercised during interpretation, so that such multiple reflections are not mistaken for first reflections from other reflecting surfaces. Intercomparison of the shapes of different echo sequences of a given recording together with accurate measurement of travel-time relationships generally serves to identify multiple reflection traces.

As previously mentioned, the path, source-to-reflector-to-receiver, is generally not vertical, and with the present instrumentation there is no means of measuring the vertical angle of individual reflections. The subject of interpreting continuous reflection records has been discussed by Pinke (1938) and De Vanssay de Blavous (1930, 1933) among others. Much can be deduced from closely-spaced profiles by reasoning that a reflector must be on an elliptical surface of equal travel-time which has the source and receiver as foci. Where source and receiver are identical and fixed the reflector must be on a sphere. It is common practice to plot the profile of an uneven surface by the arc-swinging technique, which is based on the assumption that the next approximation to the true profile is generated by the envelope of arcs equal to the soundings swung from the successive positions of the source/receiver. Hersey and Rutstein (1958) give an example of arc-swing interpretations. We have experimented with arc-swinging corrections for the present study, and have found that only in very few places could the correction make changes that are noticeable on our scales.

Velocity Profiling

The scale lines superimposed on the records indicate depth based on sound propagation velocity of 4800 ft/sec. In order to convert this to an accurate depth scale, velocities of propagation of sound must be known. These velocities are measured by increasing the distance between the spark water electrode and the hydrophone (Fig. 5B), and analyzing the change in the travel-time of a reflected wave that has passed through the material in question.

At discrete points along a velocity profile record, the times of arrival of the direct water-wave and the corresponding reflected waves are measured. The reflection travel-times are then plotted against direct water-wave travel-time (Plates 4 and 5). The following analysis is used to obtain analytical curves to fit the experimental data:

For a single reflection on the bottom between a sound source and receiver (Fig. 7A):

$$t_w = 2 \left(\frac{d_w}{V_w} \right) \sec \theta_w \quad = \text{travel-time of bottom reflection}$$

$$t_d = 2 \left(\frac{d_w}{V_w} \right) \tan \theta_w \quad = \text{travel-time of direct water-wave}$$

Now consider a single reflection between a source and receiver from a subbottom layer (Fig. 5B):

$$t_{w_1} = 2 \left(\frac{d_w}{V_w} \right) \sec \theta_w + 2 \left(\frac{d_1}{V_1} \right) \sec \theta_1 = \text{travel-time of 1st subbottom reflection}$$

$$t_{D_1} = 2 \left(\frac{d_w}{V_w} \right) \tan \theta_w + 2 \left(\frac{d_1}{V_1} \right) \tan \theta_1 = \text{travel-time of corresponding direct water-wave}$$

where $\frac{V_w}{V_1} = \frac{\sin \theta_w}{\sin \theta_1}$.

We can generalize for a reflection from the n^{th} subbottom horizon:

$$t_{w_n} = 2 \left(\frac{d_w}{V_w} \right) \sec \theta_w + 2 \left(\frac{d_1}{V_1} \right) \sec \theta_1 + \dots + 2 \left(\frac{d_n}{V_n} \right) \sec \theta_n =$$

travel-time for the n^{th} subbottom layer reflection,

$$t_{D_n} = 2 \left(\frac{d_w}{V_w} \right) \tan \theta_w + 2 \left(\frac{d_1}{V_1} \right) \tan \theta_1 + \dots + 2 \left(\frac{d_n}{V_n} \right) \tan \theta_n =$$

travel-time for corresponding direct water-wave

where $\frac{V_w}{V_1} = \frac{\sin \theta_w}{\sin \theta_1}$, $\frac{V_n}{V_{n+1}} = \frac{\sin \theta_n}{\sin \theta_{n+1}}$

Now $\sin \theta_1 = \frac{V_n}{V_w} \sin \theta_w$, so that

$$t_{w_n} = 2 \left(\frac{d_w}{V_w} \right) \sec \theta_w + 2 \sum_n \frac{d_n}{V_n} \sec \theta_n$$

$$t_{D_n} = 2 \left(\frac{d_w}{V_w} \right) \tan \theta_w + 2 \sum_n \frac{d_n}{V_n} \tan \theta_n$$

where $\theta_n = \sin^{-1} \left(\frac{V_n}{V_w} \sin \theta_w \right)$.

For an incident path normal to horizontal reflecting horizons, i. e. $\theta_w = 0$,
 $t_{dn} = 0$

$$t_{wn} = 2 \left(\frac{dw}{V_w} \right) + 2 \sum_n \frac{dn}{V_n}$$

where t_n then represents the vertical travel-time for a reflection to the n^{th} layer. These values can be measured on the travel-time plot at "O" water-wave time, if the reflecting surfaces are horizontal.

With these known quantities, trial values of θ_w can be taken for assumed values of V_n , and the general equation can be used to compute t_{wn} and t_{dn} for all n . Computations are made by assuming V first. Trial V_1 's are taken until the resulting curve fits the data. Next with the best-fit V_1 , and assumed V_2 , a best-fit for V_2 is sought. The same procedure is then followed to determine $V_3 \dots V_n$.

This analysis, of course, is developed on the assumption that the reflecting layers are homogeneous, isotropic, and horizontal, that the sound energy travels in straight line paths, and that Snell's Law holds. When velocity data were taken in the field, areas were chosen in which the reflecting horizons appeared to be nearly horizontal.

TRAVEL-TIME DATA AND SEISMIC REFLECTION SECTIONS

Velocity Measurements

Velocity profiles were made at several locations (Fig. 1A). The profile records and sections of related traverse records along with corresponding travel-time plots are shown on Plates 4 and 5. Table I presents the computed velocities of discernible horizons.

A low velocity first layer underlain by higher velocity material is present at velocity profile 1 location in the West Passage. Farther south (velocity profile 2), a low velocity layer occurs between materials having higher velocities. In both cases this low velocity material has a computed propagation velocity of about 0.80 water-wave velocity, and must represent material of relatively low density, due perhaps to the presence of gases or to a high water content.

Computations from data taken in the East Passage (velocity profiles 3 and 4) indicate that the first layer similarly has a lower-than-water sound propagation velocity. A refraction arrival from bedrock was close to the bottom. Analysis indicates an apparent velocity of sound propagation in this material of approximately 15,000 ft/sec. It was not possible to obtain a corresponding bedrock velocity by reflection techniques, since no reflections from horizons below the bedrock surface were identified on any of the velocity profiles.

GEOLOGICAL INVESTIGATIONS

Purpose

The purpose of the geological investigations was to map the rock outcrops along the shore in the hope that a knowledge of the shore geology would aid in the interpretation of the seismic reflection data taken in southern Narragansett Bay in May, 1958 and May, 1960 as described in this report.

Field Methods

The field work was carried out in May, 1960. United States Coast and Geodetic Survey Chart 236, Narragansett Bay, 1:20,000, 1959 was used as a base map for the area.

The shore outcrops were walked out and formation contacts were plotted on the field map. Dips and strikes were determined with a Brunton compass and locations were determined by sighting to three or more known points.

Two previous maps were consulted to aid in observation, description and naming of the rocks in the area. The geologic map of the Narragansett Pier Quadrangel completed for the U. S. Geological Survey by David R. Nichols in 1956 was consulted for the western half of the area; a generalized geologic map of Rhode Island by Alonzo Quinn (Quinn, 1953, p. 265) was used for the eastern portion.

Physiography and Geology

The area described below is the portion of Narragansett Bay between $71^{\circ}20'W$ and $71^{\circ}26'W$ and between $41^{\circ}26'N$ and $41^{\circ}31'N$ (Fig. 3). It is located in southern Rhode Island within the seaboard lowland of the New England Physiographic Province (Fenneman, 1938, map in folder), and is divided into two passages by Conanicut Island — East Passage and West Passage. The area is about 5.5 miles long and 4 miles wide; over half of it is under water at low tide.

The coast is low and irregular, and is characterized by bays, salt ponds, rugged headlands, islands, and beaches (Mc Master, 1959). There are cliffs 10 to 30 feet high along the Bonnet, the southern side of the eastern portion of Conanicut Island, and along Newport Neck.

Interpretation of structure and relationship is difficult due to the fact that, with a few exceptions, the rock types are different on opposite sides of the Passages.

West Passage

The portion of West Passage studied trends north-south and is irregular in outline. It is bounded on the south by Rhode Island Sound, on the east by Conanicut Island, and on the west by Rhode Island proper.

The outcrops along the west shore from Saunderstown to about $41^{\circ}27'13''N$ consist of sandstone, shale, meta-anthracite and pegmatite. Most authors agree that these rocks are Carboniferous in age and represent the lower part of the Rhode Island formation. The Narragansett Pier granite is found to the south of the Rhode Island formation and contains inclusions of schistose sandstone near the contact. Outcrops along the east shore of West Passage are phyllite, representing the upper part of the Rhode Island formation. The only exceptions are small outcrops of sandstone, shale, and meta-anthracite on Fox Hill, on Conanicut Island, and on Dutch Island. These small outcrops represent the lower part of the Rhode Island formation thus suggesting a syncline on Dutch Island.

East Passage

East Passage trends northeast-southwest and is more irregular in outline than West Passage. It is bounded on the south by Rhode Island Sound, on the east by Newport Neck and on the west by the two portions of Conanicut Island split by Mackerel Cove.

The rock outcropping on the Beaver Neck portion of Conanicut Island is the same phyllite of the Rhode Island formation that outcrops on the east shore of the West Passage. The portion of Conanicut Island east of Mackerel Cove is more complex. The southern shore is formed of the porphyritic granite which is believed to be pre-Pennsylvanian in age. North of this on the Mackerel Cove side is the Pondville conglomerate, presumed to be younger than, and derived from, the porphyritic granite and older than the phyllite which outcrops to the north of it. Along the shore north of Bull Point greenstone was found north of the granite. No granite-greenstone contact was found. The greenstone is presumed to be pre-Pennsylvanian in age, but younger than the granite.

There are two faults in this area. One, on which slickensides are prominent, is just northeast of Beavertail Point. The second fault cuts across the portion of Conanicut Island east of Mackerel Cove and brings the Pondville conglomerate against the phyllite of the Rhode Island formation. The fact that these formations, though different in age, are on the same elevation is evidence for the presence of this fault.

DISCUSSION OF SEISMIC RESULTS

Comparisons of Seismic Reflection Results with Coring

During the work in 1958 traverses were made along three sections where cores had previously been taken along the Jamestown Bridge (Fig. 1A), west of Patience Island, and between Prudence and Aquidneck Islands (Fig. 2).

Jamestown Bridge Section (Fig. 8)

Figure 8 shows the data and section based on borings and, at the same scale, our interpretation of the echo patterns on one of the clearer seismic records. The original seismic record is on Plate W5. We do not understand the mechanism which causes the series of intense multiple reflections. They were correlated with passing the piers of the bridge and there is evidence to suggest that the multiples are all side-echoes from corner reflectors formed by the piers. Elsewhere along the section it is obvious that we cannot follow the bedrock reflection except near the sides of the channel where it appears to agree well with the core data. The structure inferred from coring in the soft sediments in the eastern half of the profile appear to be well confirmed by the echo patterns there.

West of Patience Island (Fig. 9)

Two cross-sections have been constructed from data taken between Round Rock and Patience Island. One is based on information from borings, the other on seismic profiler records.

The bottom profiles on both cross-sections are very much the same, although the seismic record shows irregularities on the west side of the channel which would not be apparent in the borings.

The undulating subbottom horizons, to a depth of 100 feet, would seem to be due to variations in the composition or compaction of the gray clay shown in that area on the cross-section from the borings.

The deepest reflection, which varies from 30 feet below sea level near Round Rock to a maximum of about 140 feet at FD-2 may well come from bedrock. Bedrock was encountered only in FD-6 as sandstone at 110 feet. The reflection there is at 111 feet. Unfortunately there is no other sampling of bedrock along the traverse.

Prudence Island to Aquidneck Island (Fig. 10)

Two cross-sections have been constructed between Prudence and Aquidneck Islands. One of these is from borings taken by the U. S. Army Corps of Engineers and the U. S. Navy, and the other is from Traverse Y of the 1958 reflection survey.

We presume the bottom profile of the boring section was made by connecting the tops of the bore holes, and thus the shoaler region in the reflection profile is not depicted. In the borings there is an obvious increase in blow count which corresponds to the top of a layer of sand and gravel. The reflection section corresponds well with the borings except at FD-7 and FD-9. The correlation of the subbottom reflection which is traceable from the eastern end becomes uncertain near mid-channel (close to FD-9). One possible interpretation is that the reflecting layer, which deepens from the east side of the channel to slightly over 120 feet, shoals suddenly in mid-channel to within a few feet of the bottom where it appears to form the elongated shoal evident on U. S. C. and G. S. Chart 236, but not shown on the cross-section prepared by the U. S. Army Corps of Engineers in 1957. It seems quite possible that FD-7 and FD-9 fall slightly to either side of the area where this layer is shallow. If so, there is no necessary disagreement between the borings and the reflection section. The comparison certainly suggests that the prominent subbottom reflecting layer on this profile is the till layer. If so, the short subbottom echo sequences near the western end of the traverse may also come from a similar layer of till.

Analysis of the Seismic Reflection Observations in West and East Passages

Recordings from all traverses shown in Fig. 1 have been studied with great care to discriminate between first reflections and multiple reflections of all kinds. The first reflections were then scaled to a common depth scale and fitted by means of the navigational data to a scale of distance along the given traverse from a known point. In this way a complete set of profiles of first reflections was prepared. These show, without correction for actual propagation velocity for side-echo effects, the depth to various reflectors, including the bottom, and sediment and rock interfaces below the bottom, as a function of position along the traverse. The depth scale is based on a sound velocity of 4800 ft/sec since this practice permitted us to scale directly from the records. All depths referred to in the text and on the figures are in feet below sea level.

The average sound velocity, determined from bathythermographs taken during the 1958 survey, was 4880 to 4890 ft/sec. Thus the water portion may be corrected by a factor of 1.017 to 1.019. We have discussed the results of measurements of velocity in the sediments previously. They may be used to

adjust individual profiles but will change them only slightly. Since so few determinations of velocity were made during the survey they provide a basis for estimate only.

Records from the work of 1958 are reproduced in Plates W1 to W6, and E1 to E5. We have not similarly reproduced the records of 1960, but rather have presented the results in summary through Fig. 11. This interpretation is based on careful study of the first reflection profiles both separately and combined in three dimensional glass models. The original records and models may be inspected at Woods Hole.

WEST PASSAGE SEISMIC RESULTS

Deep basins, elongated roughly parallel to the long, north-south dimension of the West Passage, suggest a continuous channel extending from Jamestown Bridge to a point just west of the northern extremity of Beaver Neck. This channel has several interruptions though it is in all instances deeper than the surrounding bottom. There is a possible branching around the southern tip of Dutch Island. We do not know if these basins are being maintained by the scouring action of modern currents or are being filled with sediment.

There is a remarkably persistent reflection 20 to 60 feet deeper than the bottom to be found on all records taken in West Passage. Comparison at the track crossings strongly supports the surmise that the reflection comes from a single but irregular surface. There is considerably more relief in it than there is in the modern bay floor. Also, there are places, such as on Plate 6, where there is clearly a second reflection indicating a thin but deeper layer. In some places the second layer lies beneath, or is associated with, a deep place in the first reflecting surface. We have not mapped this second layer in detail, but it seems possible that these deep places are ancient channels buried beneath the first layer with the second layer as deposits in the channels.

Deeper reflections fall into two classes. One class can be traced to outcrops on shore, or as close to shore as the survey vessel could safely be brought. On such shores late Paleozoic outcrops are found. In other places this same reflection deepens rapidly toward the center of the channel, and shallower reflections terminate against it. Thus it behaves as one would expect an erosional surface of Paleozoic bedrock to do; we interpret this class to come from such a bedrock surface. More often than not we are unable to correlate these reflections with certainty across the deep part of the channel. As noted elsewhere in this account the Paleozoic rock types are seldom the same on opposite sides of the channel.

The second type of deep reflection lies between 250 and 300 feet and has an irregular profile which terminates against the first type (Plate 7). There are at least two possible interpretations of such records between which our present control cannot distinguish. Firstly, this reflection could represent the bedrock surface, while the deeper continuation of the reflection of the first type could be a reflection from the side of the bedrock channel. Alternatively, it could be the top of a sedimentary or glacial deposit, with the deeper continuation of the first type representing the side of the still deeper bedrock channel. On each of the three consecutive cross-sections on Fig. 11 at $41^{\circ}27'30''N$, $41^{\circ}28'N$, and $41^{\circ}28'30''N$, there are three interfaces at approximately

the same depths. Our data suggest that these correspond from section to section; unfortunately we have no clue to their nature from cores. They are somewhat uneven and may possibly be ancient glacial erosional surfaces.

The pattern of the reflections shows that bedrock in West Passage forms a trough of variable width and depth. Figure 11 shows a series of synthetic reflection profiles based on the data, but not copies of actual traverses. (These latter may be seen upon request.) The depth to bedrock near the center of the channel is lacking, except for short distances where deep reflections are traceable on transverse profiles between the latitudes of the southern tip of Beaver Tail and Bonnet Point (sections at $41^{\circ}27'N$ and $41^{\circ}28'30''N$). Of course these deeper reflections may not be the bedrock surface but they often appear to be continuations of the bedrock reflections on the sides that are ultimately traceable to outcrop on shore. If they are bedrock reflections, then in places the bedrock floor lies between 350 and 400 feet below sea level. As mentioned above there are shallower reflections from 250 to 300 feet (sections at $41^{\circ}27'30''N$ through $41^{\circ}28'30''N$) which might be bedrock. We have identified them on records only between $41^{\circ}27'N$ and $41^{\circ}28'30''N$. It seems most unlikely that bedrock lies shallower than these latter reflectors, there being no shallower reflections of comparable intensity to those interpreted as bedrock except those that are clearly multiples from the shallower layers discussed above. There is some argument, then, for placing bedrock as shallow as 250 feet in mid-channel, and there is excellent evidence for supposing an irregular surface between 350 and 400 feet to be bedrock. There are some profiles which suggest that bedrock is deeper than 400 feet (section at $41^{\circ}27'30''N$).

From Bonnet Point north, all of the north-south profiles indicate a radical shoaling of bedrock which might extend from the northern end of the Bonnet (at $41^{\circ}29'N$) to a point just south of Fox Hill on Conanicut Island (approximately $41^{\circ}29'15''N$). Transverse profiles are lacking over this section and, similarly, there is an awkward gap in the spacing of north-south profiles.

In this vicinity we have recorded examples of an unusually strong set of multiple reflections which bear on the interpretation of the reflections near this ridge. Similar reflections have been recorded elsewhere in Narragansett Bay. A typical strong multiple series is characterized by the occurrence of many (in some instances ten to fourteen) multiple reflections between the reflecting layer and the water-air surface (Plate 8). Wherever such a reflection is recorded usually no deeper reflection can be discerned even though such may be present and very strong both before and after the sequence of multiples. Several suggestions have been made to explain these echoes.

- 1.) A gravel bed within the sediment
- 2.) A bedrock pinnacle
- 3.) A cemented sand layer
- 4.) A corner reflector
- 5.) A sediment containing gas bubbles, etc.

We have estimated that the effective reflectivity of such a reflector is of the order 0.8. Virtually any consolidated rock in contact with water or soft mud would have a comparable reflectivity. Thus gravel beds, bedrock pinnacles, and cemented sand layers all seem quite possible. Furthermore all three are to be expected within the bay, and hence are likely explanations. The idea of corner reflectors seems contrived in a natural environment, but for a profile made parallel to the Jamestown Bridge where multiple reflections were recorded it may well prove to be the correct explanation (Plate W5, Profile A). We have no special reason to expect to find gas-filled sediments, and hence will disregard this possibility. We have seen isolated reflections in similar surveys south of Cape Cod which have been interpreted as large glacial erratic boulders. Hoskins and Knott (1961) have found others in Cape Cod Bay. The strong reflectors in Narragansett Bay appear to be similar and we believe them to come from a continuous surface. In places the accompanying pattern of reflections would seem to rule out bedrock, as in Plate W2, Profile 1. We cannot rule out bedrock east of the Bonnet, however, neither can we rule out sand or gravel. Plate W2 shows the original record of a north-south profile and our interpretation of the pattern of reflections. This locality is of special interest because if the strong reflector here is bedrock, then shallow bedrock, not more than a few feet to tens of feet deeper than the bay floor, could extend from the northern end of the Bonnet northeastward across the channel to Fox Hill. A fine-grained reflection survey of the cross-hatched area in Fig. 12 would provide a more critical test, and refraction profiles along the supposed ridge would be an even stronger test. After such a survey a minimum coring program could be designed that would identify the rock forming the ridge.

North of this ridge the channel clearly is shallower and broader than it is south of the ridge, changing character rather little up to the Jamestown Bridge. Here deep reflections are not recorded continuously. On two north-south profiles the bedrock reflection appears to be interrupted several times by occurrences of the strong shallow reflector with its many multiples. It is possible but it seems unlikely that the shallow reflection is shallow bedrock. Gravel beds seem a more likely explanation, but our data are incomplete, and no interpretation is more than an educated guess. Depth to bedrock was not determined all the way across the channel since no east-west profiles were made between South Ferry and Jamestown Bridge. However, reflections probably from bedrock are recorded at about 200 feet ($\pm$ 20 feet) on north-south profiles near the center of the Passage. There is no clear evidence that the

bedrock channel is much deeper than 250 feet at the deepest point between the Bonnet and Jamestown Bridge.

Summary of West Passage Seismic Results

- 1.) Elongate depressions in the bay floor suggest channels which, though not continuous, follow a common trend from the eastern side under Jamestown Bridge to the west side around Dutch Island and back to the eastern side as far south as Beaver Neck. A branch from east of Dutch Island joins this channel south of Dutch Island.
- 2.) There is a reflecting surface 20 to 60 feet below the bay floor which has much more relief than the bay floor itself. This surface is found under most of the West Passage.
- 3.) In places evidence of a layer is found below the reflecting surface of 2.) above, suggesting that it is a deposit in ancient channels such as 1.).
- 4.) West Passage is underlain by a trough cut in a bedrock of metamorphosed Paleozoic sediments which is divided by a ridge extending from the northern tip of the Bonnet to the inlet south of Fox Hill on Conanicut Island. The ridge may be very shallow (just below the bay floor) or it may be between 100 and 200 feet deep depending on the interpretation of complex echo patterns.

North of the ridge the trough is broad and may well not be appreciably deeper than 250 feet. This area has been scantily studied. South of the ridge, where many more reflection profiles have been recorded, the trough is considerably narrower and deeper than to the north. It is unlikely that the depth of the center of the trough is less than 250 feet. In places there are reflections from surfaces lying between 250 feet and 400 feet which could be the bedrock floor. In still other places no reflection can be traced continuously from side to side at depths of 400 feet or less. The trough continues to be well-developed, narrow, and at least 350 feet deep on the southernmost profile.

EAST PASSAGE SEISMIC RESULTS

The control for the study of East Passage is shown in Fig. 1. This passage is deeper than West Passage, having depths greater than 150 feet in the narrow channel close to Newport Neck. The topography of the bay floor here is much more irregular than that of the West Passage.

There is a shallow reflecting surface similar to that described for West Passage and having about the same thickness (10 to 60 feet), but it varies more irregularly (Plates E1 to E5).

Bedrock reflections can be traced from near shore, but they cannot be traced continuously with confidence across the channel anywhere. However, on all of the more recent profiles made from BEAR with the Edgerton Thumper we find irregular echo sequences which may come from an exceedingly uneven bedrock surface. In the channel proper these are recorded with only minor breaks throughout the bedrock trough. Frequently two such echo sequences are recorded on the same record. They may be side-echoes or the later arrivals may be reflections from a still deeper interface in the bedrock. The records taken over the trough have somewhat the same appearance as those near and over the ridge between the Bonnet and Conanicut Island in West Passage. The pattern of the side-echoes suggests that the irregular reflecting surfaces are not merely the side-walls, but also a rugged bedrock terrain forming the floor of the trough. If this interpretation is correct the bedrock surface lies anywhere from just below the bay floor to about 400 feet below. We have the least information about the center of the trough over the southwestern portion where most of the records are poor. There the center of the trough could be over 400 feet deep.

There is a consistent, well-defined echo sequence on profiles southwest of Newport Neck which demonstrates that a ridge of bedrock trends from the neck southwestward. This ridge apparently outcrops at the bottom near $41^{\circ}26'30''\text{N}$ and $71^{\circ}23'\text{W}$. It forms the southeastern wall of the bedrock trough of East Passage, and, on our southernmost profile, appeared to be converging with a similar ridge that is the southern extension of Beaver Tail.

Summary of Seismic Results from East Passage

- 1.) The floor of East Passage is deeper and much more uneven than that of West Passage. Near Castle Hill there is a channel which is deeper than 150 feet.

- 2.) A shallow reflecting surface is found that is less continuous and more uneven than the corresponding one in West Passage.
- 3.) There is a bedrock trough which is tentatively interpreted as having rugged relief throughout, probably varying in depth from the bay floor to more than 400 feet below sea level.
- 4.) A ridge, traced southwestward from Newport Neck, crops out in 40 to 60 feet of water to form the southeastern wall of the trough in bedrock (probably the Blackstone series found on Newport Neck).

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FIGURE 1-A

FIGURE 1-B

FIGURE 2

PRUDENCE ISLAND TRAVERSES

RECONNAISSANCE GEOLOGY of SOUTHERN NARRAGANSETT BAY RHODE ISLAND

FIGURE 3

FUNCTIONAL DIAGRAM OF SPARKER EQUIPMENT

SPARKER
400 WATT SECONDS

ABSCISSA: 1×10^{-3} SEC / DIV
ORDINATE: 0.35×10^5 DYNES / CM²
SEPARATION: 4 METERS

THUMPER
1000 WATT SECONDS

ABSCISSA: 2×10^{-3} SEC / DIV
ORDINATE: 0.7×10^5 DYNES
SEPARATION 6 FEET

PRESSURE TIME CURVES OF CONTINUOUS
PROFILING SOURCES

DIAGRAMMATIC PICTURE OF CONTINUOUS HORIZONTAL PROFILING

FIGURE 5A

DIAGRAMMATIC PICTURE OF VELOCITY PROFILING

FIGURE 5B

FIGURE 6

DEPTH CORRECTION CHART

DIAGRAM OF A SINGLE BOTTOM REFLECTION

DIAGRAM OF A SINGLE SUB-BOTTOM REFLECTION

FIGURE 7A

FIGURE 7B

BORING LOGS and TRAVERSE RECORD JAMESTOWN BRIDGE

GRAPHIC LOGS OF FOUNDATION TEST BORINGS (DATA COURTESY OF U.S. ARMY CORPS OF ENGINEERS, 1957.)

FIGURE 8

BORING LOGS and TRAVERSE RECORD ROUND ROCK to PATIENCE ISLAND

FIGURE 9

BORING LOGS and TRAVERSE RECORD PRUDENCE ISLAND to AQUIDNECK ISLAND

TRAVERSE RECORD Y

(HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED)

FIGURE 10

FIGURE 11

FIGURE 12

SPARKER EQUIPMENT

THE "THUMPER"

SAMPLE RECORD SHOWING CHARACTERISTIC FEATURES

VELOCITY PROFILE 1

TRAVERSE RECORD

VELOCITY PROFILE RECORD

VELOCITY PROFILE 2

TRAVERSE RECORD

VELOCITY PROFILE RECORD

VELOCITY PROFILES - WEST PASSAGE

VELOCITY PROFILES-WEST PASSAGE

VELOCITY PROFILE 3

TRAVERSE RECORD

VELOCITY PROFILE RECORD

VELOCITY PROFILE 4

TRAVERSE RECORD

VELOCITY PROFILE RECORD

VELOCITY PROFILES - EAST PASSAGE

VELOCITY PROFILES- EAST PASSAGE

DEPTH IN FEET BELOW SEA LEVEL
 BASED ON SOUND VELOCITY OF
 4800 FT. / SEC.

BURIED CHANNEL ?
 FROM SPARKER RECORDS OF MAY, 1958 - PROFILE 1 (SOUTH END)

DEEP REFLECTION TERMINATING AGAINST BEDROCK
FROM THUMPER RECORDS OF MAY, 1960, 0914-1000

MULTIPLE REFLECTIONS - SURFACE TO BOTTOM
FROM SPARKER RECORDS OF MAY,

CROSS-CHANNEL
TRAVERSE RECORDS

BULL POINT TO
SOUTHWEST POINT

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.

Lines between records connect corresponding
points on mutually intersecting traverse paths.

THE RECORDS ARE ALIGNED NORTH TO SOUTH (TOP TO BOTTOM)
WITH RESPECT TO THEIR INTERSECTION WITH TRAVERSE 16.

— LOCATION OF TRAVERSE RECORDS INCLUDED
ON THIS PLATE.

- - - TRAVERSE RECORDS PRESENTED ELSEWHERE
IN REPORT.

— RUNS USED FOR GEOGRAPHIC REFERENCE.

PLATE E2

LONGITUDINAL TRAVERSE RECORDS

SOUTHWEST POINT TO BULL POINT

PATH OF
TRAVERSE D1

WEST ← EAST

RECORD TIME IN MILLISECONDS

0
166.7
0
166.7
0
166.7

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.
LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE D1

— LOCATION OF TRAVERSE RECORDS INCLUDED
ON THIS PLATE.
--- TRAVERSE RECORDS PRESENTED ELSEWHERE
IN REPORT.
- - - RUNS USED FOR GEOGRAPHIC REFERENCE.

TRAVERSE 16
PROJECTED

PLATE E3

SOUTHWEST ↔ NORTHEAST

PATH OF
TRAVERSE 22

CONTINUED (PLATE E4)

17

RECORD TIME IN MILLISECONDS

CROSS-CHANNEL TRAVERSE RECORDS CASTLE HILL SOUTH

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.
LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE 22.

24

10

PLATE E4

SOUTHWEST $\longleftrightarrow$ NORTHEAST

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY $\blacktriangledown$ AND ARE PLOTTED ON THE INSET MAP.
LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

TRAVERSE RECORDS
18
CASTLE HILL
TO
FORT ADAMS AND
BULL POINT

PLATE E5

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.

LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE 17.

PATH OF
TRAVERSE

PATH OF
TRAVERSE

LONGITUDINAL TRAVERSE RECORDS

SOUTHWEST POINT TO RHODE ISLAND SOUND

— LOCATION OF TRAVERSE RECORDS INCLUDED
ON THIS PLATE.
- - - TRAVERSE RECORDS PRESENTED ELSEWHERE
IN REPORT.
— RUNS USED FOR GEOGRAPHIC REFERENCE.

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.
LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ORIGINATE AT THE JAMESTOWN BRIDGE.

LONGITUDINAL TRAVERSE RECORDS

JAMESTOWN BRIDGE
TO
DUTCH ISLAND ▼

PLATE W1

NORTH ← SOUTH

— LOCATION OF TRAVERSE RECORDS INCLUDED
ON THIS PLATE.
- - - TRAVERSE RECORDS PRESENTED ELSEWHERE
IN REPORT.

RECORD TIME IN MILLISECONDS

PLATE W1

PLATE W2

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.

LINE BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE B2.

LONGITUDINAL TRAVERSE RECORDS

DUTCH ISLAND TO BONNET SHORES

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED. GEOGRAPHIC FIX POINTS ARE INDICATED ON THE RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP. LINES BETWEEN RECORDS CONNECT CORRESPONDING POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS. THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE 7.

LONGITUDINAL TRAVERSE RECORDS

PLATE W4

NORTH ← SOUTH

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.
LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

LONGITUDINAL TRAVERSE RECORDS

ENTRANCE TO WEST PASSAGE

RECORD TIME IN MILLISECONDS

PATH OF
TRAVERSE 5

— LOCATION OF TRAVERSE RECORDS INCLUDED
ON THIS PLATE.
- - - TRAVERSE RECORDS PRESENTED ELSEWHERE
IN REPORT.
- - - RUNS USED FOR GEOGRAPHIC REFERENCE.

PLATE W5 CROSS-CHANNEL TRAVERSE RECORDS JAMESTOWN BRIDGE TO BONNET SHORES

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE
RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.

LINES BETWEEN RECORDS CONNECT CORRESPONDING
POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE 2.

— LOCATION OF TRAVERSE RECORDS INCLUDED ON THIS PLATE.

--- TRAVERSE RECORDS PRESENTED ELSEWHERE IN REPORT.

--- RUNS USED FOR GEOGRAPHIC REFERENCE.

WEST ← EAST

RECORD TIME IN MILLISECONDS

PATH OF TRAVERSE 2 PATH OF TRAVERSE 3

8

9A

PLATE W6
CROSS-CHANNEL TRAVERSE RECORDS
BONNET SHORES TO WHALE ROCK

7

9B

LOCATION OF TRAVERSE RECORDS INCLUDED ON THIS PLATE.
TRAVERSE RECORDS PRESENTED ELSEWHERE IN REPORT.
RUNS USED FOR GEOGRAPHIC REFERENCE.

HORIZONTAL SCALES VARY LOCALLY WITH BOAT SPEED.
GEOGRAPHIC FIX POINTS ARE INDICATED ON THE RECORDS BY ▼ AND ARE PLOTTED ON THE INSET MAP.

LINE BETWEEN RECORDS CONNECT CORRESPONDING POINTS ON MUTUALLY INTERSECTING TRAVERSE PATHS.

THE TRAVERSES ARE ALIGNED WITH RESPECT TO TRAVERSE 2.

5

PLATE W6

<p>TABLE 1</p> <p>SUMMARY OF VELOCITY DATA</p>			
Vel. Profile #1	Vel. Profile #2	Vel. Profile #3	Vel. Profile #4
$v_1 = 3912$ $v_2 = 5135$ $v_3 = 5624$	$v_1 = 5135$ $v_2 = 3912$ $v_3 = 5135$	$v_1 = 3904$ $v_{\text{bedrock}} = 15,128$	$v_1 = 4396$ $v_2 = 5130$
(Velocities given in feet/second)			

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