SITE SURVEYS OF THE CENTRAL AND SOUTHERN NINETYEAST RIDGE FOR THE OCEAN DRILLING PROGRAM, LEG 121

by

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ABSTRACT

The Ninetyeast Ridge is one of the most striking tectonic features of the world oceans. This ridge is situated in the Indian Ocean and runs almost parallel to the 90° E meridian. The origin of this feature has been explained by either a hot spot or leaky transform fault hypothesis. The primary objective of drilling on the ridge is to ascertain its age at certain areas. The knowledge of the age in combination with paleolatitude data should help the determination of the exact rate of motion of the Indian plate before and after the collision of India with Asia as well as establishing the time of the rate change. We should be able to relate this to the events of Himalayan orogeny, and to consider the implications for models of plate-driving forces. The northward motion curve should also help to understand the dynamic, sedimentary and tectonic development of the ridge, as well as clarify some questions regarding its origin. A secondary objective is to determine the chemical composition of the underlying basalts, especially their radiogenic isotopic ratios. This should help to define the extent of mantle compositional heterogeneity, and from that one can infer mantle dynamic processes. The chemical composition information will also constrain the origin and behavior of the ridge and the Indian Ocean hot spots, Kerguelen, Amsterdam, and St. Paul islands.

Two site surveys for ODP were conducted at the central and southern areas of the Ninetyeast Ridge between DSDP sites 214 and 253 and between sites 253 and 254, respectively. The surveys were performed by the R/V CONRAD in the summer of 1986 during cruises RC 2707 and RC 2708. The survey was conducted using a single channel streamer and two 80 cubic inch water guns as sources. The single channel reflection data and the data obtained by a sonobuoy refraction survey were subsequently processed and interpreted at the University of Texas, Institute for Geophysics (UTIG), Austin, Texas. Bathymetry and basement maps were created, as well as isopach maps of the important seismostratigraphic horizons and maps of residual gravity and magnetics. The lithologic composition of five different horizons were interpreted at the central survey site, four at the southern site. Lithologies were based on the assumed mode of evolution of the ridge, lithologic composition of the neighboring DSDP sites 214, 253 and 254, and velocities obtained by the refraction surveys. At both survey sites the seismostratigraphic horizons were divided into two main groups, upper and lower. The sediments of the upper group were interpreted to be mainly deep water pelagic oozes, while the sediments of the lower group were mainly volcaniclastic sediments interlayered with basaltic lava flows deposited in shallow water or possibly subaerially.

Two possible drilling sites are suggested at the central area. Their positions are based on the thickness of sedimentary cover, the depositional setting and the depth of water (regarding time of core recovery). The suggested drilling sites in the central survey area are located at seismic line intersections for 3-dimensional control. Five seismostratigraphic units are predicted at the two suggested drilling sites. The first two units are deep water pelagic oozes; the third unit is estimated to be either chalk or a green volcanic ash; unit number four is inferred to be black volcanic ash, possibly interbedded with volcanically derived siltstone or sandstone and the last sedimentary

unit consists of lava flows interbedded with volcaniclastic sediments. Total thicknesses of the sediments at the suggested drilling sites are 493 and 401 meters, respectively. The first three horizons show little or no faulting, while the last two horizons are faulted extensively. An important tectonic feature trending in the east-west direction has been interpreted. This feature changes from an overthrust on the west side of the ridge to the normal fault on the east side, and according to interpretation of magnetic survey data may be accompanied by a basaltic dike. The age of the overthrust appears to be approximately 42 My, which is time of anomaly 18 (Middle to Late Eocene). This may suggest that this compressional feature is causally connected with a change of rate of northward motion of the Indian plate. The normal fault on the eastern side of the ridge seem to be active until present time.

Four possible drilling sites are suggested in the southern survey area. Criteria for their placement are the same as above. Unfortunately, it is not possible to place the drilling sites onto seismic line intersections because of the excessive ruggedness of sea floor and underlying layers. Four stratigraphic units are interpreted at this survey site. The upper two are again deep water pelagic oozes and belong to the upper group, the lower two horizons are composed of volcaniclastic sediments and belong to the lower sedimentary group. Thicknesses of the sediments at the suggested drilling sites in the southern survey area are 338, 186, 177 and 255 m, respectively. Tectonic setting of this survey site is different than the setting of the central site. There is no evidence for compressional tectonic activity similar to that of the central survey site.

The data used in this research were collected from the R/V CONRAD. We would like to take this opportunity to thank the captain, the crew and the scientists, who participated in RC 2707 and RC 2708, for their cooperation.

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1. INTRODUCTION

The Ninetyeast Ridge was first recognized as a major feature by Sewell (1925) and charted by Stocks (1960). It was named by Heezen and Tharp (1965) for its position close to 90° E meridian.

The Ninetyeast Ridge separates the deep Central Indian Basin from the Wharton Basin in the Indian Ocean. This strikingly linear feature is an aseismic ridge which starts north of the Kerguelen Plateau, from which it is divided by a 4000 m deep basin. It starts at approximately 31° S and continues in a direction slightly east of north to about 12° N. The last part of the ridge from about 9° N to 12° N is covered by Bengal Fan sediments. The northern part of the Ninetyeast Ridge is divided into northeast-southwest trending, en echelon segments. The ridge has a moderately flat top extending to heights of about 1500 m to 2000 m above the surrounding ocean floor. The ridge is bordered by a scarp and a deep trough on the east side (Laughton at al., 1971). Sclater and Fisher (1974) and Bowin (1973) suggested that this deep may be a remnant of a transform fault.

The origin of the Ninetyeast Ridge has been under discussion since Heezen and Tharp (1965) first suggested that the Ninetyeast Ridge delineated the northward path of motion of India. Francis and Raitt (1967) suggested that the Ninetyeast Ridge was a horst structure on the basis of evaluating the fracture zone, the scarp, and the shallow depth of the Moho, which they tentatively interpreted under the ridge. Le Pichon and Heirtzler (1968) suggested that the compression and relative motion between the Australian and Indian plates could be responsible for uplift of the Ninetyeast Ridge. McKenzie and Sclater (1971) suggested that this might have been due to a change of spreading direction of southeast Indian Ridge from north-south to northeast-southwest in the Eocene. Bowin (1973) showed that the free air gravity anomaly observed over the ridge was too small to explain a horst type feature and proved that the ridge is nearly isostatically compensated. Sclater and Fischer (1974) interpreted the Ninetyeast Ridge as an extrusive pile with a low density shallow root along a leaky transform fault.

The origin of the Ninetyeast Ridge has also been explained by using a hot spot hypothesis. Luyendyk and Rennick (1977) hypothesized that two hot spots were responsible for the creation of the ridge, one presently situated under the Amsterdam and St. Paul Islands and the other under the Kerguelen Plateau. Peirce (1978) used only one hot spot, extending the ideas of Morgan (1972). Peirce used paleomagnetic data gathered on the DSDP drilling sites along the length of the ridge to support his hypothesis, particularly basalt paleolatitudes, which indicate that the volcanic source of the ridge was approximately fixed in latitude near 50° S. The hot spot hypotheses explain well the excess volcanism needed for a creation of the ridge and its linearity, but do not explain why the ridge is so evenly shaped.

2. THE OBJECTIVES OF DRILLING ON THE NINETYEAST RIDGE

Drilling on the ridge will further our understanding of the northward motion of India. It should clarify a spreading history between sites 214 and 253 and between sites 253 and 254, which is not clearly understood due to a ridge jump or jumps of some 1200 km magnitude. This ridge jump (or jumps) must have happened sometime between 46 and 59 Ma most likely around the times of magnetic anomalies 24 or 25, i.e. 54 or 56 Ma, respectively. The data obtained on the drilling sites will enable us to better understand the dynamic development of the ridge and its tectonic and sedimentary history. The paleomagnetic analysis of the basement basalt should clarify the questions of the origin of the ridge. It should help us to unveil the dynamic processes taking place during collision of India with Asia, which took place approximately 40 Ma according to paleomagnetic data (Peirce, 1978), or 52 Ma according to magnetic anomaly survey (Patriat and Achache, 1984), and subsequent slowing of the northward movement of India. We will be able to examine more closely a rapid change of rates of motion (Figure 1) of the Indian plate and relate them to the events of Himalayan orogeny, and to consider the implication for models of plate driving forces (Peirce, 1985).

Another objective of drilling of both central and southern Ninetyeast Ridge sites is to recover basement basalt for geochemical studies. Geochemical data, especially radiogenic isotopic ratios, are used to determine compositional heterogeneity in the mantle of the earth. Mantle dynamics are closely related to these heterogeneities which range both in age and scale. This, with other compositional data, provides constraints on the processes which created these heterogeneities and the processes which enable the heterogeneities to exist for a long time in the mantle. Geochemical compositions of the Ninetyeast Ridge, Amsterdam-St. Paul and Kerguelen-Heard Island basalts, which all originated over these hot spots, differ significantly (Figure 2). If we were able to explain these differences, we would significantly contribute to the understanding of hot spots, i.e. mantle heterogeneities. The end-member geochemical models for mantle heterogeneity, which range from the extreme upper mantle streaks and veins heterogeneity, i.e. "Paisley model" (Zindler at al, 1984) to two-source model (Schilling, 1985) can be tested by analysis of these basalts. Furthermore, the origin of the Ninetyeast Ridge and the Amsterdam-St. Paul and Kerguelen-Heard hot spots can be constrained by geochemical study of their basalts (Frey, 1985).

3. PREVIOUS DRILLING SITES

3.1 Site 214

Site 214 is situated on the crest of the Ninetyeast Ridge at 11° 20.21' S and 88° 43.08' E (Figure 3). Water depth, as measured by the length of a drill pipe, is 1665 m. The hole penetrated into an acoustic basement at a depth of 490 m under the ocean bottom. The total penetration was 500 m (von der Borch, Sclater, et al, 1974).

The sediments at this site were divided into five distinctive stratigraphic units (Figure 4). The first unit is an accumulation of calcareous ooze 333 m thick. The bottom 10 m of this unit is transitional between unit 1 and 2. Unit 1 was deposited in water approximately as deep as at present. The transitional part was deposited at a somewhat shallower depth. The age of unit 1 is late Paleocene to Pleistocene. Unit 2 is glauconitic and carbonate silt and sand . This unit is 57 m thick and was deposited during the Paleocene. Unit 3 is an interbedded sequence of volcaniclastics and lignites. This unit was deposited subaerially during the Paleocene. Its thickness is 100 m. This unit is interlayered with unit 4, which is basaltic lava flows. The thickness of unit 4 is 28 m. Unit 5, acoustic basement, is vesicular, amygdaloidal, and crystalline basalts, made up of flows deposited either on land or in shallow water. The basalts are similar to those of the Amsterdam and St. Paul Islands. This evidence suggests that the Ninetyeast Ridge formed as a chain of volcanic islands, which started to submerge in the Paleocene. This evidence also supports the hot spot model. The age of the basalts was estimated to be 59 My (von der Borch, Sclater, et al, 1974). This age is based on biostratigraphic dating of the oldest microfossil *Planorotalites chapmani* (58+ My).

The reflection profile apparently does not agree (Figure 4) with the stratigraphic division with one exception - the upper surface of the fine-grained basalt flows at 440 m. The interval velocities, calculated by matching the reflectors with various stratigraphic levels (von der Borch, Sclater, et al, 1974), range from 1.55 km/sec to 2.4 km/sec with median value of 1.9 km/sec for the sediment column. The report does not quantify the error margins for these velocities. This signifies that seismostratigraphic horizons can be very different from stratigraphic units in this area and that extreme caution has to be exercised when we attempt to correlate them.

3.2 Site 253

Site 253 is situated on the crest of the Ninetyeast ridge at 24° 52.65' S and 87° 21.97' E in 1962 m of water. The drill penetrated into basement at a depth of 559 m below the ocean floor. Four main lithologic units (Davies, Luyendyk, et al., 1974) were encountered in this site (Figure 4). The top unit is 9 m thick and is a nannoplankton foraminiferal ooze. The age of this unit ranges from upper Pliocene to Recent. Unit 2 is a nannoplankton ooze grading into chalk with depth. The thickness of this unit is 144 m, and its age ranges from upper Eocene to upper Pliocene. Unit 3 is volcanic ash, vesicular basalt, and basalt scoria at the bottom. The thickness of this unit is 388 m. The age of this unit is middle Eocene. Unit 4, reached at 558 m, is the last unit of this site. It is fine-grained porphyritic basalt and was tentatively interpreted as an acoustic basement.

The acoustic velocity of the oozes reaches values of about 1.55 km/sec. The velocity increases in the volcanic ashes to 1.8 km/sec at about 153 m and increases again in the black volcanic ashes to 2.3 km/sec at 192 m. There are two distinct reflections which agree with lithologic changes. Reflections between the ooze and the green volcanic ash and between the black volcanic ash and the acoustic basement, are apparent (Figure 4). The following interval velocities were calculated by comparing the acoustic velocities with the apparent changes in lithology: 1.9 km/sec for the ooze section (to 153 m subbottom), 1.54 km/sec for the upper pyroclastic section (to 192 m), 1.87 km/sec for the middle pyroclastic section (to 318 m), 2.32 km/sec for the lower pyroclastic section (to 558 m). The 23 % discrepancy between the acoustic and interval velocities of the oozes was explained by sampling the ooze-ash contact in an approximately 25 m depression, which did not register on the seismic record (Davies, Luyendyk, et al., 1974).

These data indicate that the ridge was much shallower in the past than in the present and also that this site has migrated from the south. It could not be determined whether the volcanic ash originated from a subaerial or submarine source. The accumulation of the ash stopped in the late Eocene, and the ridge subsided slightly, creating a near shore depositional environment which lasted until late Oligocene or early Miocene. This interpretation is based on the lithology of the sediments older than the aforementioned ages. After that the ridge subsided again, and the deposition was pelagic until Recent. The age of the basalts was determined to be about 46 My, based on the lowest fossiliferous sample about 5 m above the basement basalt (Davies, Luyendyk, et al., 1974).

3.3 Site 254

Site 254 is located in the southern extremity of the Ninetyeast Ridge at latitude 30° and 58.15' S and longitude 87° 53.72' E. It was drilled in 1253 m of water. The drill reached a basaltic basement at 301 m below the ocean floor (Davies, Luyendyk, et al., 1974).

The sedimentary sequence in this hole consists of four lithostratigraphic units (Figure 4), which overlie a basaltic basement. The upper three units of the sequence are biogenic oozes whose cumulative thickness is 209.5 m. The upper 167 meters of the sediments are well dated and range through the Neogene. The sediments were dated using microfossils. Nine and a half meters immediately below the Neogene sequence the sediments are Oligocene in age. Below this the age of the sediments cannot be determined. The fourth unit is volcanically derived, poorly sorted silty clays and fine sandstones. Conglomerates with muddy matrices are also encountered in this unit. The thickness of the fourth unit is 91.5 meters. A contact between basement basalt flows and the overlying sedimentary sequence is conformable. The basalts themselves range from a coarse porphyritic type in the upper basement section through amygdaloidal to nonamygdaloidal, fine-grained autobrecciated xenolithic basalts at the bottom of the hole.

The acoustic velocity of 1.6 km/sec in the upper ooze section increases slightly below 150 meters and strongly below 210 meters marking a lithologic change from oozes into a volcaniclastic sedimentary section. The mean velocity measured in the basaltic basement is 4.75 km/sec.

Correlation of the seismic profile (Davies and Luyendyk, et al., 1974) with drilling results is good (Figure 4). Reflections are observed and correlated between the biogenic ooze, the underlying volcaniclastic sediments, and the basaltic basement. The reflection from the basement is diffuse and the last reflection at .375 seconds of two-way travel time (TWT) is considered to be a reflection of the true basement.

Seismic velocities in oozes are slightly higher than expected from the acoustic velocity measurements and come close to 2.0 km/sec. The velocity in volcaniclastics is lower, about 1.9 km/sec. The discrepancy between acoustic and interval velocities in the oozes is again about 25%. Acoustic velocities in the volcaniclastics were not given in the drilling volume, and that made any further estimate of their errors impossible.

The age of the oldest sediments and consequently of the basement is not clear due to an uncertainty of a place of deposition of the oldest identifiable (Oligocene) fossils. It is not possible to decide if the fossils in question were deposited in place or had been reworked and redeposited. The best estimate of the age of this site is about 38 My. This estimate is based on reconstructions at anomaly 13 and anomaly 18 times, which are at 35 and 43 My, respectively (Royer, personal comm.), and on the age of the oldest fossil.

The two main sedimentary groups encountered in the above mentioned drilling sites are: biogenic oozes deposited in a deep oceanic environment and volcaniclastic sediments deposited in a shallow water or a subaerial environment. I will show that these two groups can also be found at the survey sites.

4. SITE SURVEY - CENTRAL NINETYEAST RIDGE

This site survey was performed as a part of a RC 2707 cruise of the R/V CONRAD in August, 1986. The seismic survey was conducted using a single channel streamer and two 80 cubic inch water guns as sources. The site survey grid (Figure 5) covered the Ninetyeast Ridge area approximately between coordinates 16.9 - 17.2° S and 88.0 - 88.3° E.

The single channel seismic survey was recorded on two analog recorders and a digital computer. The digital recording was preliminarily processed by LDGO and the data were transcribed into SEGY format. The navigation data were recorded separately in MGD 77 format. The seismic and preliminary navigation data can be tied together using the shot numbers. The data were sent to UTIG at Austin, Texas, for further processing. The data were resampled, deconvoluted, migrated, filtered, muted, and appropriately displayed using a Digicon's interactive seismic computer (DISCO) processing package. The survey line was divided into four segments in agreement with the technical procedures intrinsic to DISCO. These lines were interpreted and tied together at the grid crossings. The ties (water bottom reflectors) sometimes did not quite agree due to an inexact preliminary navigation. The navigational data were a combination of Transit and GPS (Global Positioning System) navigation fixes with intrinsic errors depending on the number of the satellites and their elevation above the horizon. The navigational data I worked with were uncorrected and at one minute intervals. The disagreement in TWT (two-way travel time) was under 20 msec at these locations and could be corrected by relocating (under 500 m) of the appropriate seismic line.

4.1 Seismic Data Interpretation

The bathymetry of the survey area (Figure 5) is dominated by the crest of the ridge. It is a comparatively flat hill rising to a depth of about 1650 m. The sides of the hill are sloping to the east and west to the depth below 3000 m while in the direction of the ridge NNE-SSW the maximum observed depth does not exceed about 1800 m.

The seismic data suggest that there are five distinct seismostratigraphic horizons in the site survey area. The tectonic setting of the horizons vary widely throughout the area (Figures 39 and 40). Thickness of the sediment layer also varies, from under 250 m to over 800 m (Figure 6).

These sedimentary horizons can be divided basically into two groups, upper and lower. I estimated lithologic composition of the groups on the basis of the nearby DSDP sites 214 and 253 and the seismic velocities measured by a sonobuoy refraction survey. The correlations of the seismic profiles of DSDP 214 and suggested drilling site # 2 at the central Ninetyeast Ridge survey area and ties of their seismostratigraphic horizons are shown in Figure 7. The upper group comprises pelagic oceanic sediments, e.g. biogenic oozes, which may or may not grade into chalk with depth. This group has an approximately the same seismic velocity of 1.8

km/sec. This velocity is slightly higher than the acoustic velocities in the oozes at sites 214 and 253 (1.55 and 1.6 km/sec, respectively). An isopach map of this unit is shown in Figure 8. The lower group is formed either by volcanically derived sediments, i.e. silts or sands grading into pebble conglomerates, or volcanic flows intermingled together. An isopach map of the most important sedimentary horizon of this group is presented in Figure 9. This group conformably overlays a basaltic oceanic basement.

The topmost layer (first layer of the upper group) is seismically transparent. The amplitudes of the seismic reflections are low and of medium frequency. The boundary of this layer is mostly indistinct and may be interpreted as a gradual change of lithology between the layer in question and the layer immediately below. The determination of the actual boundary sometimes depends rather on the character throughout the layer than on any specific reflective surface. The thickness of this horizon is almost constant across the survey area and ranges between approximately 20 to 60 meters. This layer follows closely all topographic highs and lows of the unit below. There are few faults in this layer. The deposition is pelagic and very slow in the Recent (Davies and Luyendyk, et al., 1974). With regard to the neighboring DSDP drilling sites (214 and 253) the lithology of this unit is probably a foraminiferal-nannoplankton ooze.

The second horizon of the upper group is distinguished by medium frequency and low amplitude seismic energy reflectors. Although predominantly transparent to seismic energy, this horizon displays some very high amplitude local reflections.

These reflections are invariably situated along the flanks of the ridge crest and may be interpreted as small basin deposits (Payton et al., 1977) which probably consist of slightly coarser material (silt or sand) than the surrounding sediments (see figure 39). These slope basin deposits were created by gravity transport of the appropriate sediment from the slopes of the ridge. The faulting is infrequent. The composition of this layer is probably nannoplankton ooze grading into chalk. The basin fill deposits within this layer create a sufficient lithologic contrast perceived as high amplitude reflections. The thickness of this layer is variable and ranges from approximately 60 to 250 meters throughout the survey area. A comparatively strong seismic reflector denotes the base of this layer, though it is not always apparent. This may be explained by a local similarity of the physical properties to the layer below. The bottom surface is disconformable.

The third layer of the upper unit is thinly draped over the lows and highs of the underlying horizon. It is fairly transparent to seismic energy and terminates at the bottom by a strong reflector. This reflector denotes a boundary between the upper and lower groups. The amplitude is somewhat greater than observed in the above layers. The thickness of this layer varies slightly from about 20 to 100 meters throughout the area. The lithologic composition is probably chalk or (with regard to the neighboring DSDP site) a green volcanic ash.

The fourth layer (lower group) rests conformably on the layer below. While the seismic frequency of this layer is approximately the same as that of the layers described above, the amplitude is highly variable, probably due to local changes in lithology. The faulting is extensive, and it had to be concurrent with the deposition of this unit because the faults in many instances do not continue through the top surface of this horizon. If they do, the displacement along the fault planes at the top of the layer is small in comparison with the displacement at the bottom. The thickness varies greatly, from approximately 20 to 450 meters, especially in places where the layer rests on downfaulted blocks of the basement (Figure 9). The expected composition of this unit is a black volcanic ash interbedded with sand or silt. The top of the fourth unit in msec of TWT (two-way travel) time is shown in figure 10.

The fifth layer differs from the previous layers by its higher amplitude of the seismic signal. Basement is not easily recognizable and has been determined by a change of character of the seismic signals and with regard to interval velocity, which is too slow for basement basalts (2.4 km/sec). The seismic waves change from a predominantly orderly pattern into a chaotic pattern below in the basement. The thickness of the fifth layer ranges from approximately 30 to 240 meters. I estimate that this layer is composed of vesicular and amygdaloidal lava flows extruded onto the surface or in a shallow marine environment. The flows are possibly interspersed with volcanic ash layers. This layer may be considered a "false" basement. The interpretation of this unit must be considered tentative since the seismic signals may be interpreted as a "diffuse" basement reflector. If this were the case the top of this horizon would be the basement. Topography of the top of the fifth horizon in depth is shown in figure 11, in TWT time in figure 12.

The basement (Figure 13) is a true crystalline basaltic basement as inferred from its acoustic velocity of approximately 4 km/sec. There were no other significant reflectors observed on the seismic profile beneath the basement reflector. The only indication of any deeper structures was a single refraction observed on a air gun sonobuoy seismogram (Figure 14). This refraction indicated a velocity increase to about 5.9 km/sec at a depth of approximately 4 km. This lower velocity basement layer could be interpreted as an extrusive pile of volcanics creating the actual ridge (Sclater and Fischer, 1974).

4.2 Seismic velocities

A sonobuoy refraction survey was performed in order to determine the velocity structure in the survey area (Figure 5). Four sonobuoy records have been processed in the following manner: After plotting the sonobuoy seismograms, the principle reflections and refractions were digitized and subsequently plotted in t-p space to determine interval velocities in different seismostratigraphic units. After these velocities were determined, the seismic signal was raytraced and plotted back in the x-t domain (Stoffa, 1985). This was compared to an actual x-t seismogram and, if needed, the velocities were adjusted until an agreement was reached. The final velocities are listed in table 1. After comparison of the velocities obtained by the processing of one air gun sonobuoy (Figure 14), three water gun sonobuoys, and acoustic velocities obtained on the neighboring sites 214 and 253, a simple velocity structure (Table 1) for determining the depths and thicknesses of the seismic horizons was developed. Seismic velocities were averaged stressing the best sonobuoy (air gun sonobuoy at shot point 6790) and largely disregarding the worst one (water gun sonobuoy at shot point 4177). Interval velocities obtained by the sonobuoy survey were subjected to a certain error due to an uneven terrain over which the measurements were performed. I calculated a standard deviation (s) of the interval velocities in the appropriate horizons and the basement in order to quantify this error. The values of s (subscripts identify the appropriate horizons) are as follows: s_1=.14 km/sec, s_2=.14 km/sec, s_3=.08 km/sec, s_4=.21 km/sec, s_5=.21 km/sec, s_{base}=.47 km/sec.

4.3. Magnetics and Gravity

Magnetic data at the central site have been reduced by substracting the International Geomagnetic Reference Field (IGRF). The map shown in figure 15 is a map of the residual magnetic field. The units used are gammas; contour interval is 50 gammas. The magnetic gradient changes significantly in the N-S direction, from under -50 gammas in the north to over 200 gammas in the south. The values in the southernmost part decrease slightly again. This gradient change may be explained most easily by a dike of basaltic material running in an approximately E-W direction through the survey area. The dike position is delineated by letters D, E, F, and C in figure 15. It is possible that the dike position coincides with the position of a major fault, which is suggested in the tectonic setting section of this paper.

Gravity measurements have also been reduced. Reduction was performed by using an International (Potsdam) free-air gravity reduction formula. The residual gravity map is shown in figure 16. The gravity values range widely from under -20 mgals to over 50 mgals; contour interval is 10 mgals. The gravity signature at the central site is noisier than at the southern site despite the southern site's much more rugged terrain and varying sedimentary thickness. In our opinion, the uneven distribution of the gravity highs and lows at the central site has been caused mainly by errors in navigation. We think that if we smoothed the gravity values in the area by averaging, we would observe that the resulting highs and lows on the gravity map would follow the relief of the underlying basement because the sedimentary cover at this site is draped over the basement horizon and practically constant in thickness.

4.4 Age of Sediments

The age of the sediments at the central survey site is constrained by the age of sediments at DSDP sites 214 (north) and 253 (south) and by the rate of motion of northward movement of India. Site 214 shows an age of 42 My (upper Paleocene) at the top of volcaniclastic sediments, and its basalts are 59 My old (Paleocene) (von der Borch, Sclater, et al, 1974). The age at the top of volcaniclastic sediments at DSDP site 253 is also 42 My, and the age of basalts is approximately 46 My. This could be explained by assuming that the volcaniclastics (ashes) come from the same source, possibly from Java-Sumatra arc volcanoes. A hypothesis that the volcanic ash is local is more feasible for two reasons. Chemical composition of the volcanic ash is basaltic, not andesitic, as it would be, if the ash were from a volcanic arc, and the grain size is far too coarse to have been carried that far (Peirce, personal comm.).

In any case, the age of the highest layers of volcanic ashes at the central survey site is also estimated to be approximately 42 My. The age of basalts at the central survey site can be calculated by extrapolation, using the age of the basalts and the latitudes of appropriate DSDP sites. The age ranges from 52 My (DSDP sites 216 and 214) to 57 My (DSDP sites 254 and 253) (Davies, Luyendyk, et al., 1974). The age of the basalts at the central survey area can also be calculated by interpolation between sites 253 and 214, this interpolation gives the age 53 My.

4.5 Tectonic Setting

The sediments of the upper group drape evenly over the lower group sediments and show almost no faulting. On the contrary, the lower group of sediments is extensively faulted, with a major fault running in the W-E direction. This fault is an overthrust (compressional regime) on the western side and changes into a normal fault (extensional regime) on the east side. The fault pattern and the absence of young faults (overthrust side) may be the result of complicated boundary conditions between the Indian plate on the west and the Australian plate on the east. Figure 17 shows magnetic anomalies at the proximity of the Ninetyeast Ridge (Royer, 1987). The age of the prominent fault on the ridge may be 42 My or a little older. This age corresponds to the extinction time of the old ridge system and the opening of Kerguelen Ridge system. The change in the spreading direction is shown in the figure 13 between anomalies 18 (43 My) and 20 (46 My). This change may have contributed to a compressional regime along the ridge. The overthrust fault supports this hypothesis. Correspondence of the ages of anomalies 18 and 20 to the ages obtained by drilling on the ridge is evidence that the ridge is attached to the Indian plate (Sclater and Fischer, 1974). A small offset of the anomalies 18 and 20 in the south of Osborne Knoll corresponds to the large offset of anomaly 32 in the north. It is apparent that the missing crust was created when the ridge jumped south. Location of the extinct ridge is probably at the vicinity of the DSDP site 215 (Sclater, von der Borch, at al., 1974). What is not apparent, though, is the exact place of the new ridge. Royer (1987) places it at the Osborne Knoll. The age of the jump is between anomalies 26 (60ma) and 28 (65ma). Figure 17 also shows anomalies in the Wharton basin. A large offset must be inferred along the Ninetyeast ridge. A position of the extinct ridge axis is indicated (Royer, 1987). Anomalies become older north of this feature and younger south of it. Transform fault between Central Indian Basin and Wharton Basin needs to be accommodated either on the ridge, or just on the east side of the ridge, before anomaly 28 (above mentioned ridge jump time) time.

4.6 Suggested Drilling Sites

Two drilling sites are recommended. Either of these sites requires short drilling time because the sediment column is only 400 - 500 m thick. The area around these sites is not disturbed by faulting, and seismic horizons are clearly and sharply defined on the seismic profiles. Both sites are situated on the intersections of the seismic lines and thus have cross-strike seismic control. The coordinates are:

Suggested drilling site 1 - shot numbers 2192 and 6866 (Figures 18 and 19)

latitude 16.9951° S longitude 88.1600° E

Suggested drilling site 2 - shot numbers 3113 and 4219 (Figures 20 and 21)

latitude 17.0847° S longitude 88.1111° E.

The water depths at the suggested survey sites are 1639 and 1705 m, respectively, sedimentary thicknesses, depths to the separate horizons, and the depths of basement are listed in table 2. The sedimentary layers expected at the suggested survey site 1 are: Foraminiferal-nannoplankton ooze as unit 1, divided by a weak reflector at .050 sec from nannoplankton ooze in unit 2. This is divided from unit 3, which is chalk or green volcanic ash, also by weak reflector at .178 sec. Next unit - black volcanic ash interbedded with siltstone or sandstone is divided from the previous unit by a strong reflector at .207 sec, and the last sedimentary unit (lava flows with volcaniclastic sediments) is divided from the previous unit by another strong reflector at .399 sec. The last unit is divided from basement by a medium strong reflector at .480 sec under the sea floor. The sedimentary succession at the suggested drilling site # 2 is the same as at # 1 site with respective reflectors at .051, .238, .266, .342, and .407 sec. The estimated lithologic columns for the two suggested sites are shown in figure 22. The two suggested drilling sites are very similar in their development. Site two gives us a better chance to reach basement, since total sediment thickness is about 100 m less than at the other site. However, site 2 shows some faulting in the last sedimentary layer.

5. SITE SURVEY - SOUTHERN NINETYEAST RIDGE

This survey was performed by a crew of R/V CONRAD as a part of an RC 2708 cruise in September, 1986. The survey area was divided into a seismic grid (Figure 23), which was shot using two 80 cubic inch water guns. Refraction surveys were performed using sonobuoys. The acquired data were processed by the same methods as described for the above mentioned central Ninetyeast Ridge site. The area covered by the survey lies approximately inside of a quadrangle bordered by 27.05° S and 27.50° S and 87.30° E and 87.70° E. The grid consists of six approximately E-W and six approximately N-S lines of different length. The ties of the seismic grid on this site had somewhat larger errors (up to 100 msec at the water bottom reflection) than the ties on the previous site. This was caused by inexact navigational data in conjunction with steeply sloping ocean bottom. For discussion on navigation see the central site survey chapter. The seismic lines had to be relocated (max. 500 m) in some cases, to offset this error. This should not cause any problems, since the suggested drilling sites lie in the comparatively flat areas.

5.1 Seismic Data Interpretation

The bathymetry (Figure 23) of this site is rugged. The sea bottom of the area is composed of highly elevated basement protrusions and small sedimentary basins. The difference in the height of the relief exceeds 1275 m in the survey area. The highest peak is only 725 uncorrected meters below sea level. The terrain is generally rougher in the northwest side of the area.

Four sedimentary horizons and a basement can be recognized in the area (Figures 41 and 42). Due to an extensively rough topography the mentioned seismostratigraphic horizons range widely in areal extent (Figure 24). I was tentatively able to correlate the horizons in the area. I attempted to carry the horizons throughout the site survey area as far as possible in order to preserve clarity of the picture. It may be that the horizons in question underwent lateral lithologic changes, especially in the transitions between terrain highs and lows, where sedimentary material might have been reworked and redeposited, given the complex nature of the sedimentary processes in this particular setting. The sediments, as it was mentioned before (in the central site survey chapter), can be divided into two main sedimentary groups. The first group comprises the first two seismostratigraphic horizons on this site. The second group is represented by a third horizon alone, since the interpretation of the fourth horizon is tentative. The following interpretation of sedimentary units is based mainly on stratigraphy of the neighboring DSDP sites 253 and 254. The correlations of the seismic profiles of DSDP 254 and suggested drilling site # 3 at the southern survey site are shown in figure 25. The upper group is again deep water biogenic oozes, while the lower group is formed by volcaniclastics or volcanically derived sediments. The isopach maps of the two groups are shown in figures 26 and 27.

The first seismostratigraphic unit shows medium frequency with low to medium amplitude reflections. It drapes over the unit below it and maintains an approximately constant thickness in the area where it exists. It is not present on the extremely steep flanks of several topographic highs. This unit does not show any faulting and rests conformably on the units below. Its thickness ranges from approximately 30 to 50 meters where the unit is developed. This unit is probably a nannoplankton ooze (see stratigraphy of DSDP sites 253 and 254). A sonobuoy refraction survey indicates that the seismic velocity in this unit is 1.55 km/sec. The bottom reflector which divides this unit from unit below is not always strong and sometimes is hardly recognizable. This is probably due to the similar physical properties of the sediments in the two layers at certain locations.

The second stratigraphic unit is frequently seismically transparent showing medium frequency, low to medium amplitude reflectors. Areal extent of this unit is the smallest, as the unit covers less then the half of the area. The unit shows some faulting. Its thickness ranges greatly, from 0 to approximately 250 meters. This unit is probably biogenic ooze, not unlike the topmost unit, possibly interbedded with thin layers of siltstones, mudstones, or chalks as indicated by amplitude changes. This unit lays conformably on the unit below it and is divided from it by a medium to strong reflector. This reflector constitutes a boundary between upper and lower sedimentary groups. The measured seismic velocity is about 1.8 km/sec.

The third unit shows medium frequency and low to high amplitude reflectors. This unit is often faulted. Its thickness ranges from 0 to almost 400 meters. I estimate that this unit is either volcaniclastic sediments, siltstone interbedded with conglomerates and mudstones, or any combination of the above. Seismic velocity of this unit has been determined to be 2.3 km/sec from a very wide range of velocities

(Table 3). This unit lays conformably on the top of the last sedimentary unit from which it is divided by a very strong reflector. The isochron map of top of this unit is shown in the figure 28.

The fourth seismostratigraphic unit shows medium frequency, high amplitude reflections. It covers most of the area. It also shows extensive faulting. Its thickness ranges from 0 to almost 300 meters, but generally is about 100 meters. This unit probably is lava flows intermingled with volcanically derived sediments. This interpretation is tentative for the same reasons as the interpretation of the similar unit at the central Ninetyeast Ridge survey area. It is also possible that it is the uppermost part of the basement basalt, which due to amygdales, fissures, and weathering has a comparatively low measured seismic velocity of about 3.1 km/sec. For this reason (possible weathered basement layer) the topographic map of the top of this layer is shown (Figure 29), as well as isochron map (Figure 30).

Underlying this layer is a basaltic basement (Figure 31). We cannot recognize a strong reflection which would separate the oceanic basement from overlying sediments. The seismic velocity of this upper part of the basement is about 3.7 km/sec. This velocity increases deeper in the basaltic layer to a value of about 4.5 km/sec. A reflection, which would denote this change of parameters is not discernible on the reflection profile.

5.2 Seismic Velocities

Seismic velocities in the area were obtained by a refraction sonobuoy survey (Figure 23). Seven sonobuoys were processed by the same methods as described for the previous site. The velocities we obtained were quite scattered due to an extremely rough topography encountered on this site. The surrounding DSDP site acoustic velocities, lithologies and the estimated lithology of this site were taken into consideration when deciding the "average" velocities for the velocity structure. The quantitative errors in the interval velocities are expressed by the standard deviations (s). Subscripts mark different sedimentary or basement horizons: s_1=.23 km/sec, s_2=.33 km/sec, s_3=.58 km/sec, s_4=.70 km/sec, s_{base}=.26 km/sec, $s_{subbase}$=.72 km/sec. Notice that the standard deviations are larger at southern survey area. The increase is caused by more rugged terrain. The final velocities are the best estimate taking into account the above mentioned circumstances. Velocities for separate sonobuoys and the final velocities are collated in table 3.

5.3 Magnetics and Gravity

Magnetic and gravity data at this survey site have been reduced using the same procedures as at the central site. The residual magnetic data (Figure 32) range from under -250 gammas to over 200 gammas. There are several extreme highs and lows at the southern site. These extremes are caused by ocean bottom surface proximity of the basement basalts and by varying thicknesses of the sediments.

On the contrary, the residual gravity map (Figure 33) does not show a wide range of values. The lowest value is about -20 mgals on the flank of the ridge (lower right hand corner). The highest value is over 60 mgals above a major underwater peak. The values are generally highest along the top of the ridge, falling off along the sides.

5.4 Age of Sediments

The age of sediments at the southern survey site is similarly constrained as the age of sediments at the central survey site (Davies, Luyendyk, et al., 1974). Unfortunately, the oldest reliably dated fossils at DSDP site 254 belong to the upper (biogenic ooze) group. The tentative age of the oldest sediments at this DSDP site is lower Oligocene, possibly around 38 Ma. The age of the top of the lower group could not be determined with any accuracy. The only information we have is that the rate of accumulation of the lower group was much higher. With regard to much younger age of the survey site I did not consider its age by extrapolation of the ages of DSDP sites 214 and 253, but only by interpolation between sites 253 and 254. The age of the basalts of the southern survey site thus calculated is approx. 43 My.

5.5 Tectonic setting

This site shows much more relief than any DSDP site on the Ninetyeast Ridge. The upper group of sediments seem to have less faults than lower group, but the overall picture, due to the ruggedness of the terrain, seems confusing. It is not quite clear from seismic record, whether the basement protrusions were created tectonically or by volcanism. Deep reaching faults seem to continue into the basement in some cases. I was not able to see any evidence of compressional tectonics as at the central survey site. That means, if my interpretation of the cause of similar tectonics at the central survey site is correct, that this site originated after the change of rate and direction of northward motion of the Indian plate. That may agree with the approximate age of the site and also with position of magnetic anomalies (Royer, 1987) to the west of the site.

5.6 Suggested Drilling Sites

I have determined the positions of four possible drilling sites on the southern Ninetyeast Ridge. Water depths of these sites are: 1810, 1456, 1539, and 1511 m, respectively. Total sediment thicknesses are: 338, 186, 177, and 255 m. Depths of basement, depths to the different units and their thicknesses in meters are compiled in table 4. The lithologies of the sites are as follows: Unit 1 is nannoplankton ooze, divided from unit 2 by a weak reflector, unit 2 is biogenic ooze interbedded with mudstone, siltstone or sandstone, divided from unit 3 by a strong reflector. Another strong reflector divides unit 3, which is volcaniclastic sediments mixed with mudstone or siltstone, from unit 4. Unit 4 is the last sedimentary unit and is formed by volcaniclastics interbedded with lava flows or possibly a topmost weathered amygdaloidal basalt. This unit is divided from basement by a diffuse reflector. All the suggested drilling sites have a complete stratigraphic development, except for suggested site # 4, which lacks unit # 3 (figure 34). The subbottom seismic reflectors at the suggested sites 1 - 4 were encountered at these times: Site 1 - .053, .167, .290, and .324 sec of two-way travel time (TWT). Site 2 - .052, .121, .147, and .181 sec of TWT. Site 3 - .046, .104, .177, and .180 sec of TWT. Site 4 - .054, .179, and .248 sec of TWT. The sites are located at following positions:

Suggested drilling site 1 - shot point 11462 (Figure 35)

latitude 27.5120° S longitude 87.4514° E

Suggested drilling site 2 - shot point 12812 (Figure 36)

latitude 27.3000° S longitude 87.4952° E

Suggested drilling site 3 - shot point 13670 (Figure 37)

latitude 27.3256° S longitude 87.4615° E

Suggested drilling site 4 - shot point 13920 (Figure 38)

latitude 27.3623° S longitude 87.6116° E.

The suggested survey sites range in sedimentary thickness from 177 to 338 m. It would be to our advantage to drill site # 1, because of its thick sediment cover and a good chance to recover some fossils. If we failed to reach basement with this site, we could then drill at the site # 3, which has a sediment cover of only 177 m and reach basement there, comparatively quickly.

6. CONCLUSIONS

A detailed seismic processing and seismostratigraphic interpretation was performed for the central and southern Ninetyeast Ridge survey sites. We constructed isopach maps for the most important horizons in the areas of the surveys as well as bathymetry and basement depth maps. We suggested two drilling sites at the central Ninetyeast Ridge survey area and four at the southern Ninetyeast Ridge survey area. W processed the interval velocity information obtained by a sonobuoy refraction survey to determine a thickness of each horizon for the purpose of drilling and construction of the above mentioned maps. The total thickness of sediments at the suggested drilling site # 1 (central survey area) is 493 m, at site # 2 it is 401 m. Site # 2 offers a thicker section of biogenic oozes, whose age is important to determine, and a lower total sediment thickness, which is an advantage for drilling. On the other hand, sites # 2 and # 3 are situated comparatively close to major faults. Total sediment thicknesses at the four suggested drilling sites at the southern survey area range from 177 (site # 3) to 338 m (site # 1). The thicker sedimentary cover offers a better chance to find the age, on the other hand the thinner cover offers a better chance of reaching basement and recovering basement basalts. These advantages and disadvantages will have to be considered while selecting a drilling site.

The suggested drilling sites show a good development of the seismostratigraphic horizons. We achieved a cross-strike control of the suggested drilling sites at the central site by placing them at the intersections of the seismic lines. This was not possible at the southern site, where the terrain is very rugged. The four suggested drilling sites of the southern survey were placed in areas of comparatively flat and well developed sedimentary horizons. The estimated lithologies of the suggested drilling sites were based on the hypothesized evolution of the ridge, on the lithologies of the neighboring sites 214, 253 and 254; and on the velocities obtained by a sonobuoy refraction survey.

The sediments of the ridge can be divided into two basic categories. Pelagic oozes, the main constituent of the first sediment category, were deposited in a deep water environment since the Late Paleocene (site 214), Miocene (site 253) and probably lower Oligocene (site 254) to Recent. This means that the ridge subsided earlier in the north than in the south. Volcaniclastics, which range from ashes often interbedded with lava flows to volcanically derived sandstones are the second main category of the sediments on the ridge. This category of the sediments was deposited in a shallow water environment, and some lava flows may have been deposited subaerially. These sediments overlie conformably basaltic basement.

The age of the sediments and basement basalts and paleolatitude data of the ridge are very important constraints in our understanding the rates of motion of India and their change. These data should help us relate the Himalayan orogeny to the plate driving forces. It should also clarify the spreading history of the ridge between DSDP sites 214 and 254. After analysis of the neighboring DSDP sites we estimated that the age of the basal sediments at the central survey site would be in the range from 52 - 57 My and the top layer of the volcanic ash would be approximately 42 My old. The age of basal sediments at the southern site should be around 43 My.

The central and the southern survey areas differ significantly in their tectonic development. The central area basement does not show as much relief as the southern area basement, on the other hand the central area shows more faulting in the older horizons (older then top of volcanic ash, i.e. approximately 42 My). The central site shows evidence of compressional tectonics, which is lacking at the southern site. This tectonic evidence can be tentatively tied to a change of rate and direction of motion in the northward movement of the Indian plate at the time between anomaly 18 and 20 (43 and 46 Ma).

We should be able to obtain paleolatitude samples younger than 42 My at the central survey area and also paleolatitude samples of the basement. Older samples will have to be taken from volcaniclastic sediment layers. Samples taken from the altered volcaniclastic sediments are not often of sufficient quality to be considered (Peirce, personal comm.). The southern survey area should produce samples younger than 43 My. This will help to better constrain the lower part of the line shown in the figure 1. The upper part of the data set will gain only one or two data points - the basement data from the both sites. Drilling at the suggested sites should also yield the ages of the sediments based on stratigraphic analysis. Unfortunately, we will probably not be able to date the volcaniclastic sediments with any accuracy. That means that we will have problems to date sediments older than 42 My at the central site. I have not been able to determine the age of volcaniclastic (or volcanically derived) sediments at the southern site.

The chemical composition of the basalts will be used to evaluate hot spots as mantle heterogeneities and thus help to explain dynamic processes in the mantle. The comparison of the ridge basalts with Kerguelen-Heard and Amsterdam-St. Paul Island basalts should help to clarify the problems of the origin of the ridge.

APPENDIX

Table 1. Interval velocities for the central Ninetyeast Ridge survey site area. The velocities were determined from sonobuoys shot at described shot point locations. Velocities are in km/sec.

<table>
<tr><th colspan="6">SEISMIC VELOCITIES in km/sec</th></tr>
<tr><th>Unit \ Shot #</th><th>4177</th><th>4586</th><th>5143</th><th>6790</th><th>aver.</th></tr>
<tr><td>1</td><td rowspan="2">2.10</td><td rowspan="3">1.80</td><td rowspan="2">1.95</td><td rowspan="3">1.80</td><td>1.80</td></tr>
<tr><td>2</td><td>1.80</td></tr>
<tr><td>3</td><td>1.80</td><td>1.96</td><td>1.80</td></tr>
<tr><td>4</td><td>1.85</td><td rowspan="2">2.00</td><td>2.30</td><td>2.22</td><td>2.20</td></tr>
<tr><td>5</td><td>2.30</td><td>2.30</td><td>2.52</td><td>2.40</td></tr>
<tr><td>Basement</td><td>4.46</td><td>5.00</td><td>4.05</td><td>3.97</td><td>4.00</td></tr>
<tr><td>Sub basement</td><td>-</td><td>-</td><td>-</td><td>5.88</td><td>-</td></tr>
</table>

<u>Table 2.</u> Site parameters for suggested drilling sites for the central Ninetyeast Ridge survey area. Thicknesses are in meters, depths are in uncorrected meters.

SITE PARAMETERS		
	SITE 1	SITE 2
THICKNESS - UNIT 1	45	46
THICKNESS - UNIT 2	115	168
THICKNESS - UNIT 3	26	25
THICKNESS - UNIT 4	210	84
THICKNESS - UNIT 5	97	78
TOTAL THICKNESS	493	401
WATER DEPTH	1639	1705
DEPTH TO UNIT 2	1684	1751
DEPTH TO UNIT 3	1799	1919
DEPTH TO UNIT 4	1825	1944
DEPTH TO UNIT 5	2035	2028
DEPTH TO BASEMENT	2132	2106

Table 3. Interval velocities for the southern Ninetyeast Ridge survey site area. The velocities were determined from sonobuoys shot at described shot point locations. Velocities are in km/sec.

<table>
<tr><th colspan="9">SEISMIC VELOCITIES in km/sec</th></tr>
<tr><th>Shot # / Unit</th><th>9997</th><th>10128</th><th>11752</th><th>12137</th><th>12858</th><th>13616</th><th>13960</th><th>aver.</th></tr>
<tr><td>1</td><td rowspan="3">1.81</td><td rowspan="2">1.70</td><td rowspan="2">1.70</td><td rowspan="2">1.70</td><td rowspan="2">1.55</td><td rowspan="4">2.24</td><td>1.55</td><td>1.55</td></tr>
<tr><td>2</td><td rowspan="2">2.44</td><td>1.80</td></tr>
<tr><td>3</td><td rowspan="2">3.50</td><td>2.50</td><td>2.00</td><td rowspan="2">3.00</td><td>2.30</td></tr>
<tr><td>4</td><td>2.69</td><td rowspan="2">4.32</td><td>3.49</td><td rowspan="2">3.80</td><td>3.10</td></tr>
<tr><td>Basement</td><td>3.65</td><td>3.50</td><td>3.79</td><td>3.75</td><td>3.72</td><td>3.70</td></tr>
<tr><td>Sub basement</td><td>4.22</td><td>4.17</td><td>5.90</td><td>5.00</td><td>-</td><td>4.46</td><td>-</td><td>4.50</td></tr>
</table>

Table 4. Site parameters for suggested drilling sites for the southern Ninetyeast Ridge survey area. Thicknesses are in meters, depths are in uncorrected meters.

SITE PARAMETERS				
	SITE 1	SITE 2	SITE 3	SITE 4
THICK. - UNIT 1	41	40	36	42
THICK. - UNIT 2	103	62	52	112
THICK. - UNIT 3	141	30	84	0
THICK. - UNIT 4	53	54	5	107
TOTAL THICK.	338	186	177	255
WATER DEPTH	1810	1456	1539	1511
DEPTH TO 2	1851	1496	1575	1553
DEPTH TO 3	1954	1558	1627	1665
DEPTH TO 4	2095	1588	1711	1665
DEPTH TO BASE.	2148	1642	1716	1766

Figure 1. Paleomotion of DSDP site 216 based on paleolatitudes from all the sites on the Ninetyeast Ridge. Boxes indicate the 95% confidence intervals of each paleolatitude and the best estimate of the associated age. Squares indicate basalt data; circles indicate sediment data; and numbers indicate the site. Only paleolatitudes based on at least eight samples are plotted. For sites other than 216, a correction equal to the present latitude difference to site 216 was applied. The solid lines indicate rates of northward motion of India obtained by weighted least squares linear regression. The dashed lines indicate the 95% confidence region for the position of the site 216, assuming Student t-statistics apply to the rates of motion. Redrawn from Peirce, 1978.

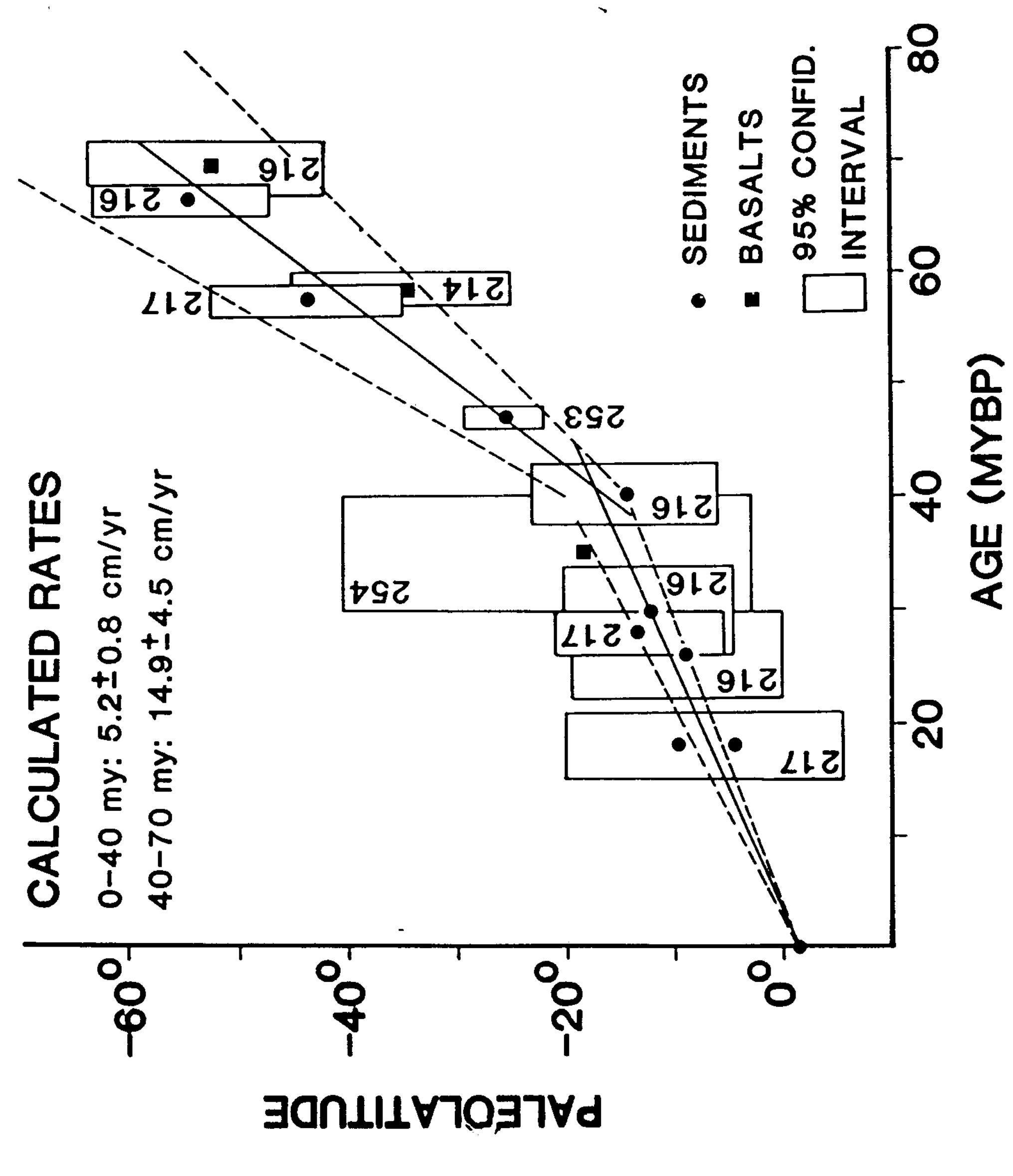
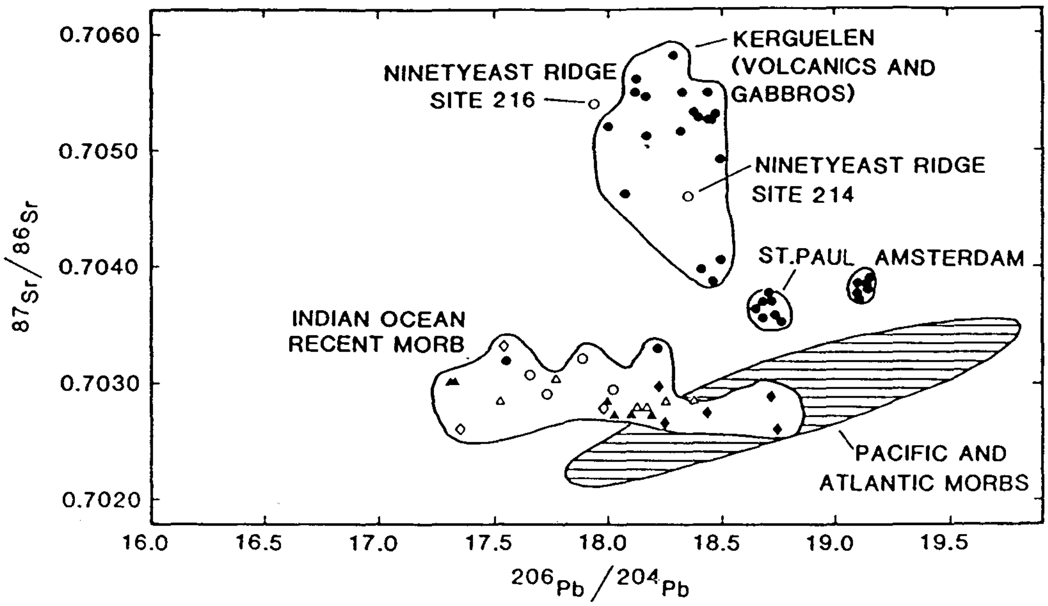
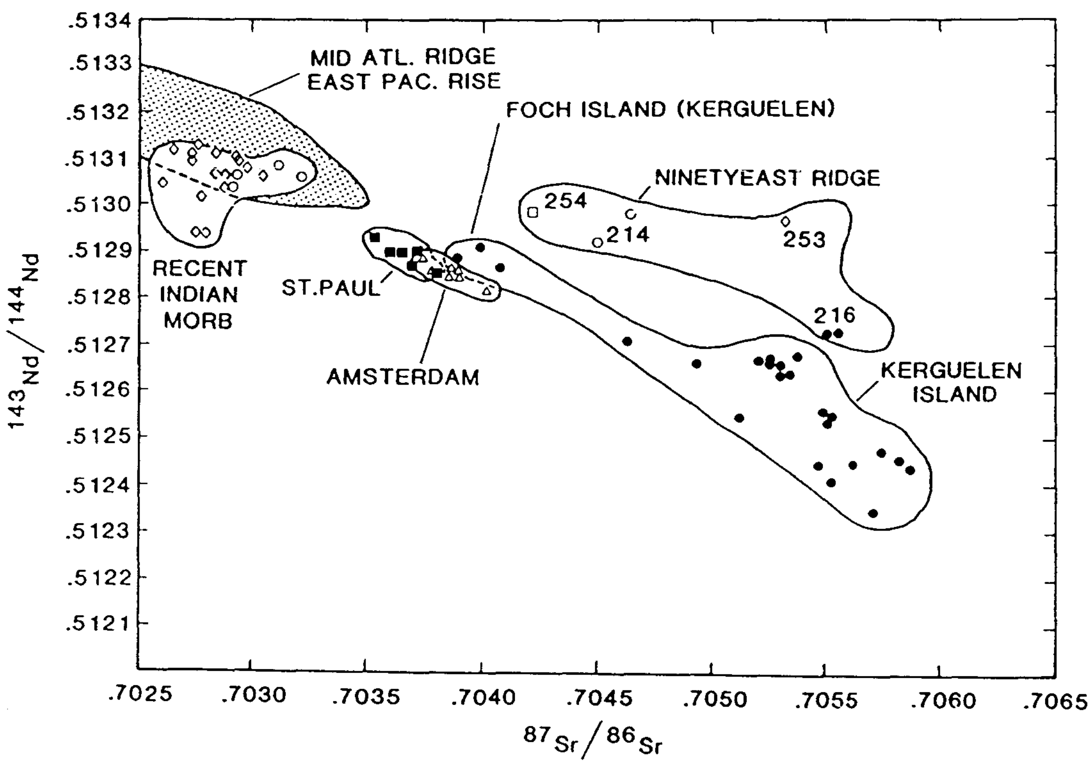

CALCULATED RATES
0–40 my: 5.2±0.8 cm/yr
40–70 my: 14.9±4.5 cm/yr
PALEOLATITUDE
-60°
-40°
-20°
0°
AGE (MYBP)
20
40
60
80
217
216
217
216
254
216
253
217
214
216
216
SEDIMENTS
BASALTS
95% CONFID. INTERVAL

Figure 2. a) Chemical composition of basement basalts expressed as $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ isotopic ratios. Redrawn from Frey, 1985.

b) Chemical composition of basement basalts expressed as $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ isotopic ratios. Redrawn from Frey, 1985.

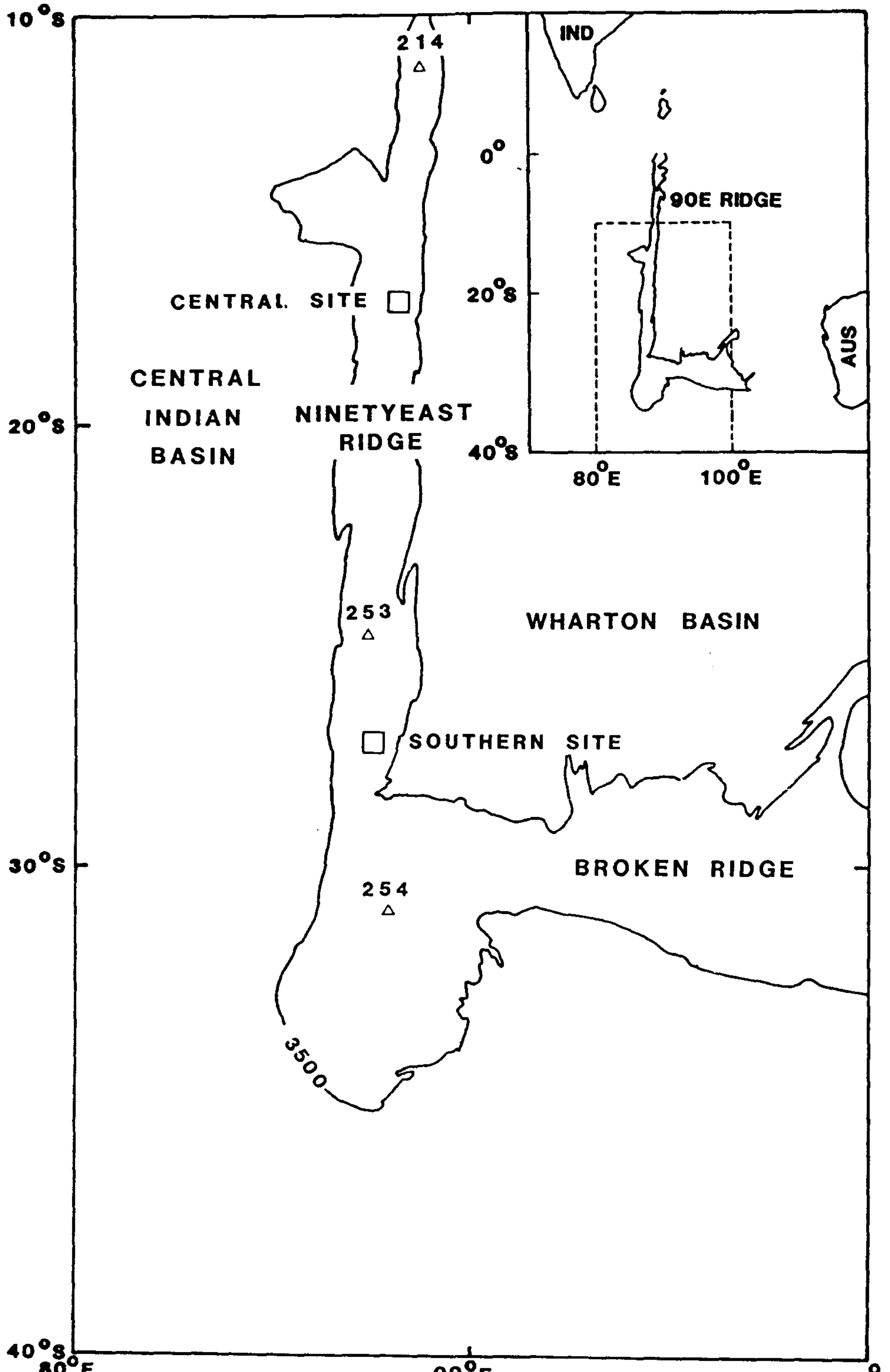


0.7060
0.7050
0.7040
0.7030
0.7020
87Sr/86Sr
16.0
16.5
17.0
17.5
18.0
18.5
19.0
19.5
206Pb/204Pb
KERGUELEN (VOLCANICS AND GABBROS)
NINETYEAST RIDGE SITE 216
NINETYEAST RIDGE SITE 214
ST.PAUL
AMSTERDAM
INDIAN OCEAN RECENT MORB
PACIFIC AND ATLANTIC MORBS



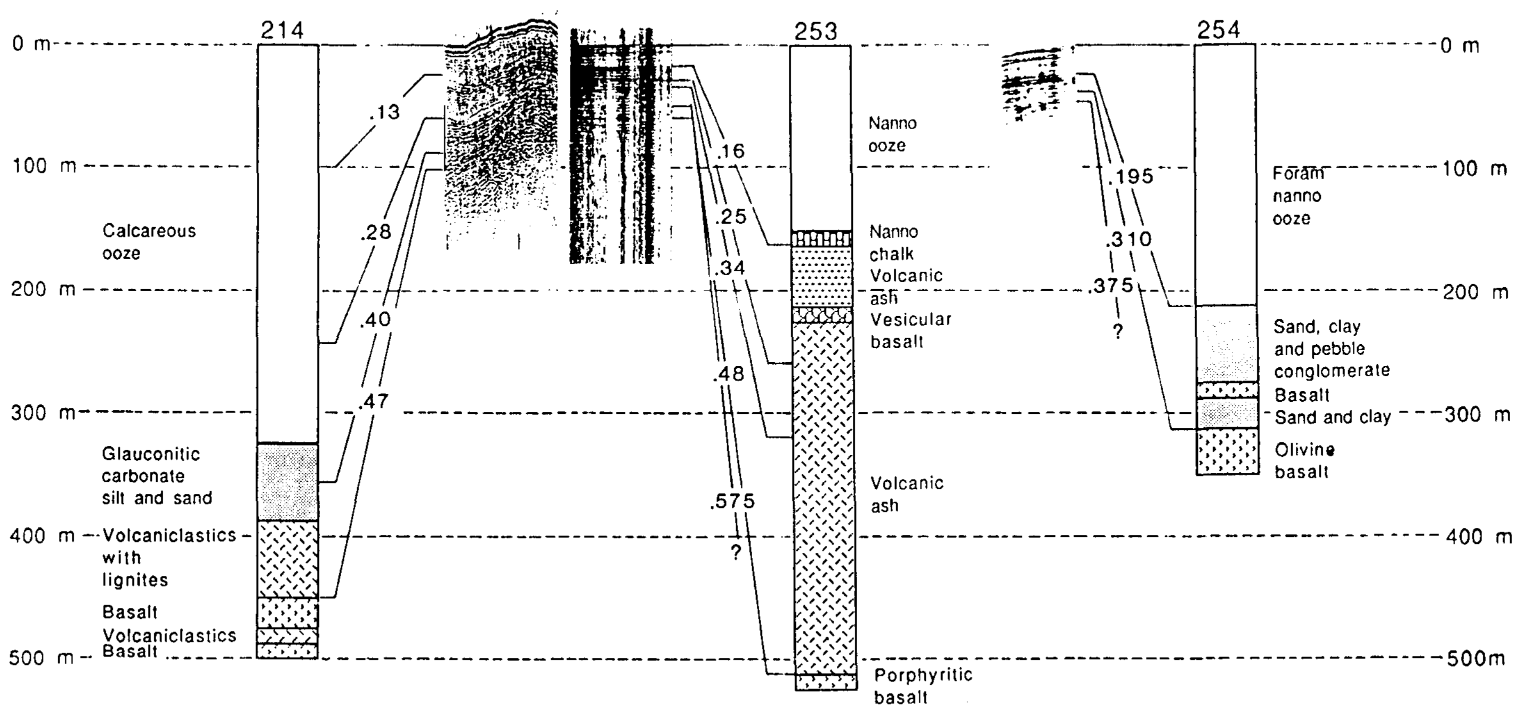
.5134
.5133
.5132
.5131
.5130
.5129
.5128
.5127
.5126
.5125
.5124
.5123
.5122
.5121
143Nd/144Nd
.7025
.7030
.7035
.7040
.7045
.7050
.7055
.7060
.7065
87Sr/86Sr
MID ATL. RIDGE EAST PAC. RISE
FOCH ISLAND (KERGUELEN)
NINETYEAST RIDGE
254
214
253
216
RECENT INDIAN MORB
ST.PAUL
AMSTERDAM
KERGUELEN ISLAND

Figure 3. General map of the area of interest. The Ninetyeast Ridge is outlined by the 3500 m contour line. DSDP drilling sites (214, 253 and 254) and survey sites (central and southern) are shown. The inset shows the area in relation to the Indian and Australian continents.



10°S
20°S
30°S
40°S
80°E
90°E
100°E
214
CENTRAL SITE
CENTRAL
INDIAN
BASIN
NINETYEAST
RIDGE
253
WHARTON BASIN
SOUTHERN SITE
BROKEN RIDGE
254
3500
IND
0°
90E RIDGE
20°S
AUS
40°S
80°E
100°E

<u>Figure 4.</u> Stratigraphic columns of sites 214, 253, and 254 with short descriptions of sedimentary units and correlation with seismic profiles. Times are in seconds of TWT. The data were compiled from site reports in DSDP volumes XXII (von der Borch, Sclater, at al., 1974) and XXVI (Davies, Luyendyk, at al., 1974).



214
253
254
0 m
100 m
200 m
300 m
400 m
500 m
500m
Calcareous ooze
Glauconitic carbonate silt and sand
Volcaniclastics with lignites
Basalt
Volcaniclastics
Basalt
.13
.28
.40
.47
.16
.25
.34
.48
.575
?
Nanno ooze
Nanno chalk
Volcanic ash
Vesicular basalt
Volcanic ash
Porphyritic basalt
.195
.310
.375
?
Foram nanno ooze
Sand, clay and pebble conglomerate
Basalt
Sand and clay
Olivine basalt

Figure 5. Ship's track with shot numbers and bathymetry of the central Ninetyeast Ridge survey area. The bathymetric contour interval is 50 m. The letters designate track turns. Circles with numbers show positions of the suggested survey sites. Diamonds with letter S show the positions of the sonobuoy refraction survey.

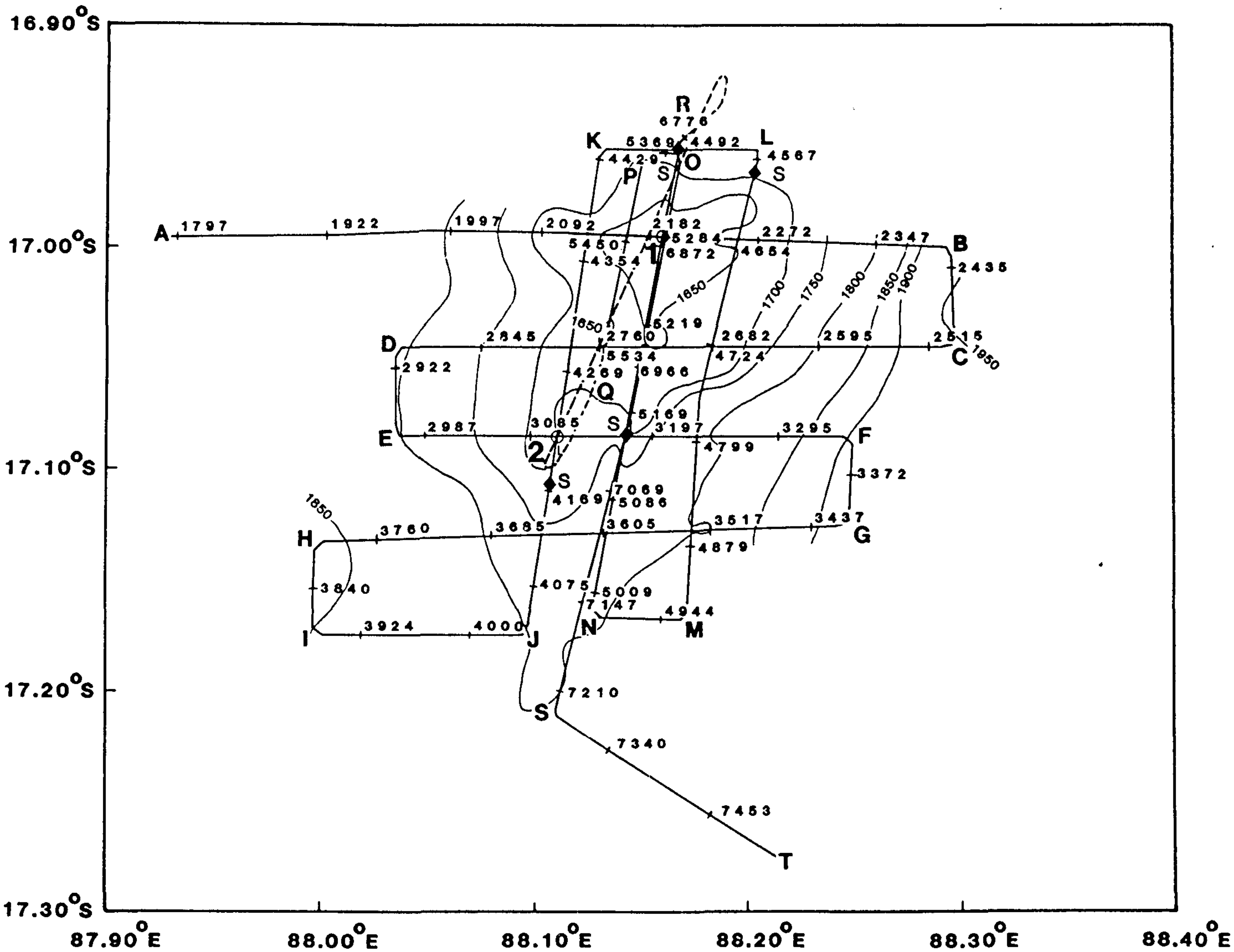

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A 1797 1922 1997 2092 2182 2272 2347 B
2435
2515 C
D 2845 2760 2682 2595
E 2987 3085 3197 3295 F
3372
H 3760 3685 3605 3517 3437 G
3840
I 3924 4000 J
K 5369 4492 L
4429 4567
P O S S
6776 R
5450 5284 4654
4354 6872
5219
5534 4724
4269 6966
Q 5169
4799
2922
1850
S 4169 7069 5086
4879
4075 5009
7147 4944
N M
7210
S 7340
7453
T
1
2
1650 1700 1750 1800 1850 1900 1950

Figure 6. Total sediment thickness map for the central Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 50 meters. Ship's track is drawn in dashed line. Letters designate the track turns. Circles with numbers show the positions of the suggested drilling sites.

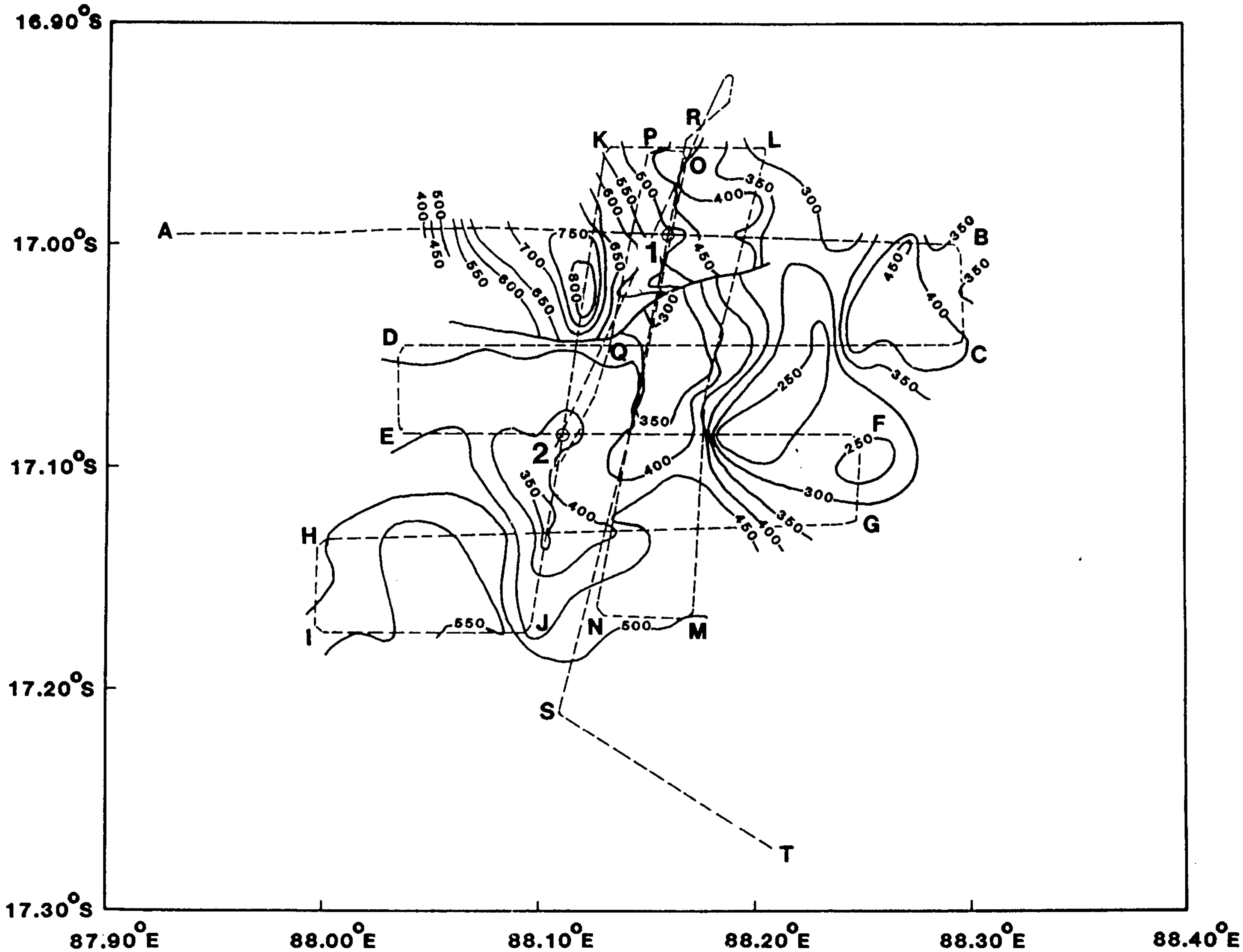

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
250
300
350
400
450
500
550
600
650
700
750
800

Figure 7. Stratigraphic column of DSDP site 214 and stratigraphic column (stratigraphy is estimated) of the suggested drilling site # 2 at the central site survey area with appropriate correlations to the seismic profiles. Times are in seconds of TWT. The stratigraphies of the two sites are tied together.

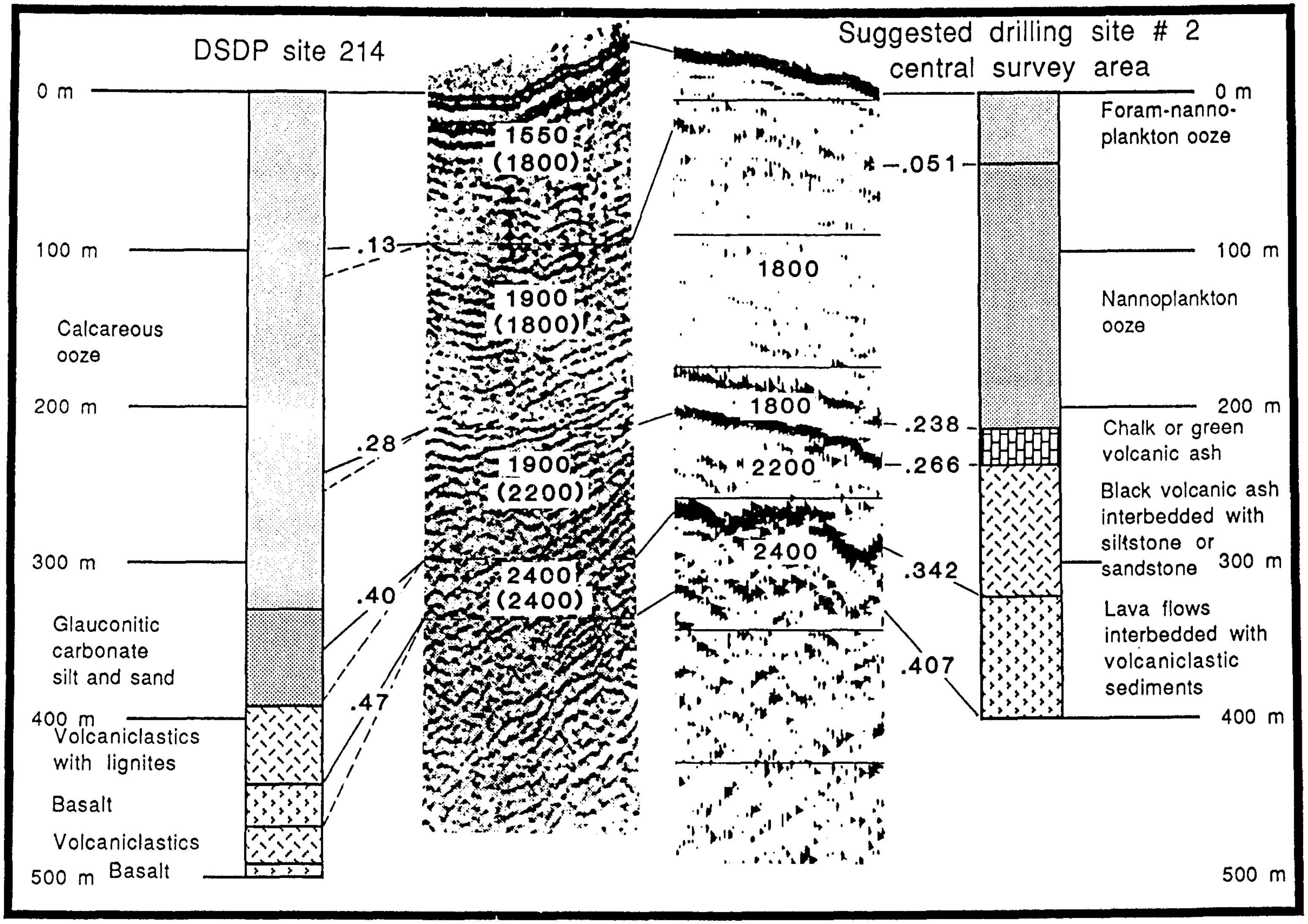

DSDP site 214
Suggested drilling site # 2
central survey area
0 m
100 m
200 m
300 m
400 m
500 m
Calcareous
ooze
Glauconitic
carbonate
silt and sand
Volcaniclastics
with lignites
Basalt
Volcaniclastics
Basalt
.13
.28
.40
.47
1550
(1800)
1900
(1800)
1900
(2200)
2400
(2400)
1800
1800
2200
2400
.051
.238
.266
.342
.407
Foram-nanno-
plankton ooze
Nannoplankton
ooze
Chalk or green
volcanic ash
Black volcanic ash
interbedded with
siltstone or
sandstone
Lava flows
interbedded with
volcaniclastic
sediments

Figure 8. Cumulative sediment thickness map of the seismostratigraphic units 1 - 3 (upper group) for the central Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 50 meters.

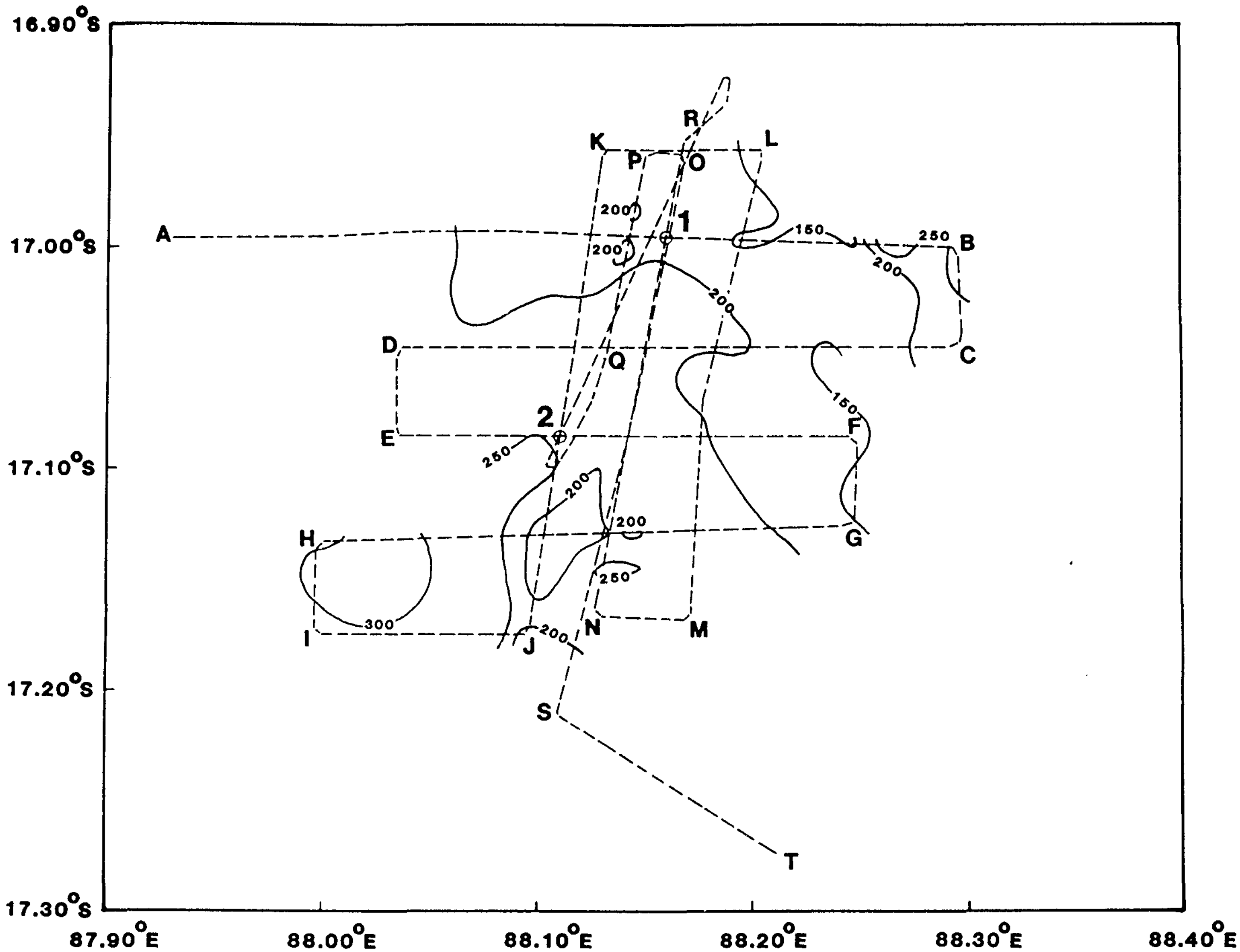

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
150
200
250
300

Figure 9. Sediment thickness map of unit 4 (lower group) for the central Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 40 m.

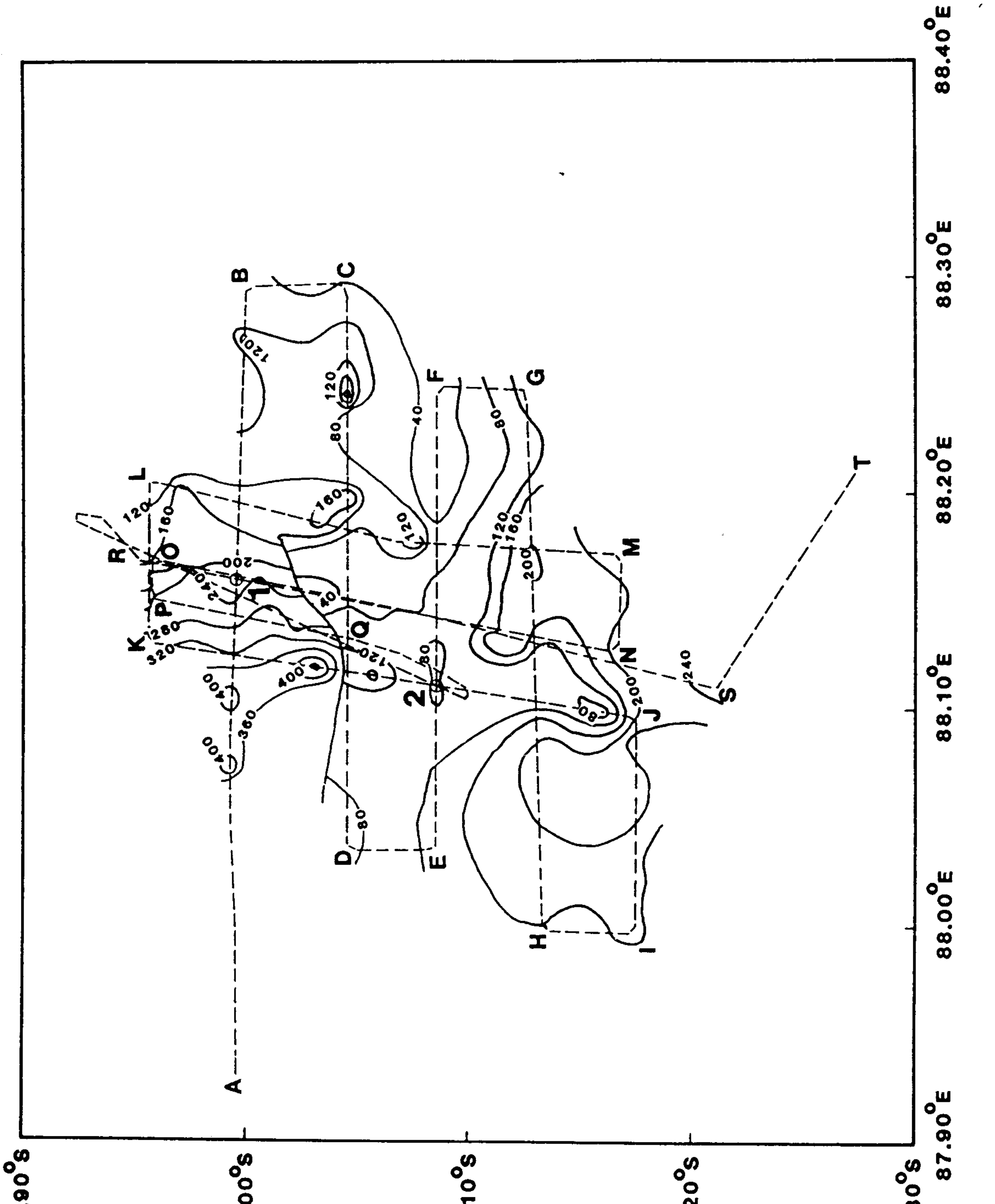
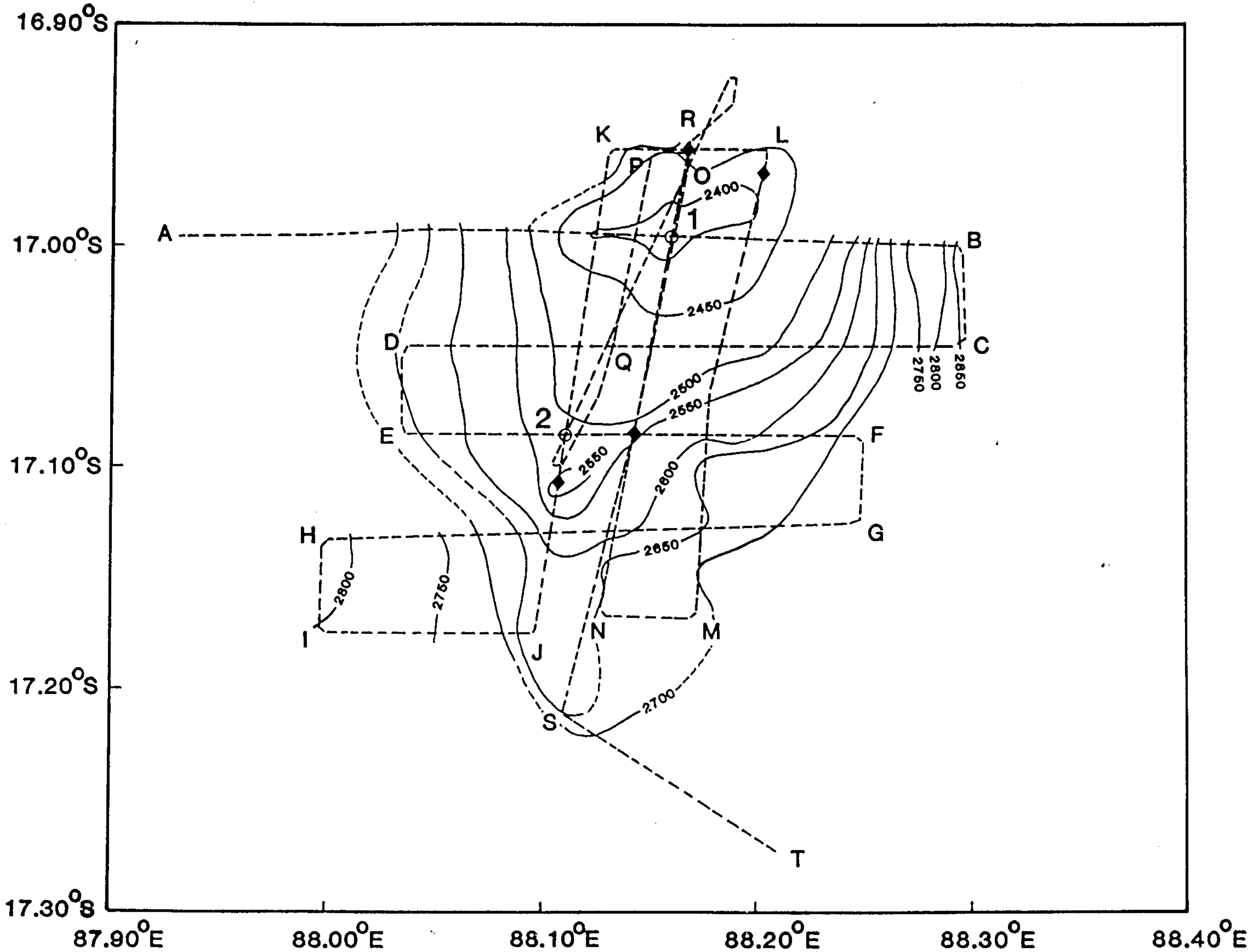

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E

Figure 10. Isochron map of the top of the fourth layer - central Ninetyeast Ridge survey area. Isochrons are in msec of TWT. Contour interval is 50 msec.



16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
2400
2450
2500
2550
2600
2650
2700
2750
2800
2850

Figure 11. Bathymetric map of the depth of the surface of the fifth layer for the central Ninetyeast Ridge survey area. Depths are in uncorrected meters. Contour interval is 50 meters. Sense of throw of the major W-E fault is shown.

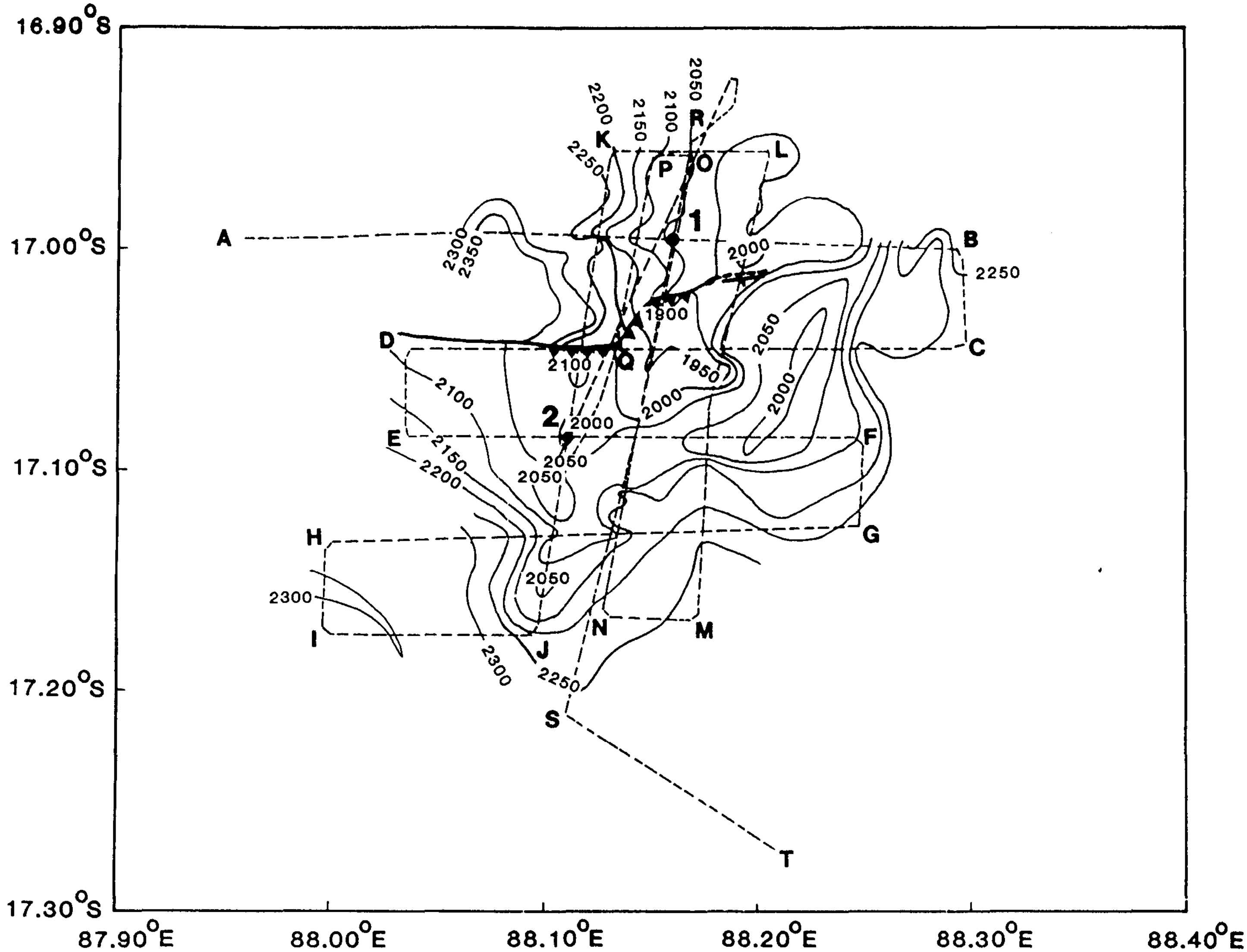

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
1900
1950
2000
2050
2100
2150
2200
2250
2300
2350

Figure 12. Isochron map of the top of the fifth layer - central Ninetyeast Ridge survey area. Isochrons are in msec of TWT. Contour interval is 50 msec.

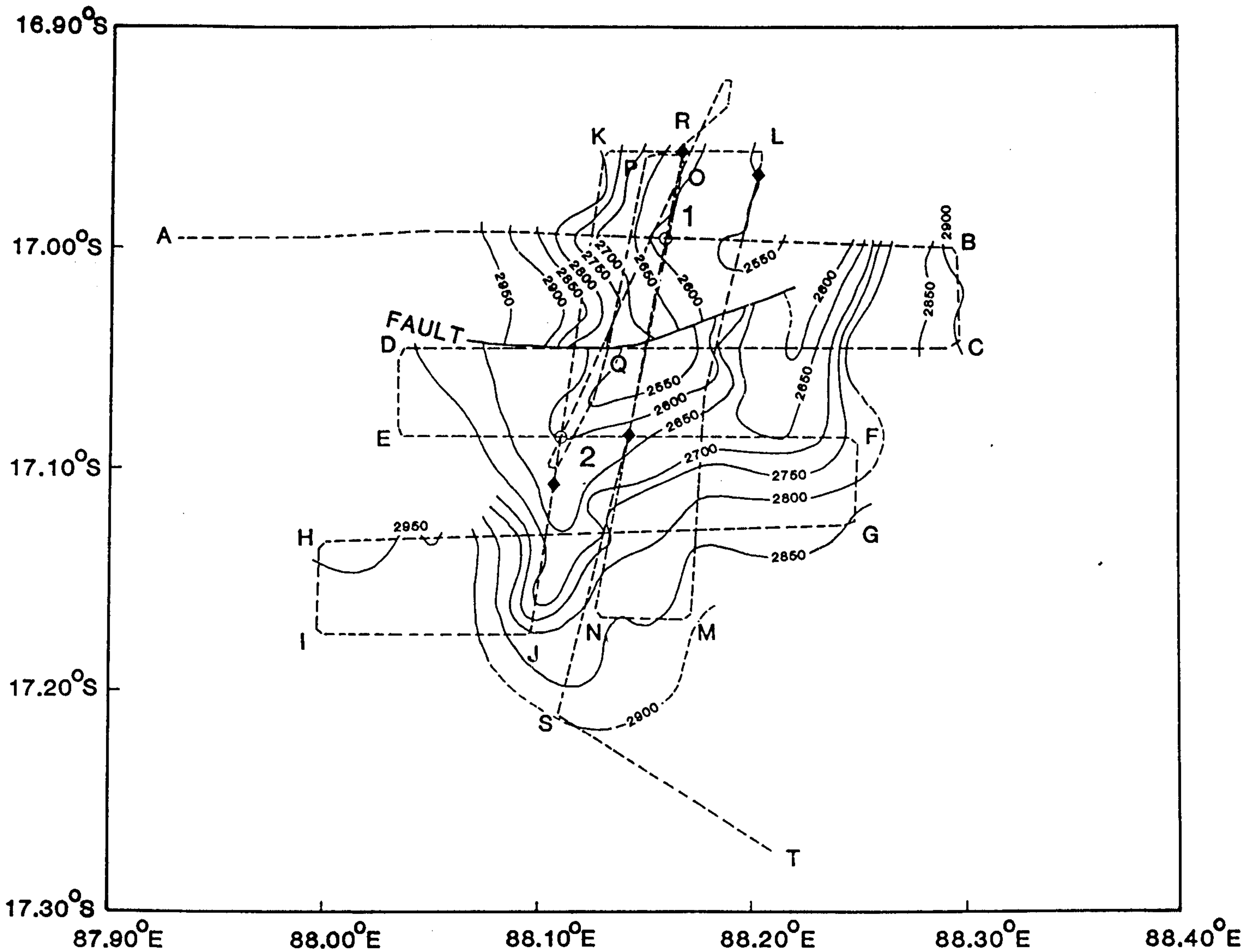
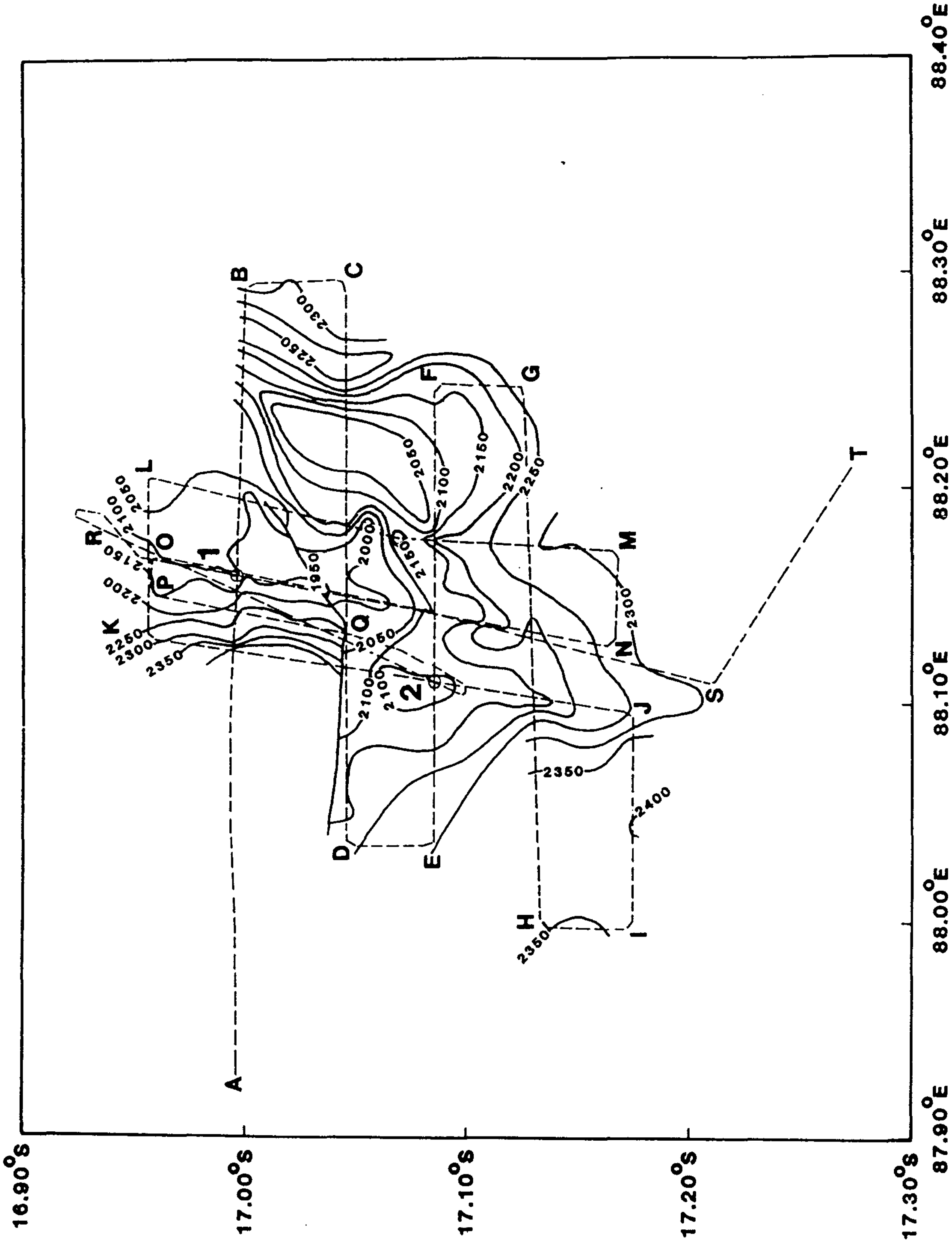

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
FAULT
2550
2600
2650
2700
2750
2800
2850
2900
2950

Figure 13. Depth of basement map for the central Ninetyeast Ridge survey area. Depths are in uncorrected meters. Contour interval is 50 meters.



16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
2300
2250
2050
2100
2150
2200
2250
1950
2000
2050
2100
2150
2200
2250
2300
2350
2400
2350
2350

Figure 14. Air gun sonobuoy record at the shot point 6790. The interval velocities are tied to the suggested lithologic column.

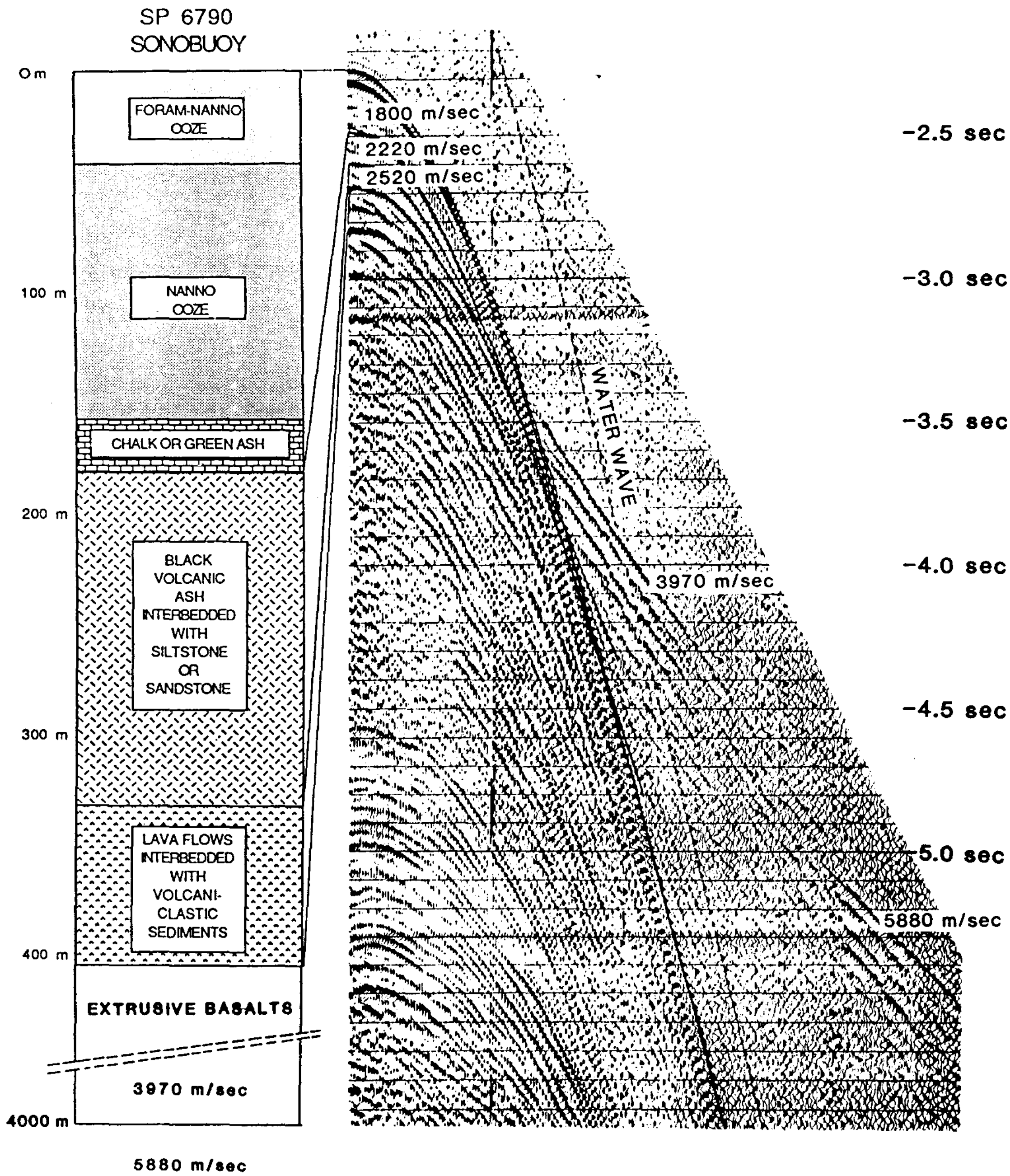
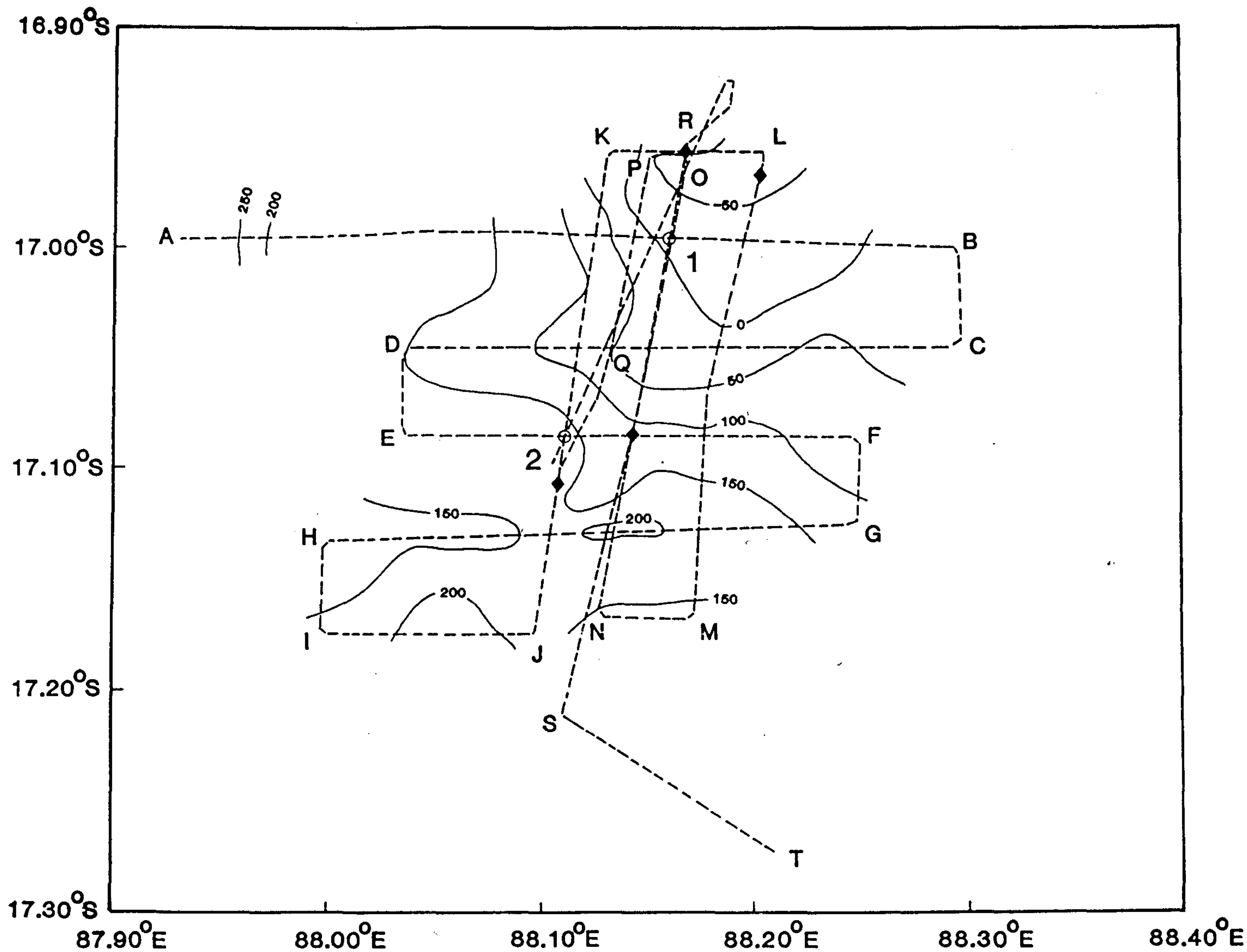

SP 6790
SONOBUOY
0 m
100 m
200 m
300 m
400 m
4000 m
FORAM-NANNO OOZE
NANNO OOZE
CHALK OR GREEN ASH
BLACK VOLCANIC ASH INTERBEDDED WITH SILTSTONE OR SANDSTONE
LAVA FLOWS INTERBEDDED WITH VOLCANI-CLASTIC SEDIMENTS
EXTRUSIVE BASALTS
3970 m/sec
5880 m/sec
1800 m/sec
2220 m/sec
2520 m/sec
WATER WAVE
3970 m/sec
5880 m/sec
-2.5 sec
-3.0 sec
-3.5 sec
-4.0 sec
-4.5 sec
-5.0 sec

Figure 15. Map of residual magnetic field - central survey area. Units of the magnetic field are gammas. Contour interval is 50 gammas.



16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
1
2
250
200
50
0
50
100
150
150
200
200
150

Figure 16. Map of residual gravity field - central survey area. Units are mgals. Contour interval is 10 mgals.

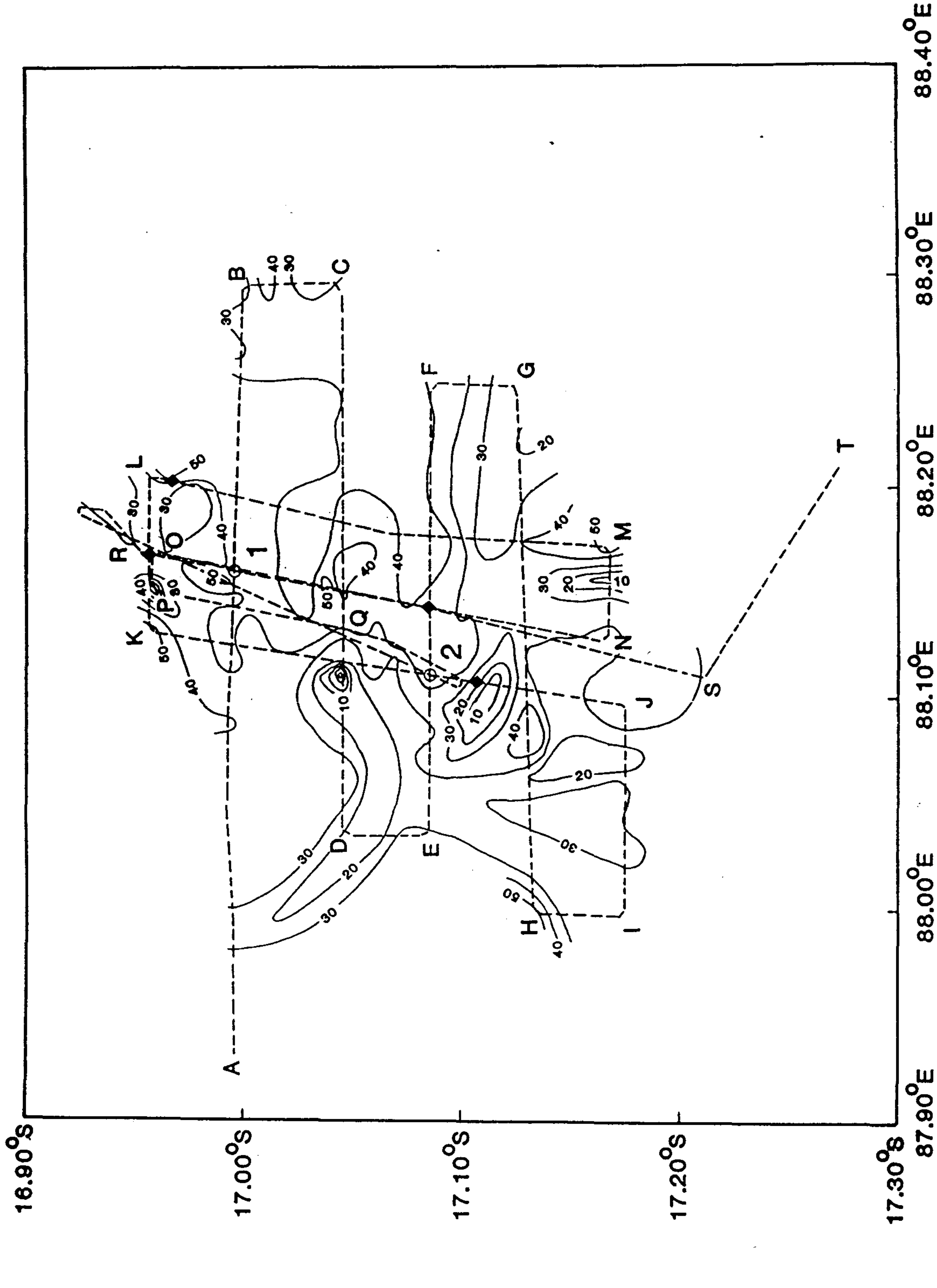
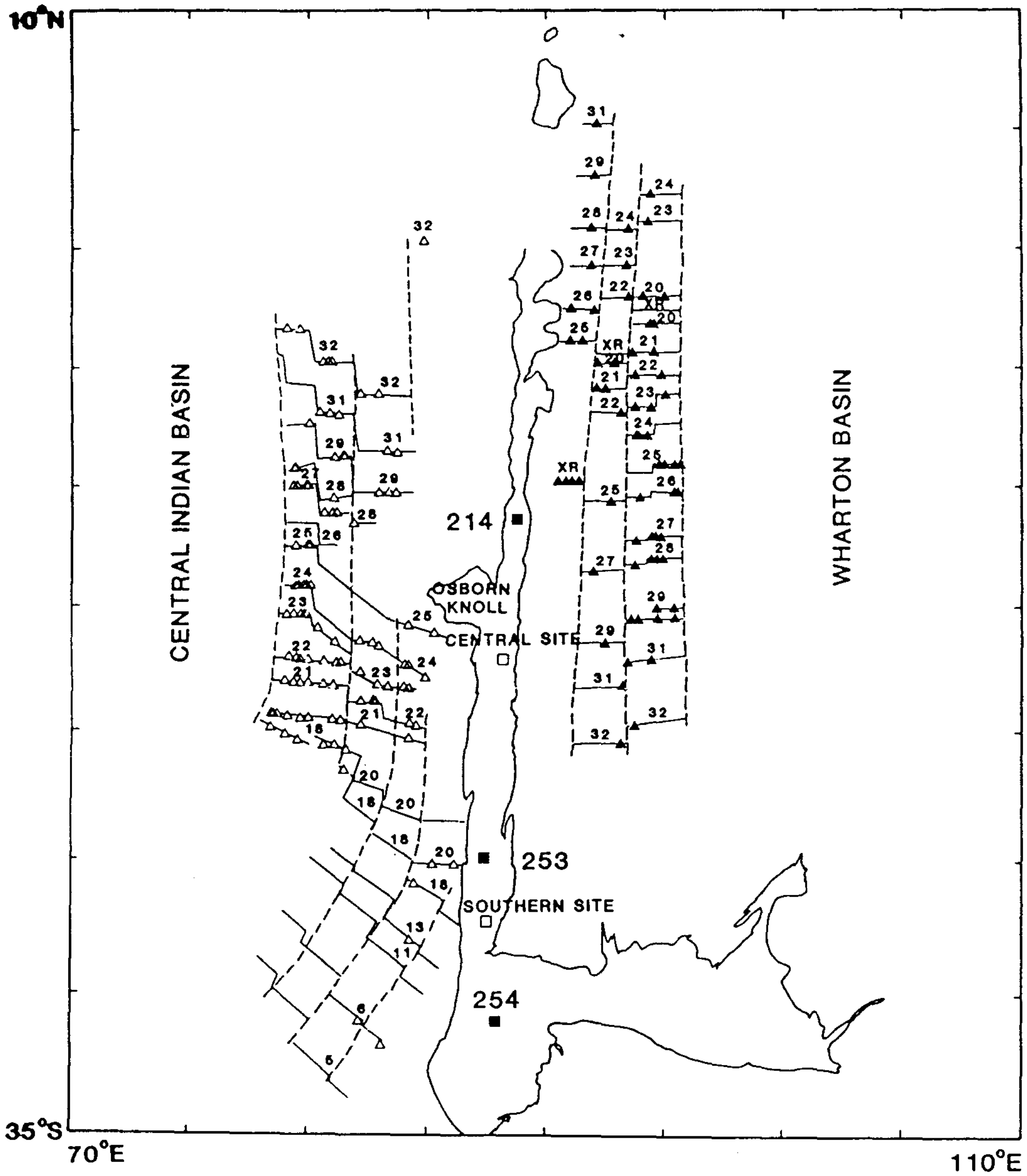

16.90°S
17.00°S
17.10°S
17.20°S
17.30°S
87.90°E
88.00°E
88.10°E
88.20°E
88.30°E
88.40°E

Figure 17. Map of magnetic anomalies in the vicinity of the Ninetyeast Ridge. Extinct ridges are marked by letters XR. Redrawn from Royer, 1987.



10°N
35°S
70°E
110°E
CENTRAL INDIAN BASIN
WHARTON BASIN
214
253
254
OSBORN KNOLL
CENTRAL SITE
SOUTHERN SITE
XR

Figure 18. Seismic section of the W-E line which crosses suggested drilling site 1 at shot point 2192 (line crossing 6866). The central Ninetyeast Ridge survey area. Both interpreted and uninterpreted sections are shown. Times are in seconds of two-way travel time.

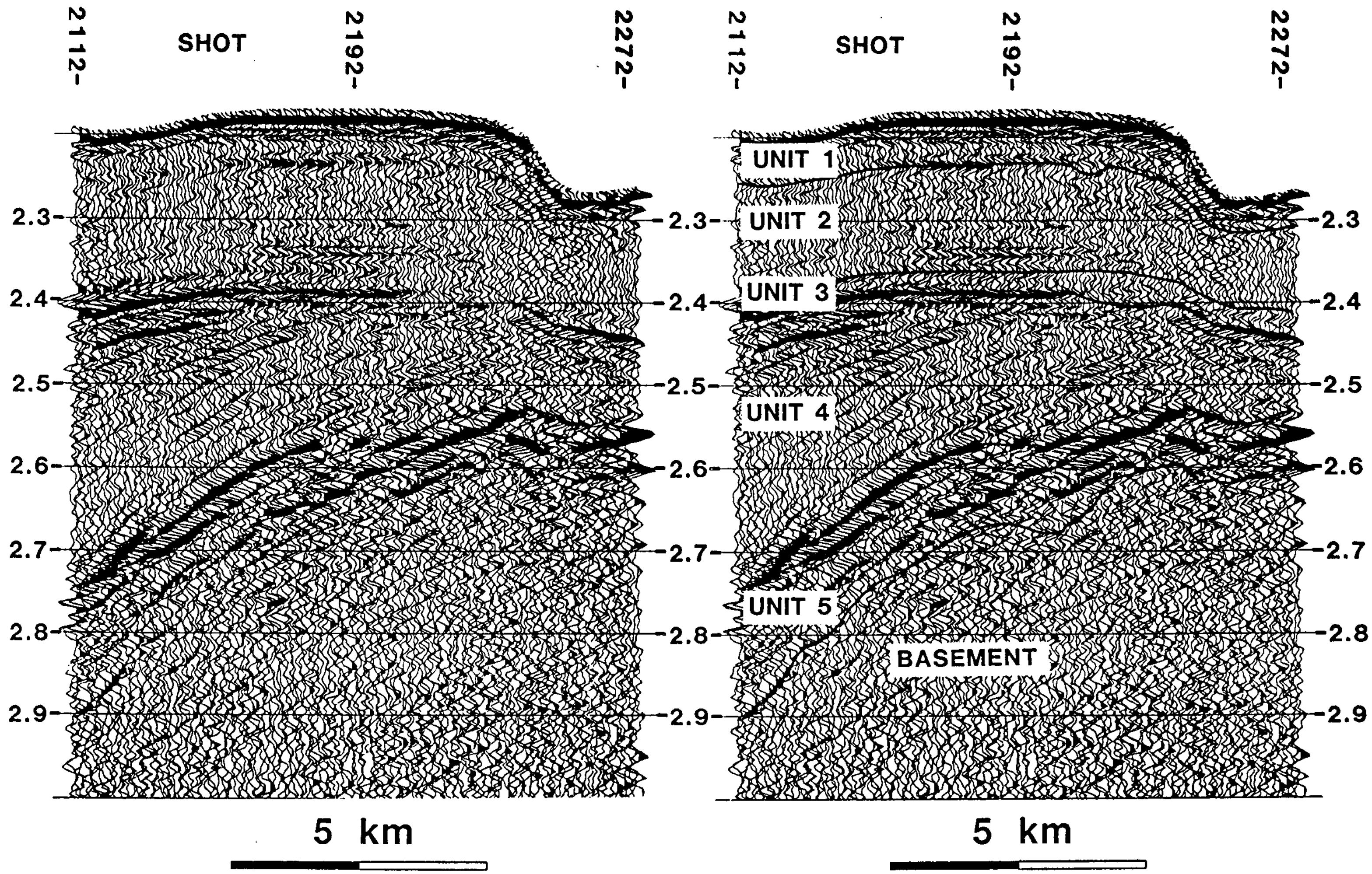

SHOT
2112
2192
2272
2.3
2.4
2.5
2.6
2.7
2.8
2.9
UNIT 1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
BASEMENT
5 km

Figure 19. Seismic section of the N-S line which crosses suggested drilling site 1 at shot point 6866 (line crossing 2192). The central Ninetyeast Ridge survey area.

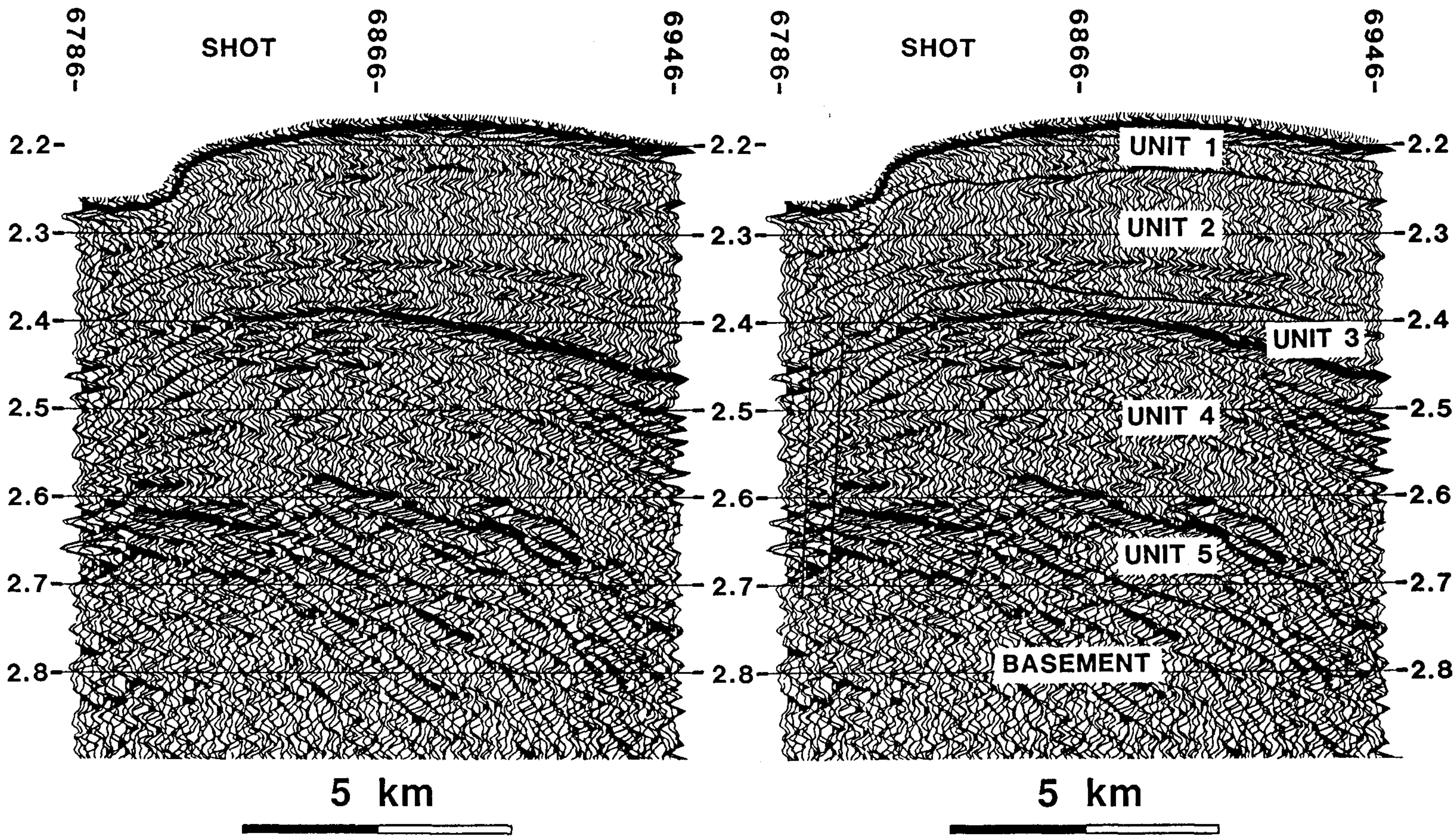

6786
SHOT
6866
6946
2.2
2.3
2.4
2.5
2.6
2.7
2.8
5 km
6786
SHOT
6866
6946
UNIT 1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
BASEMENT
2.2
2.3
2.4
2.5
2.6
2.7
2.8
5 km

Figure 20. Seismic section of the W-E line which crosses suggested drilling site 2 at shot point 3113 (line crossing 4219). The central Ninetyeast Ridge survey area.

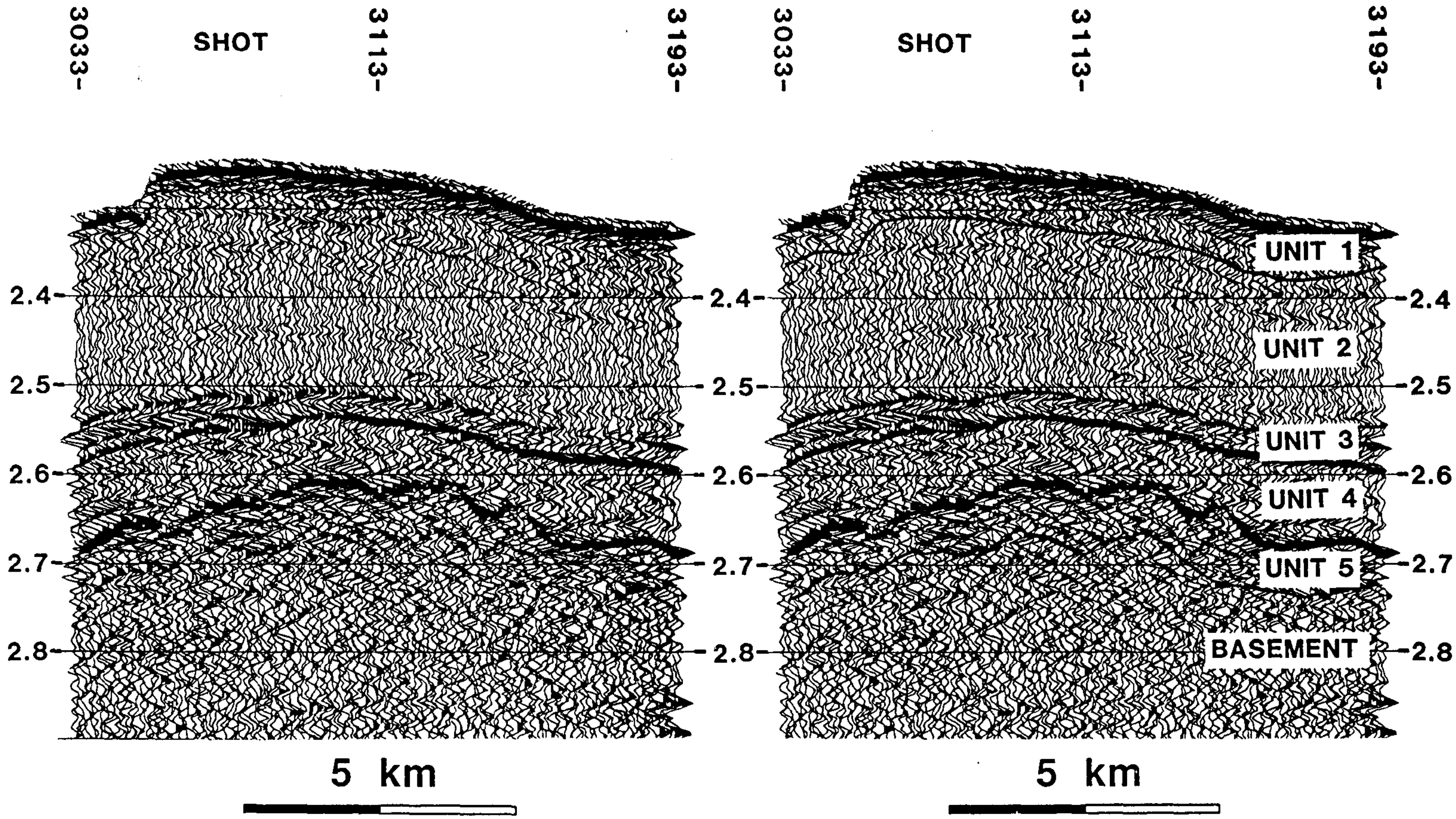

3033-
SHOT
3113-
3193-
3033-
SHOT
3113-
3193-
2.4
2.5
2.6
2.7
2.8
UNIT 1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
BASEMENT
5 km
5 km

Figure 21. Seismic section of the S-N line which crosses suggested drilling site 2 at shot point 4219 (line crossing 3113). The central Ninetyeast Ridge survey area.

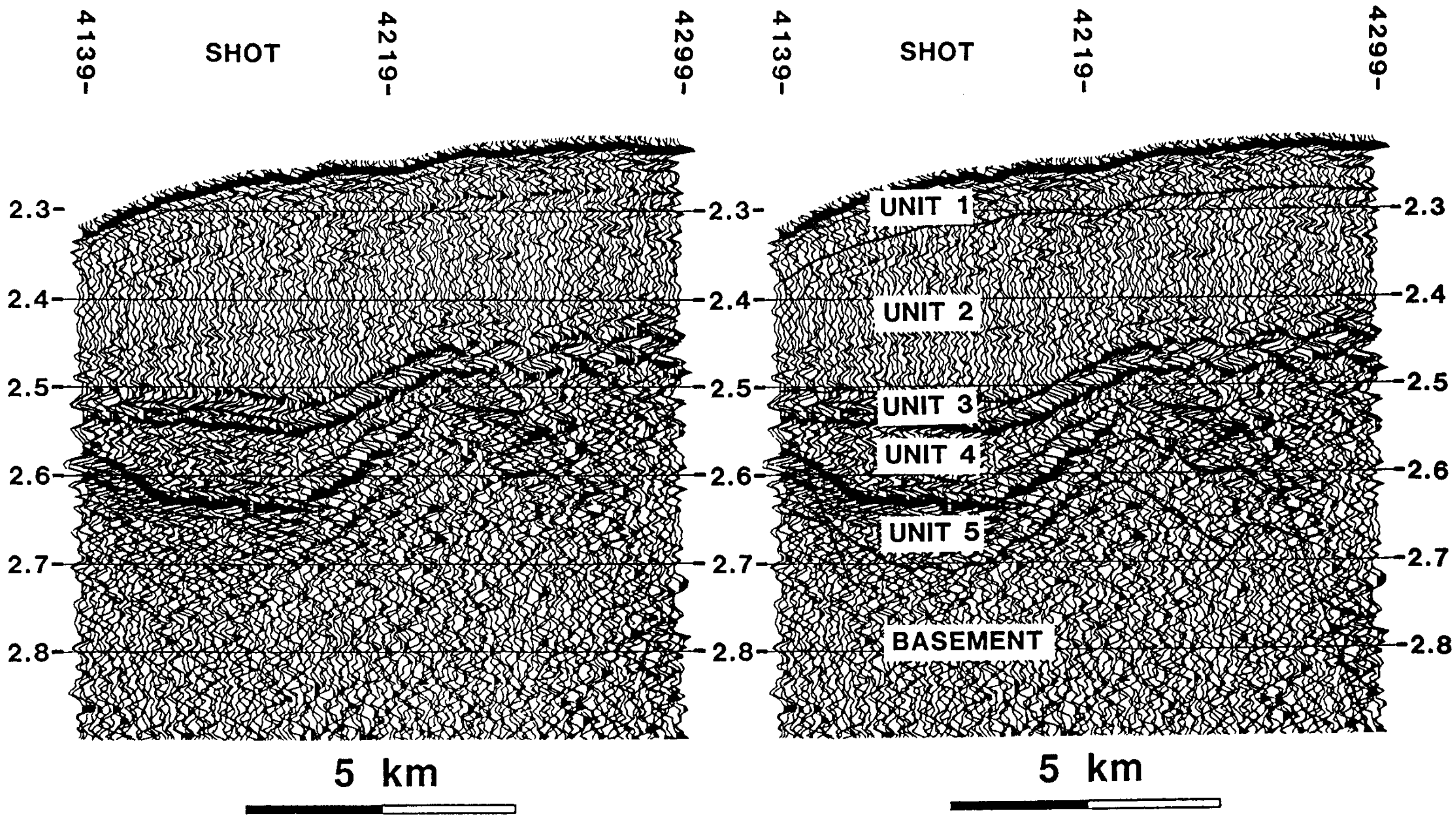
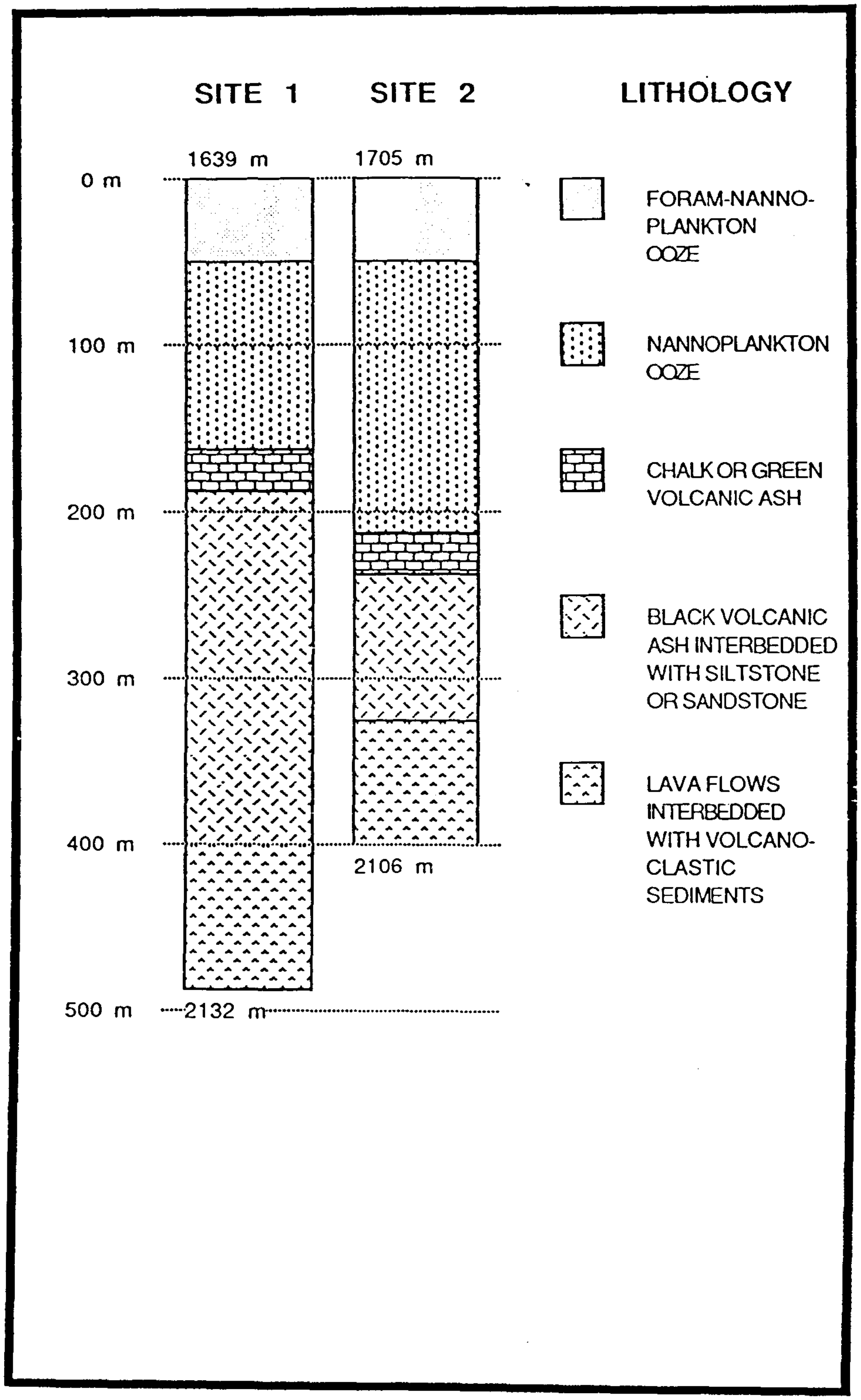

SHOT
4139-
4219-
4299-
2.3
2.4
2.5
2.6
2.7
2.8
5 km
SHOT
4139-
4219-
4299-
UNIT 1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
BASEMENT
2.3
2.4
2.5
2.6
2.7
2.8
5 km

Figure 22. Estimated stratigraphic columns of the suggested drilling sites for the central Ninetyeast Ridge survey area.



SITE 1
SITE 2
LITHOLOGY
1639 m
1705 m
0 m
100 m
200 m
300 m
400 m
500 m
2106 m
2132 m
FORAM-NANNO-PLANKTON OOZE
NANNOPLANKTON OOZE
CHALK OR GREEN VOLCANIC ASH
BLACK VOLCANIC ASH INTERBEDDED WITH SILTSTONE OR SANDSTONE
LAVA FLOWS INTERBEDDED WITH VOLCANO-CLASTIC SEDIMENTS

Figure 23. Ship's track with shot numbers and bathymetry of the southern Ninetyeast Ridge survey area. Bathymetry contour interval is 100 m. The letters designate track turns. Circles with numbers show positions of the suggested survey sites. Diamonds with letter S show positions of the sonobuoy refraction surveys.

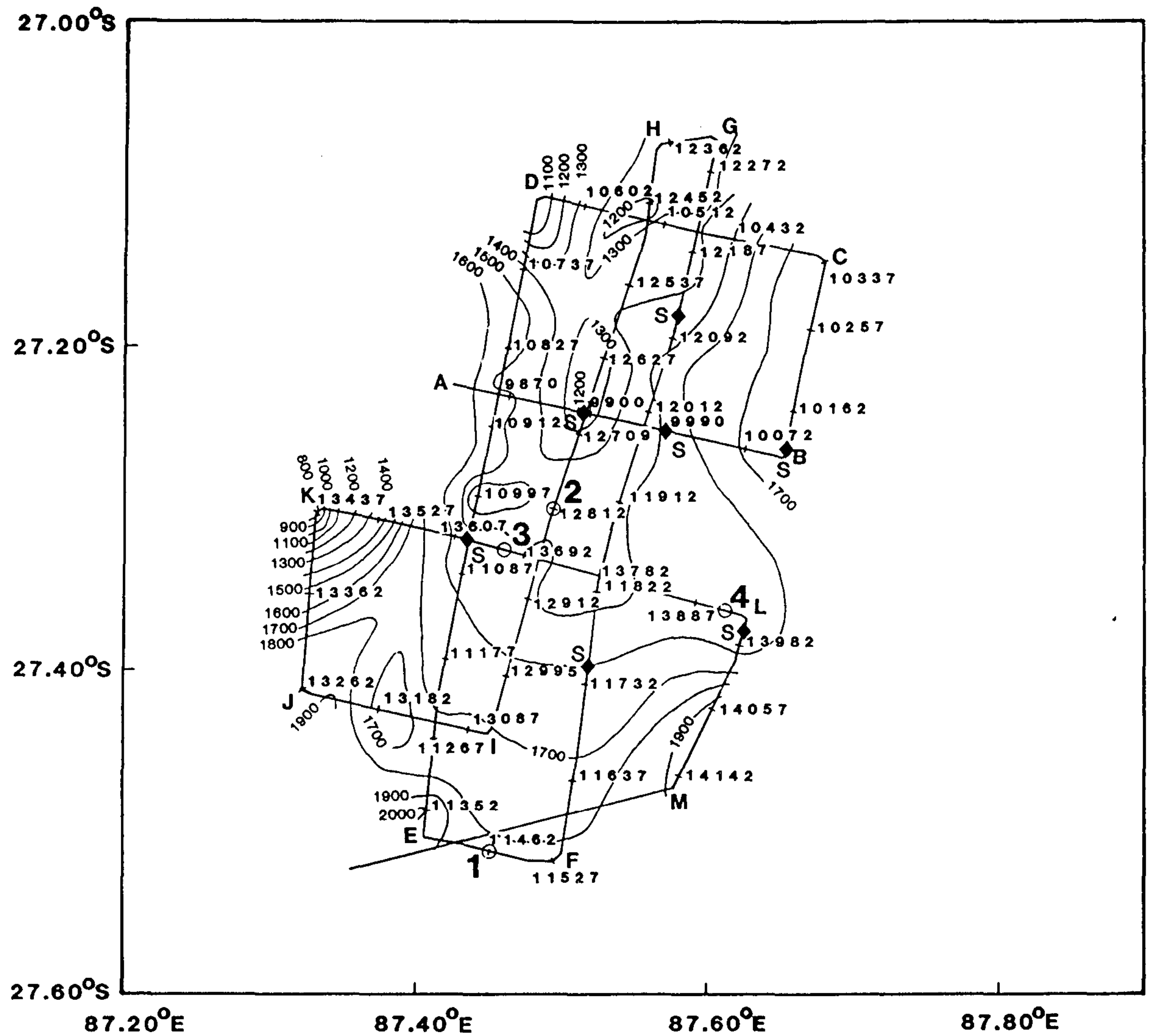

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
S
10337
10257
10162
10072
10432
12272
12362
10602
12452
10512
12187
10737
12537
12092
10827
12627
9870
9900
12012
9990
10912
12709
10997
11912
12812
13437
13527
13607
13692
11087
13782
11822
12912
13887
13982
13362
11177
12995
11732
14057
13262
13182
13087
11267
11637
14142
11352
11462
11527
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

Figure 24. Total sediment thickness map for the southern Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 100 meters. Ship's track is drawn in dashed line. Letters designate the track turns. Circles with numbers show the positions of the suggested drilling sites.

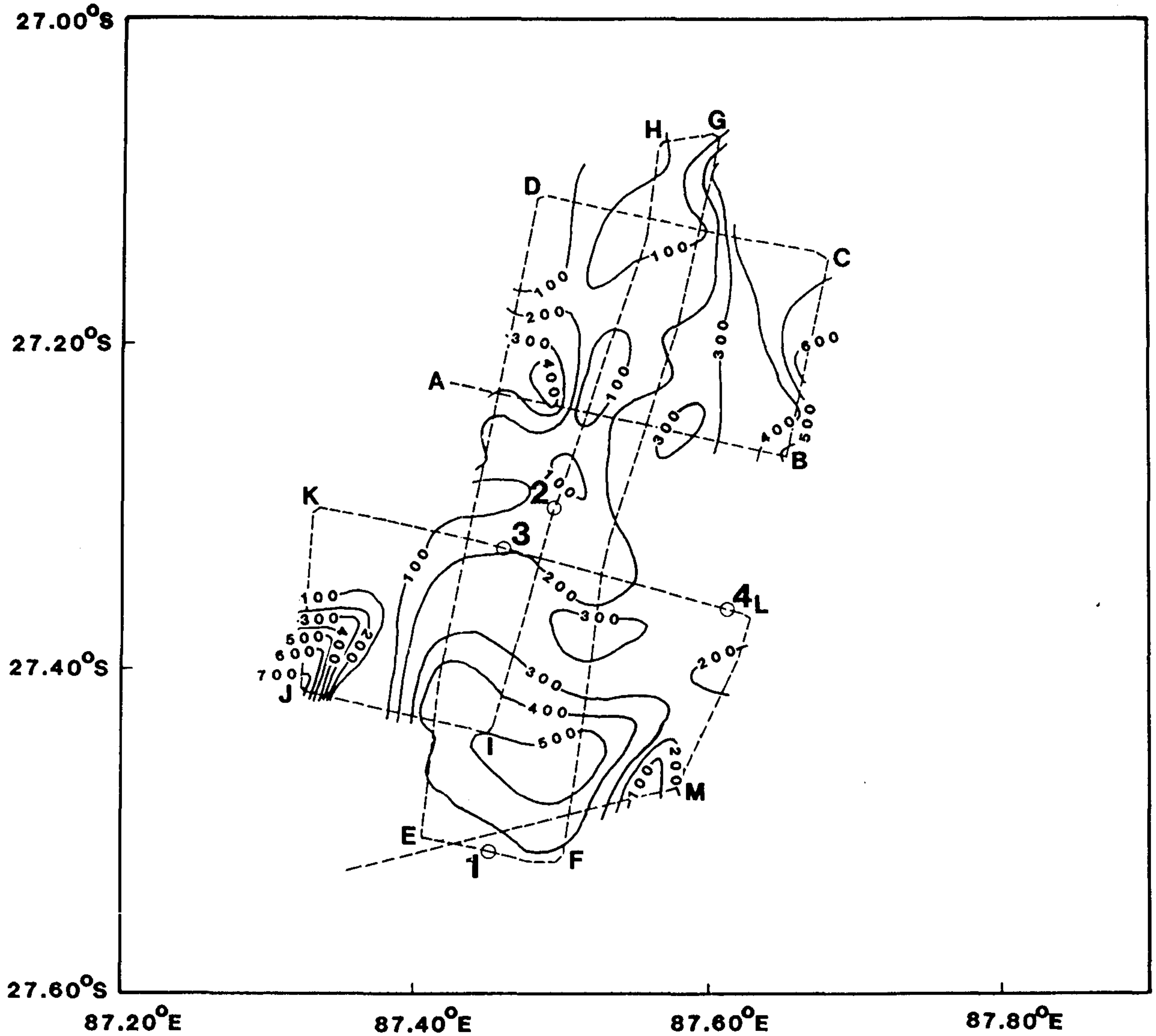

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
100
200
300
400
500
600
700

Figure 25. Stratigraphic column of DSDP site 254 and stratigraphic column (stratigraphy is estimated) of the suggested drilling site # 3 at the southern site survey area with appropriate correlations to the seismic profiles. Times are in seconds of TWT. The stratigraphies of the two sites are tied together.

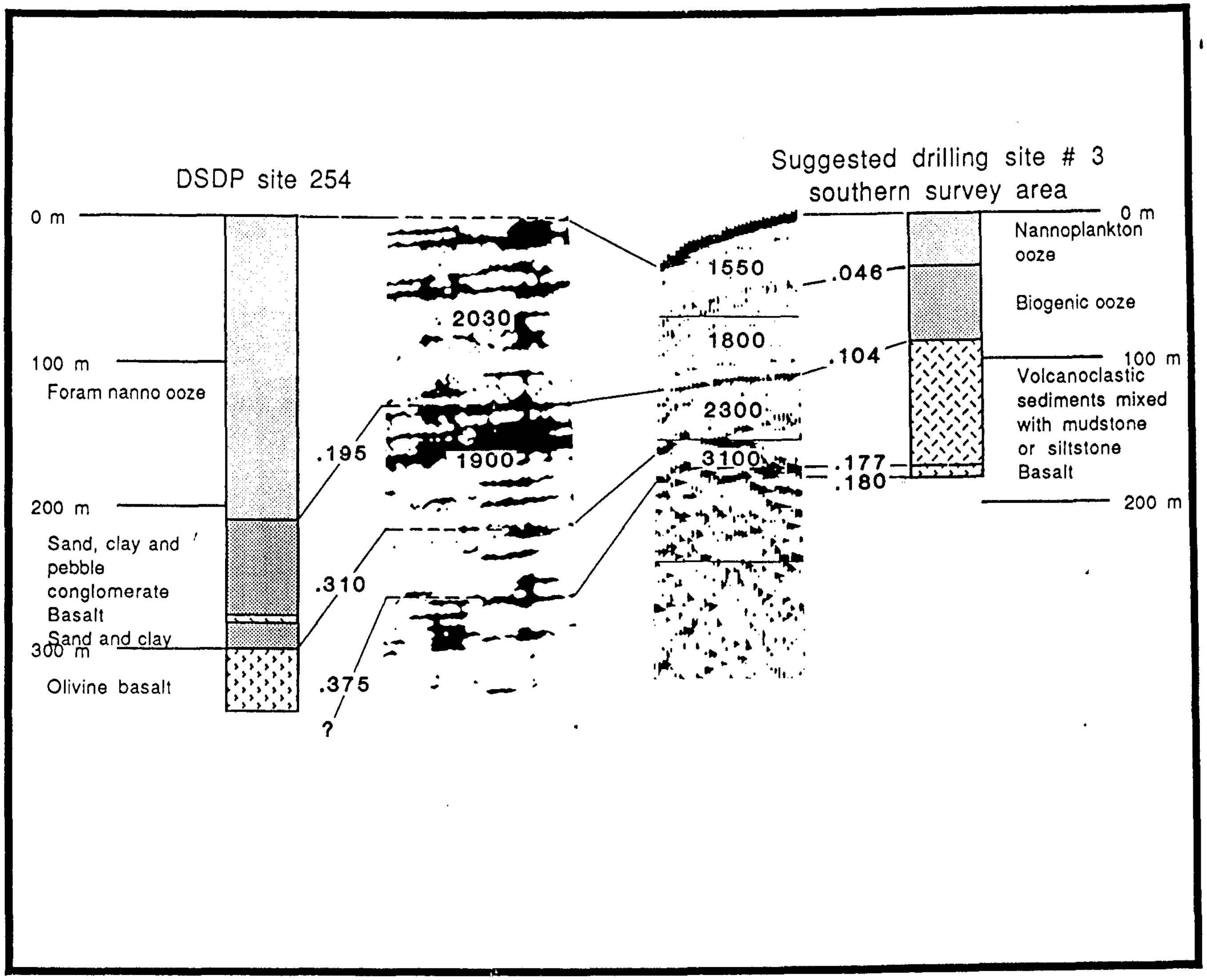

DSDP site 254
Suggested drilling site # 3
southern survey area
0 m
100 m
Foram nanno ooze
200 m
Sand, clay and
pebble
conglomerate
Basalt
Sand and clay
300 m
Olivine basalt
.195
.310
.375
?
2030
1900
1550
1800
2300
3100
.046
.104
.177
.180
0 m
Nannoplankton
ooze
Biogenic ooze
100 m
Volcanoclastic
sediments mixed
with mudstone
or siltstone
Basalt
200 m

Figure 26. Cumulative sediment thickness map of the seismostratigraphic units 1 - 2 (upper group) for the southern Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 50 meters.

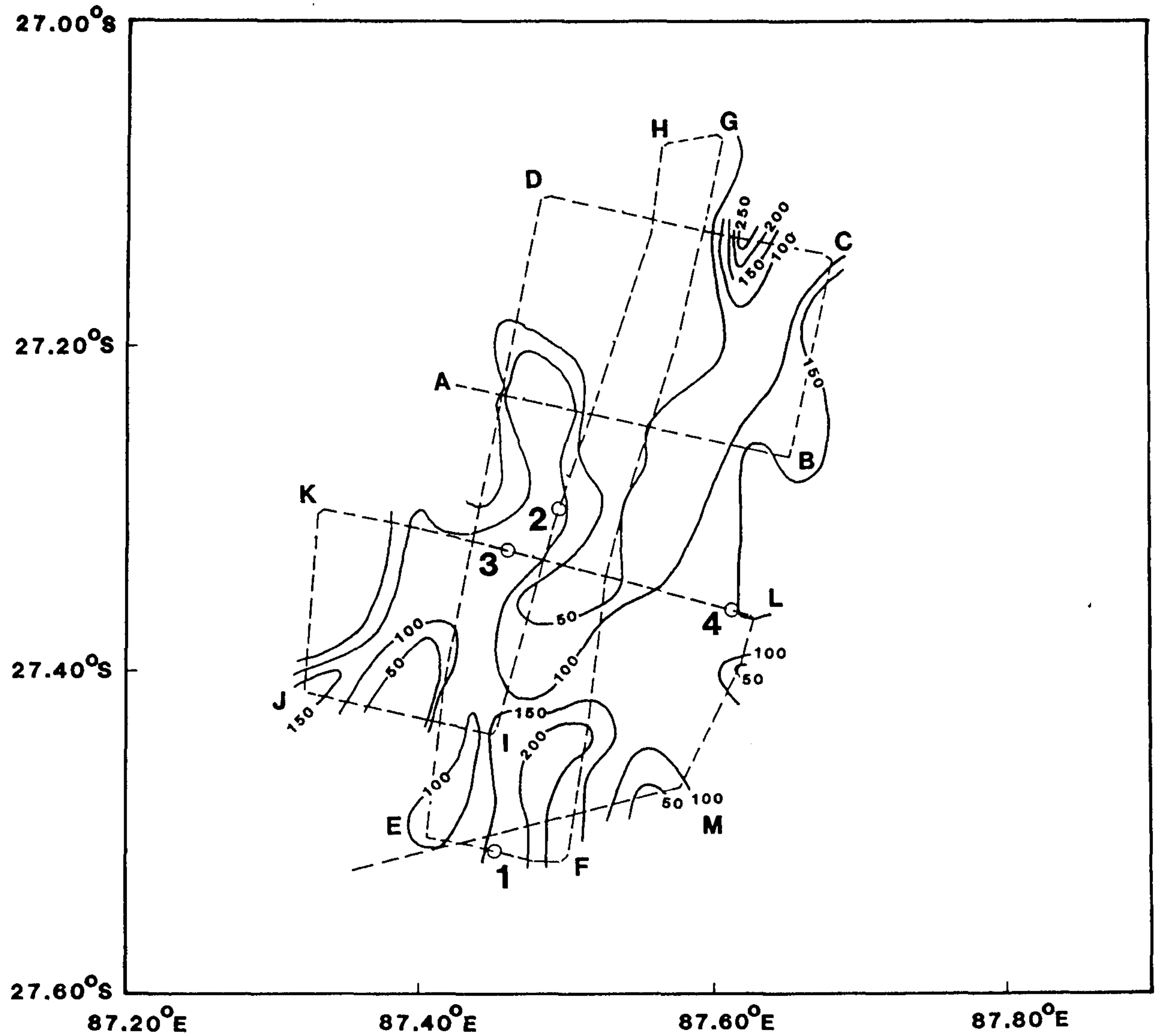

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
50
100
150
200
250

Figure 27. Sediment thickness map of unit 3 (lower group) for the southern Ninetyeast Ridge survey area. Sediment thickness is in meters. Contour interval is 50 m. Ship's track is drawn with a dashed line. Letters designate the track turns. Circles with numbers show the positions of the suggested drilling sites.

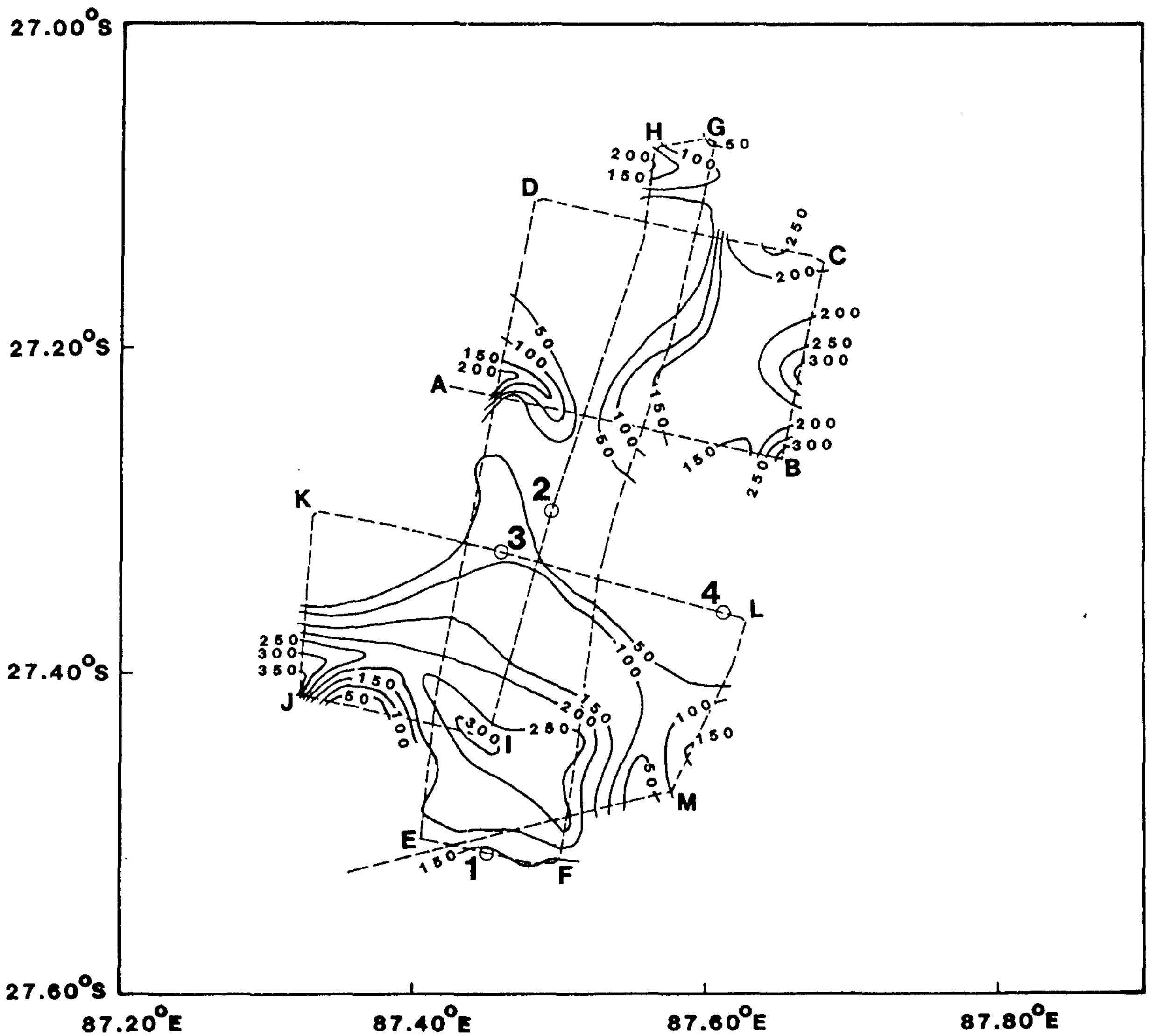

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4

Figure 28. Isochron map of the top of the third layer - southern Ninetyeast Ridge survey area. Isochrons are in msec of TWT. Contour interval is 100 msec.

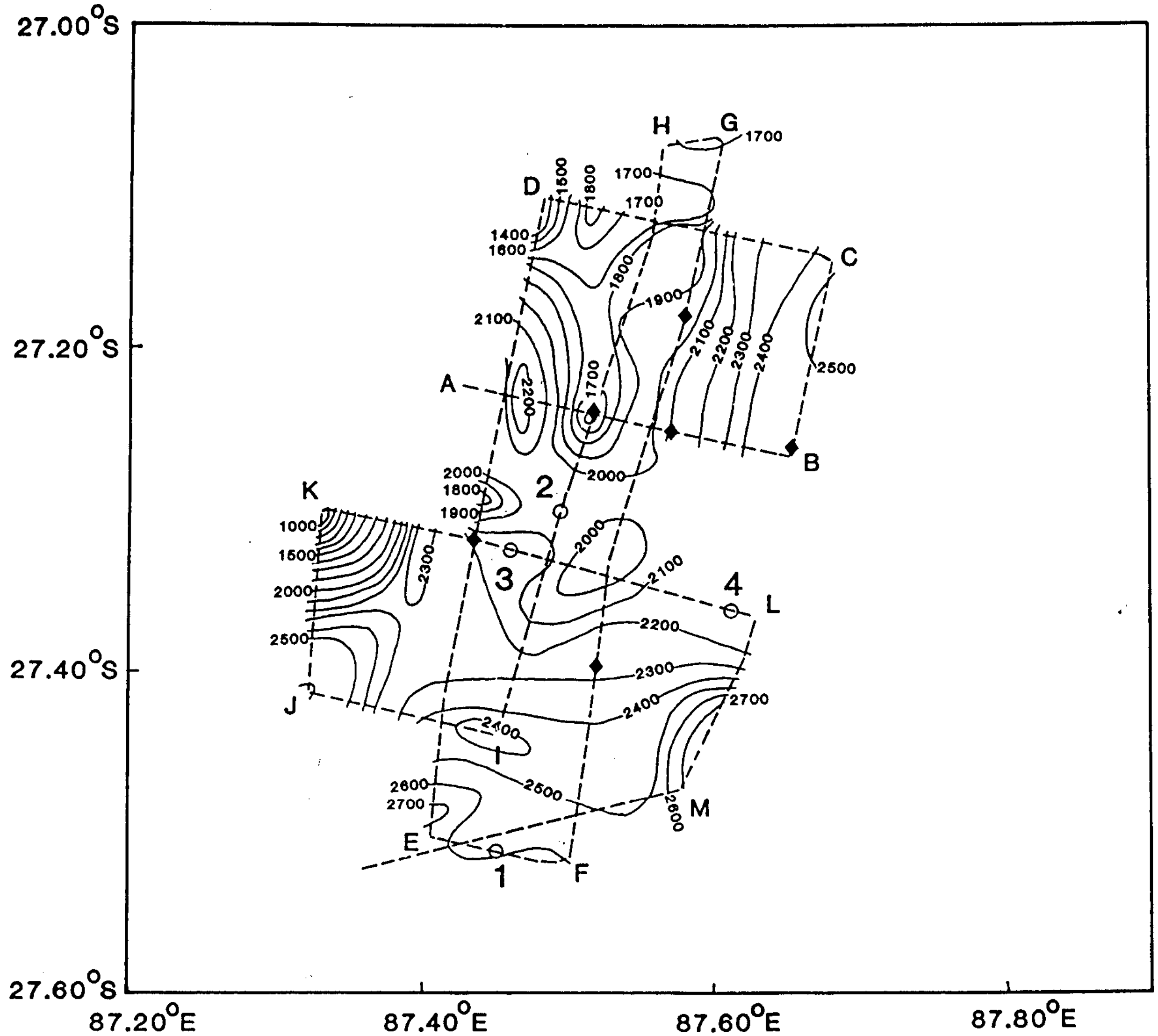

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
J
K
L
M
1
2
3
4
1000
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700

Figure 29. Depth of the surface of the fourth layer for the southern Ninetyeast Ridge survey area. Depths are in uncorrected meters. Contour interval is 100 meters. Ship's track is drawn in dashed line. Letters designate the track turns. Circles with numbers show the positions of the suggested drilling sites.

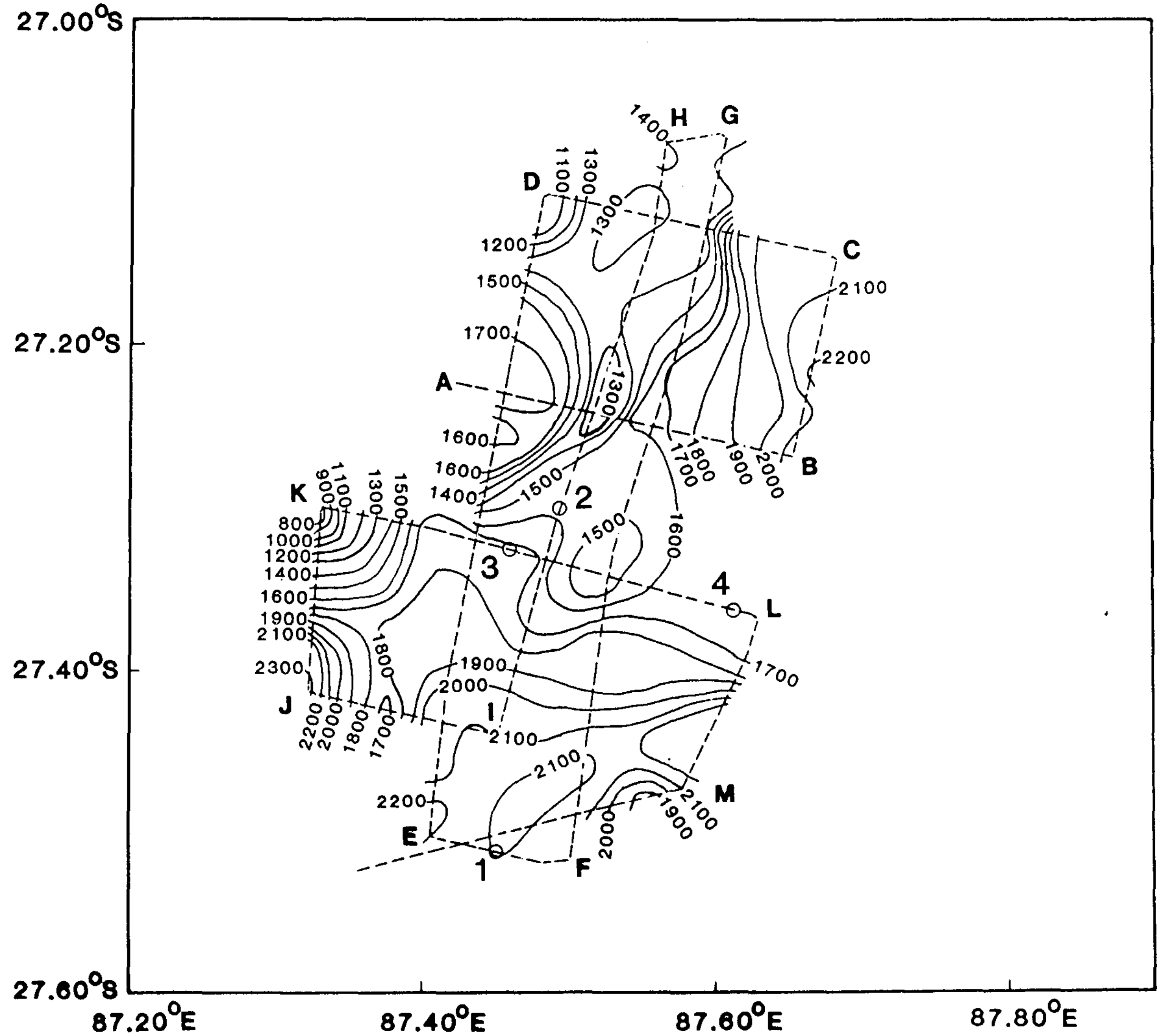

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4

Figure 30. Isochron map of the top of the fourth layer - southern Ninetyeast Ridge survey area. Isochrons are in msec of TWT. Contour interval is 100 msec.

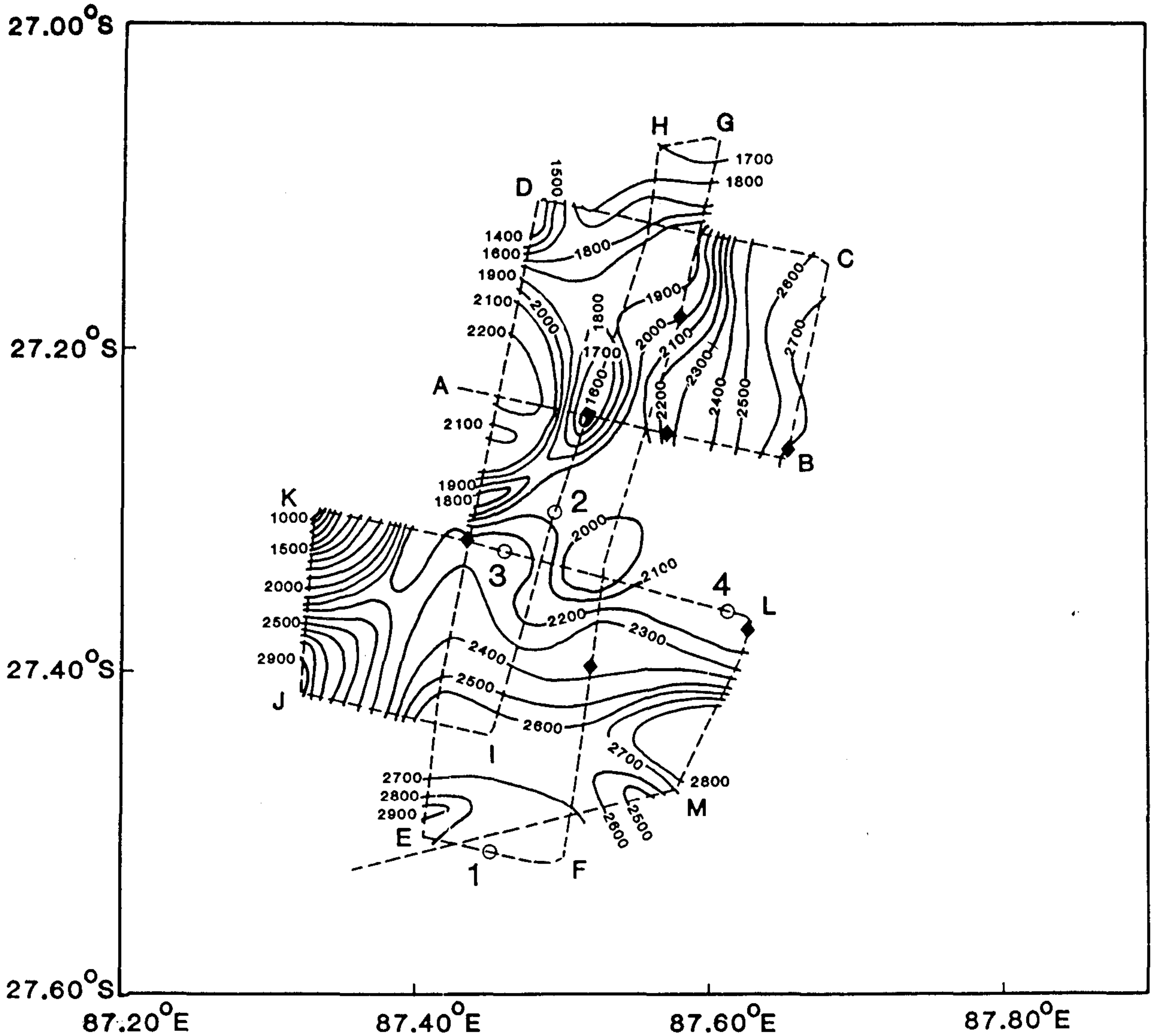

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
1000
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900

Figure 31. Depth of the basement for the southern Ninetyeast Ridge. Depths are in uncorrected meters. Contour interval is 100 meters. The ship's track is drawn with a dashed line. Letters designate the track turns. Circles with numbers show the positions of the suggested drilling sites.

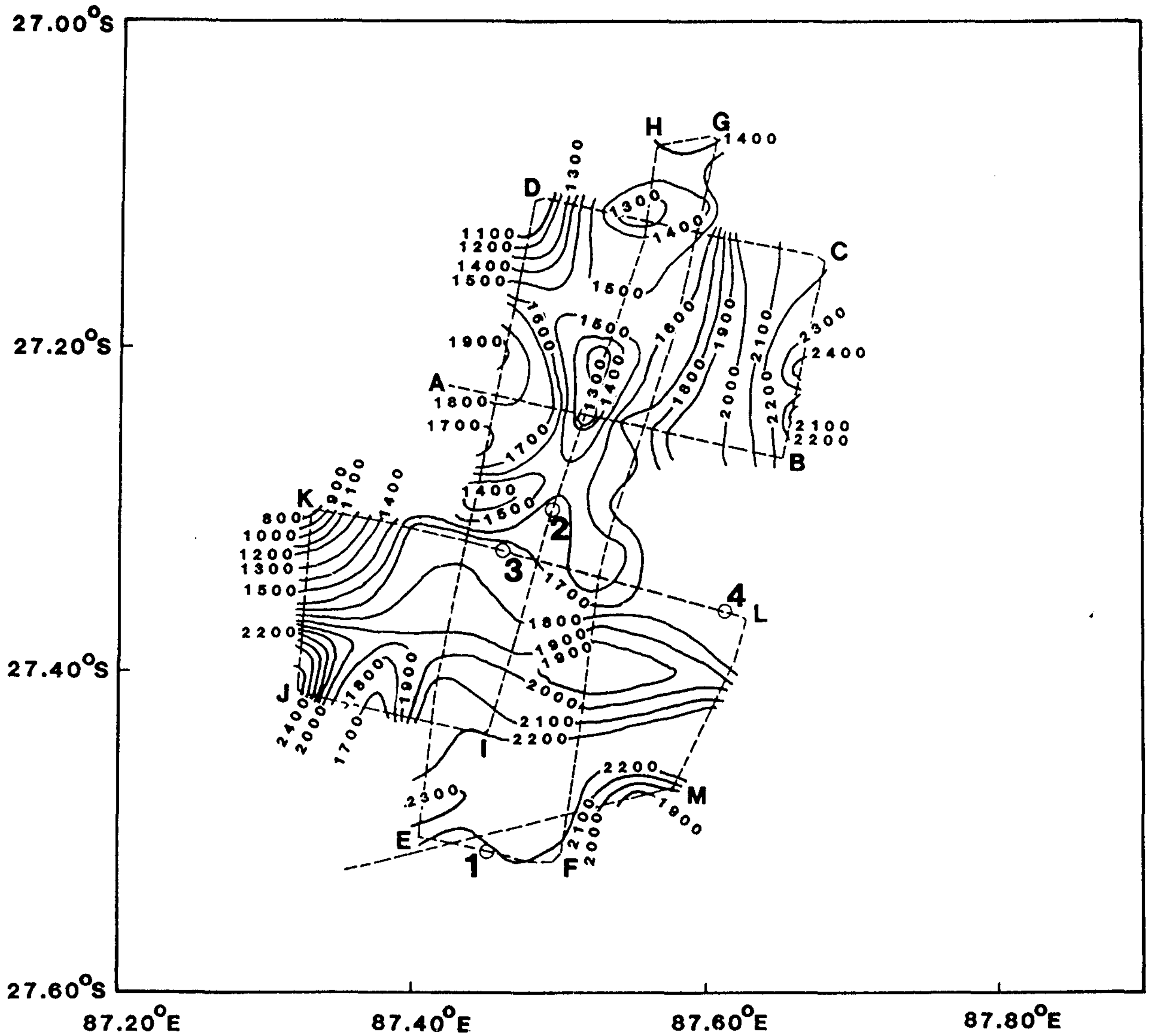

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4

Figure 32. Map of residual magnetic field - southern survey area. Units of the magnetic field are gammas. Contour interval is 50 gammas.

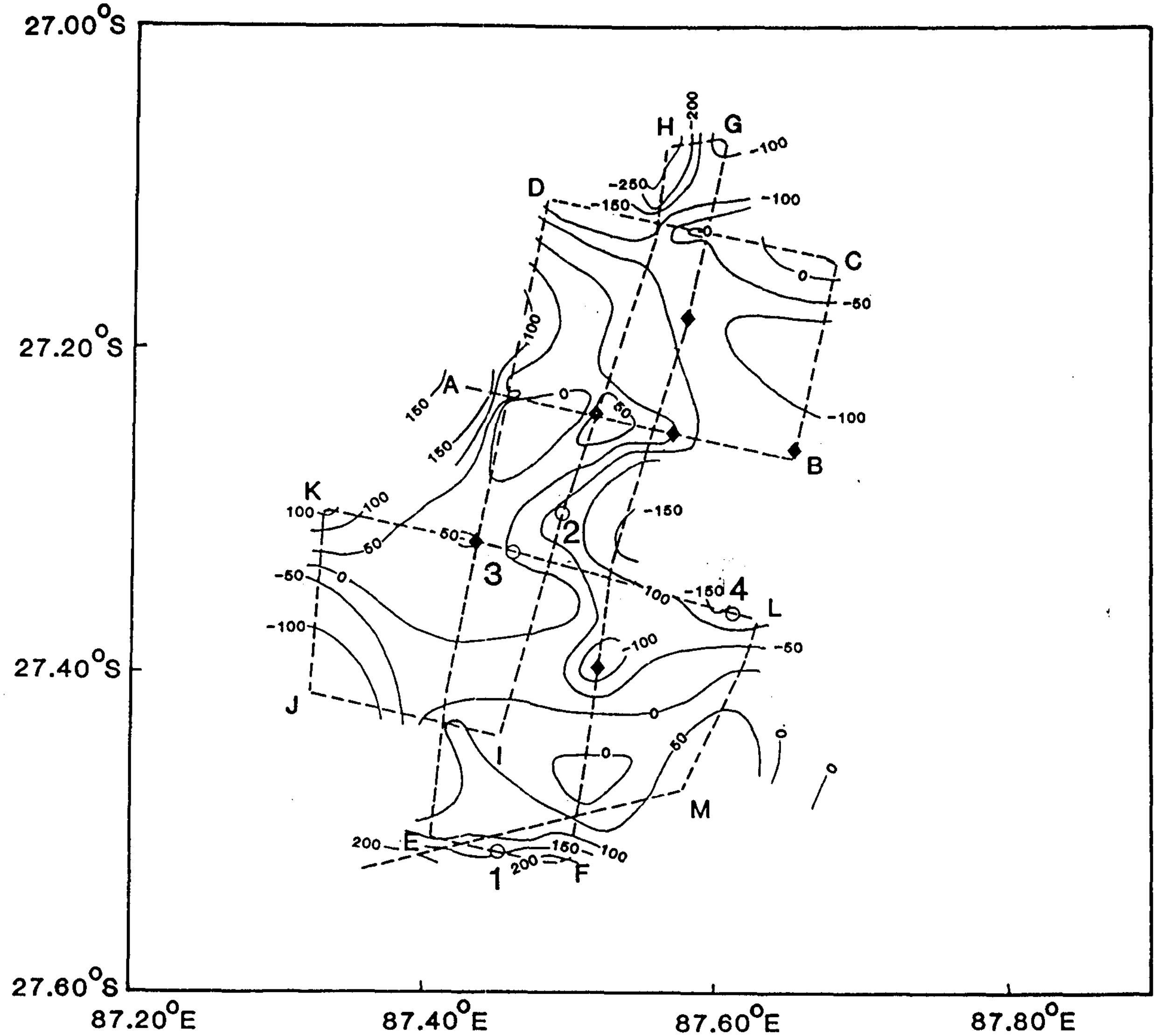

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
-250
-200
-150
-100
-50
0
50
100
150
200

Figure 33. Map of residual gravity field - southern survey area. Units are mgals. Contour interval is 10 mgals.

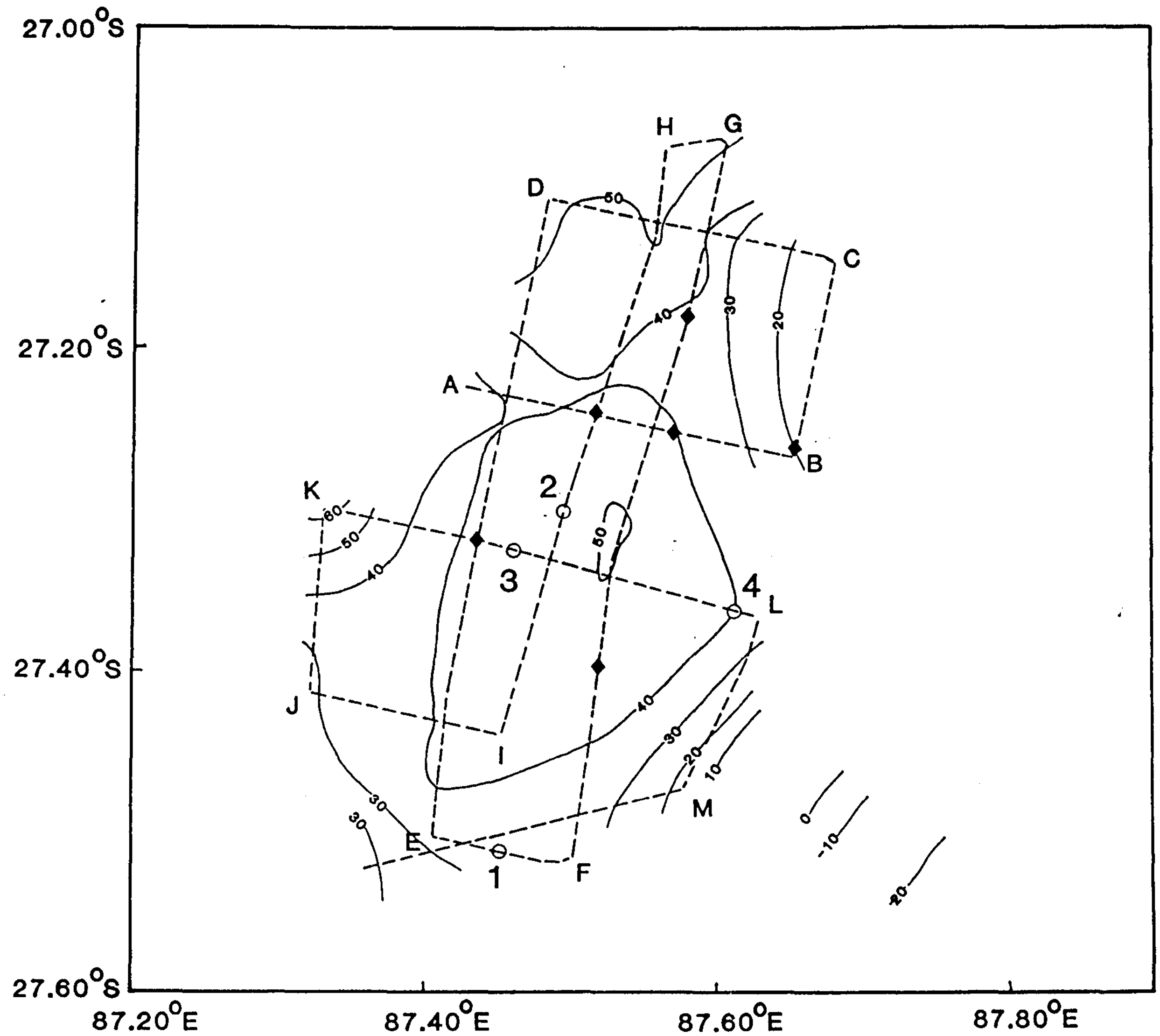

27.00°S
27.20°S
27.40°S
27.60°S
87.20°E
87.40°E
87.60°E
87.80°E
A
B
C
D
E
F
G
H
I
J
K
L
M
1
2
3
4
50
40
30
20
10
0
-10
-20
60

Figure 34. Estimated stratigraphic columns of the suggested drilling sites for the southern Ninetyeast Ridge survey area.

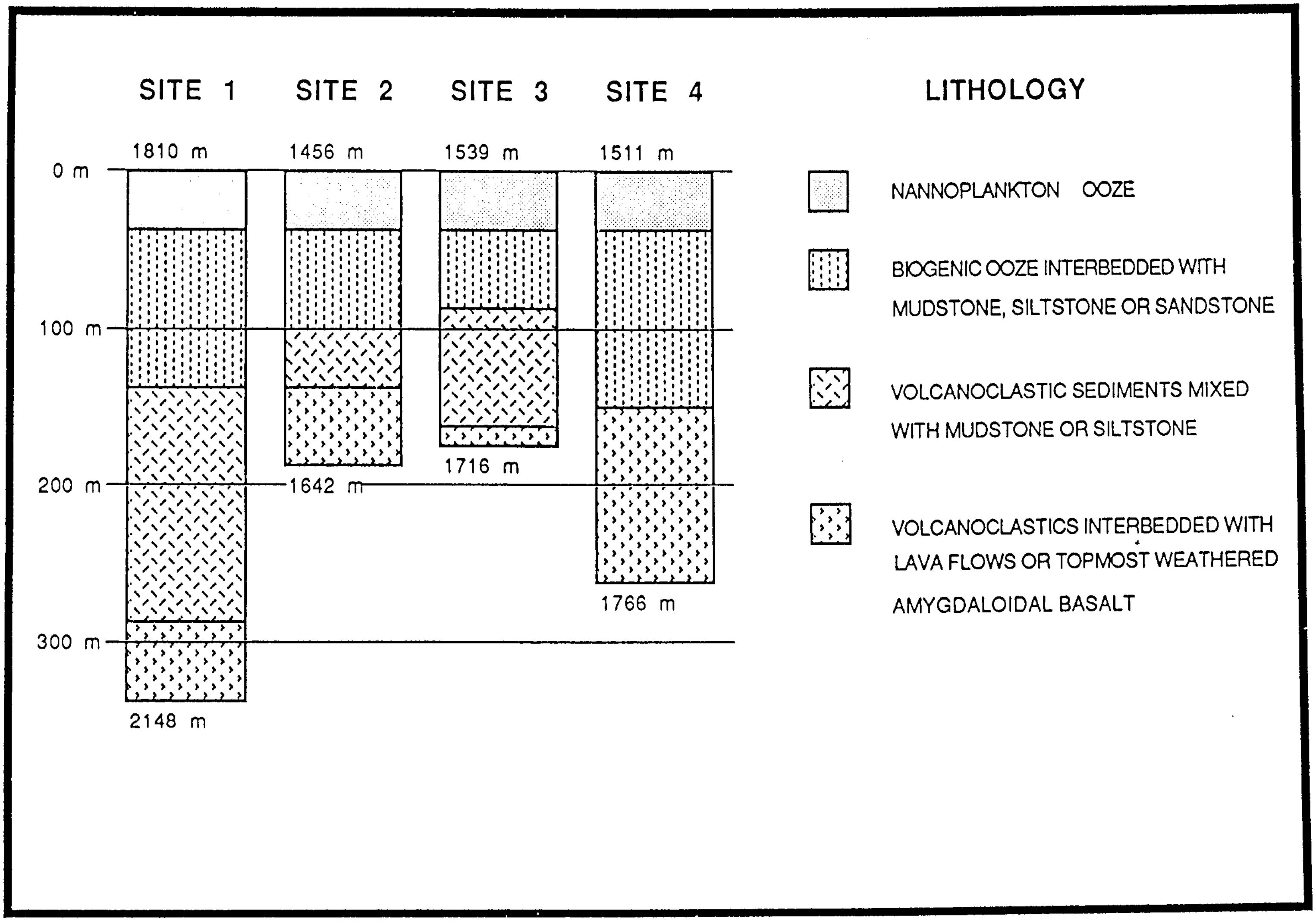

SITE 1
SITE 2
SITE 3
SITE 4
LITHOLOGY
1810 m
1456 m
1539 m
1511 m
0 m
100 m
200 m
300 m
1642 m
1716 m
1766 m
2148 m
NANNOPLANKTON OOZE
BIOGENIC OOZE INTERBEDDED WITH MUDSTONE, SILTSTONE OR SANDSTONE
VOLCANOCLASTIC SEDIMENTS MIXED WITH MUDSTONE OR SILTSTONE
VOLCANOCLASTICS INTERBEDDED WITH LAVA FLOWS OR TOPMOST WEATHERED AMYGDALOIDAL BASALT

Figure 35. Seismic section of the W-E line which crosses suggested drilling site 1 at shot point 11462. The southern Ninetyeast Ridge survey area. Both interpreted and uninterpreted sections are shown. Times are in seconds of two-way travel time.

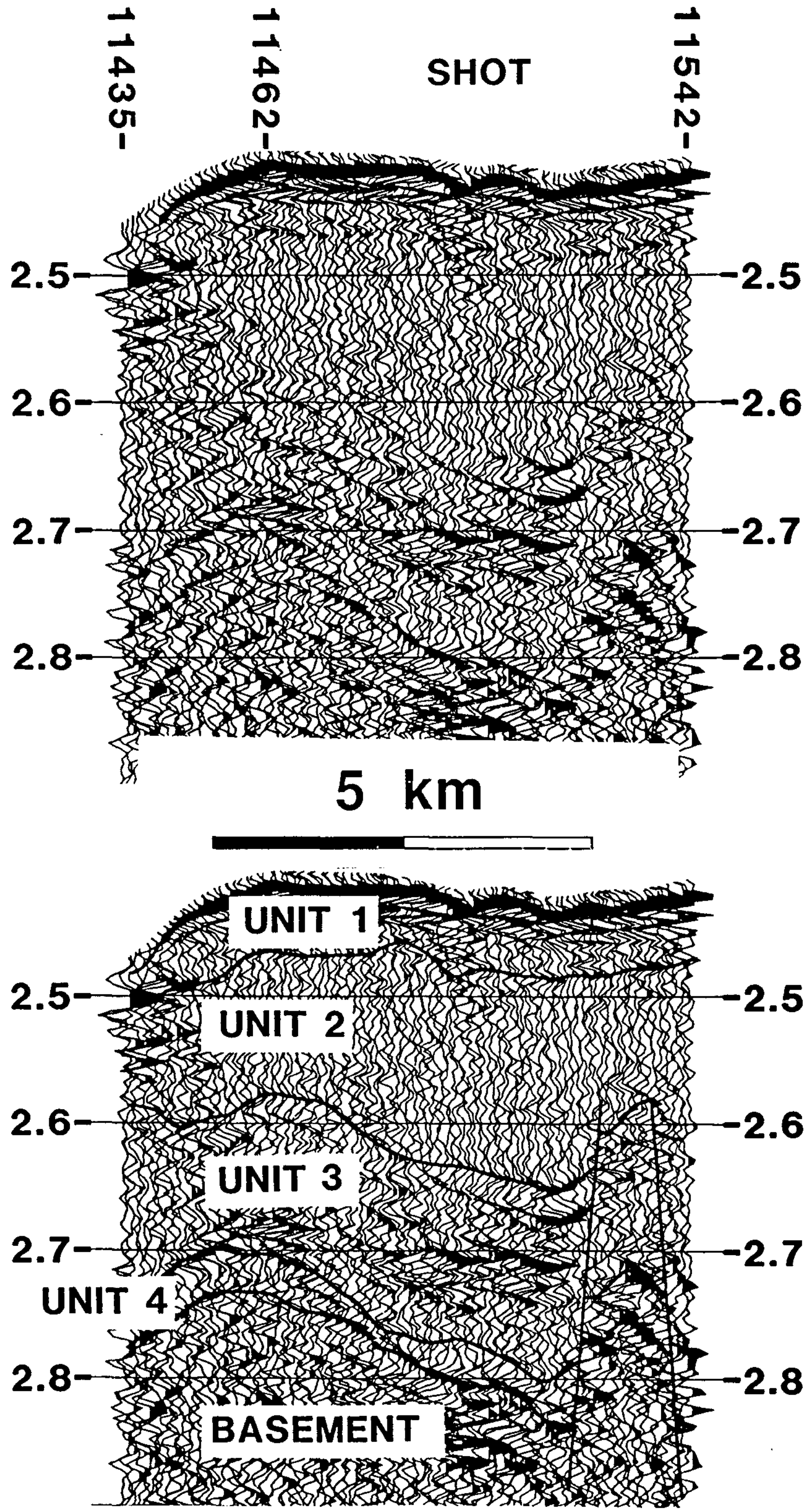
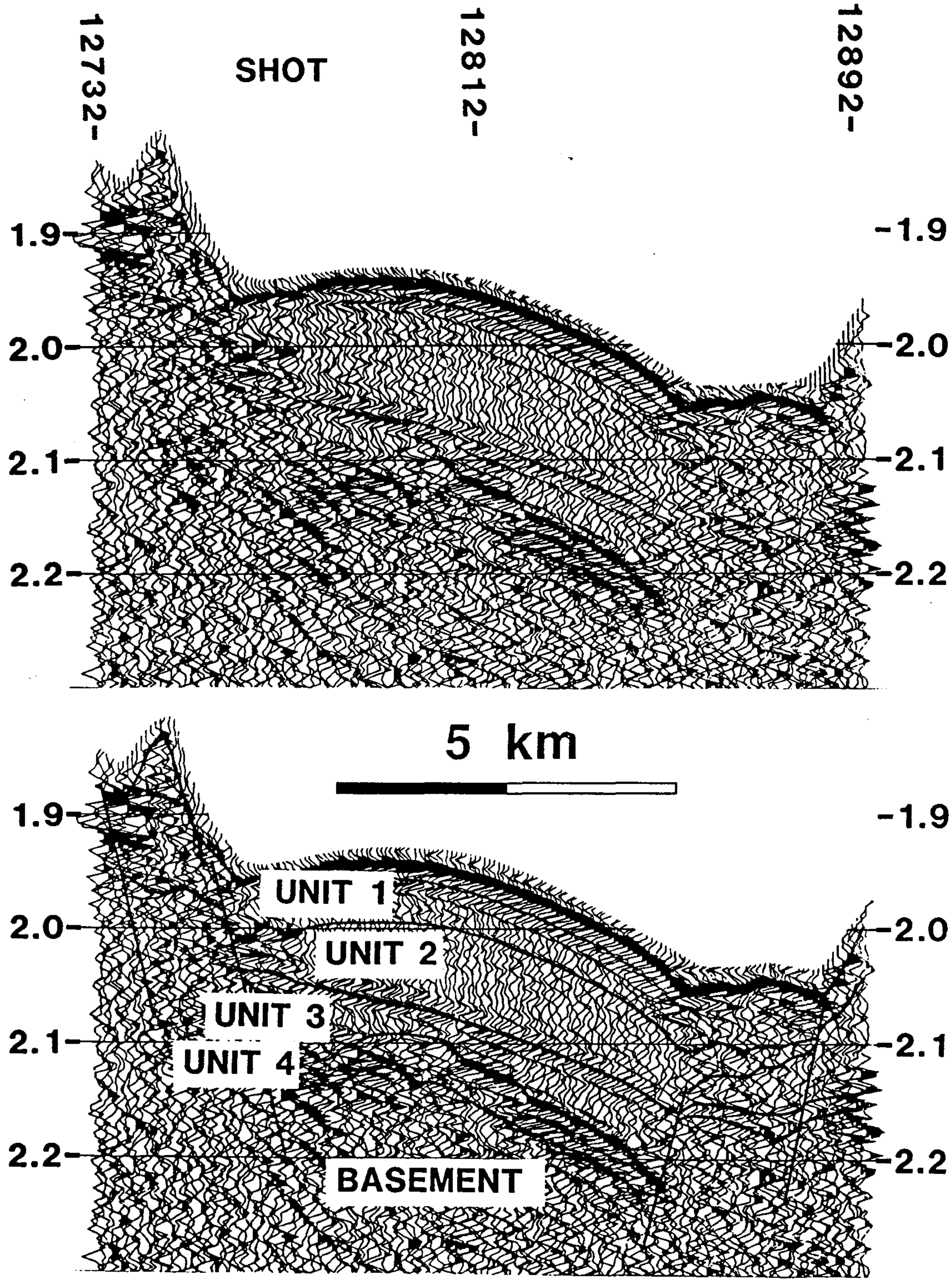
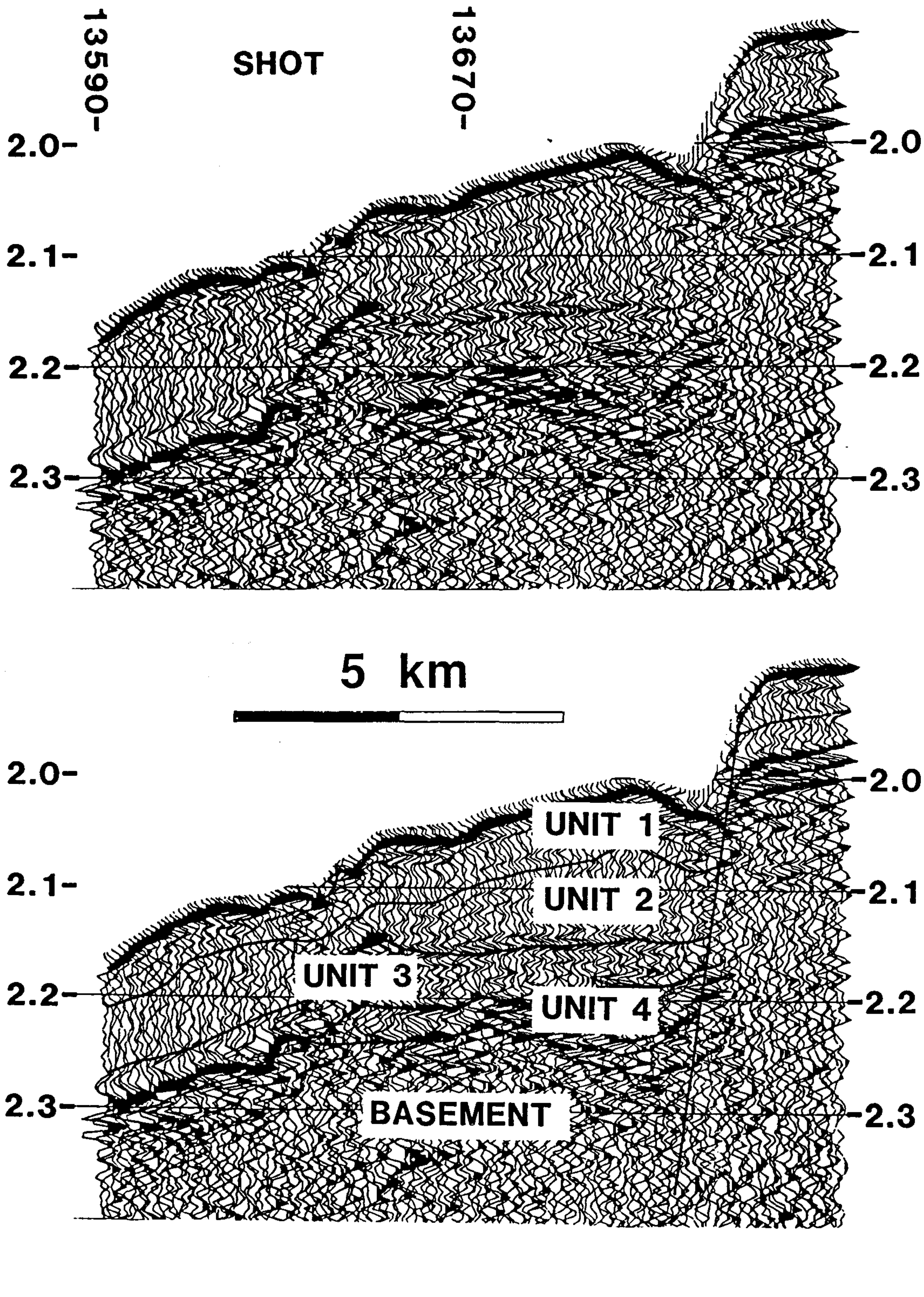

11435-
11462-
SHOT
11542-
2.5
2.6
2.7
2.8
5 km
UNIT 1
UNIT 2
UNIT 3
UNIT 4
BASEMENT

Figure 36. Seismic section of the N-S line which crosses suggested drilling site 2 at shot point 12812. The southern Ninetyeast Ridge survey area. Both interpreted and uninterpreted sections are shown. Times are in seconds of two-way travel time.

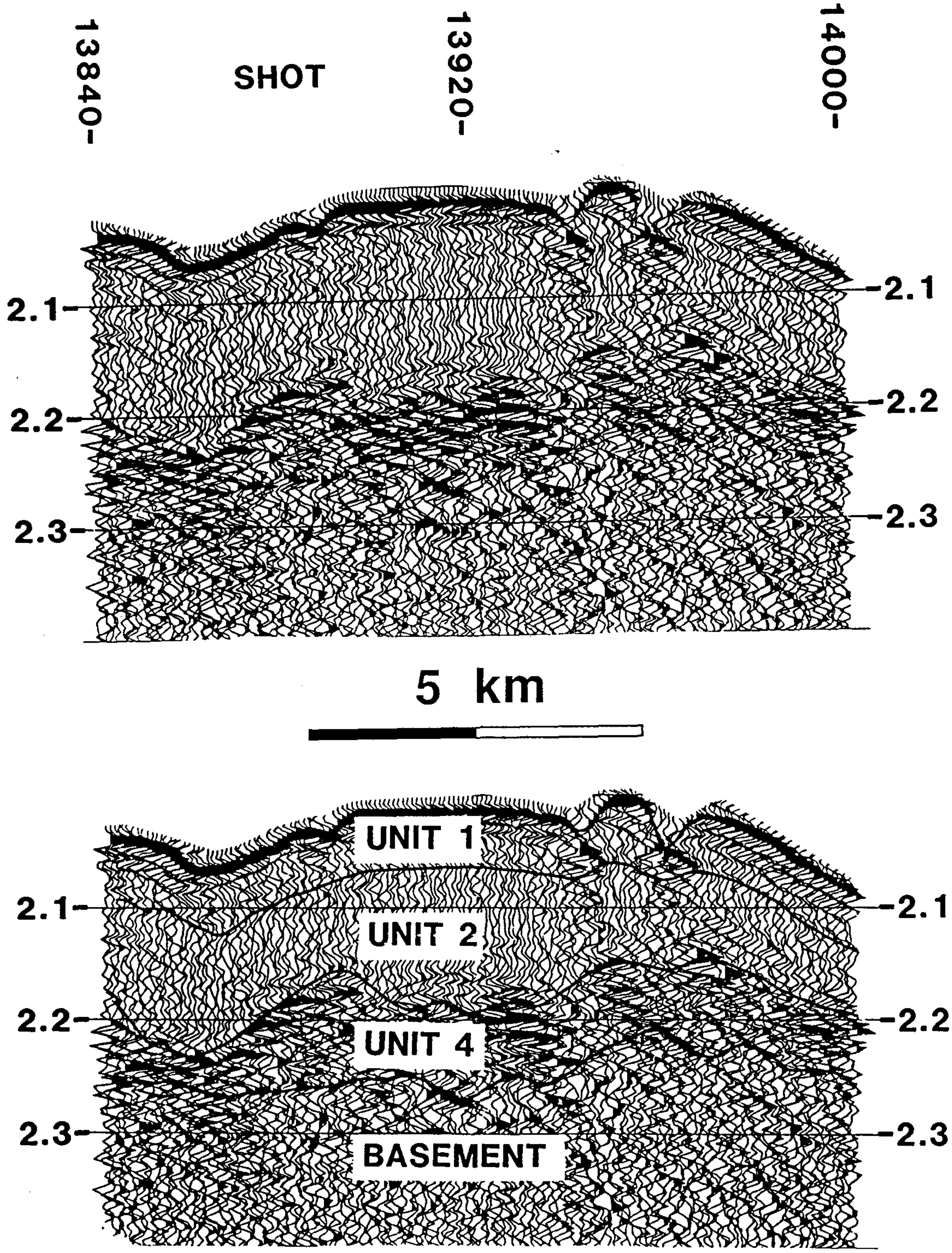


12732-
SHOT
12812-
12892-
1.9
2.0
2.1
2.2
-1.9
-2.0
-2.1
-2.2
5 km
UNIT 1
UNIT 2
UNIT 3
UNIT 4
BASEMENT

Figure 37. Seismic section of the W-E line which crosses suggested drilling site 3 at shot point 13670. The southern Ninetyeast Ridge survey area. Both interpreted and uninterpreted sections are shown. Times are in seconds of two-way travel time.


13590-
SHOT
13670-
2.0-
2.1-
2.2-
2.3-
-2.0
-2.1
-2.2
-2.3
5 km
UNIT 1
UNIT 2
UNIT 3
UNIT 4
BASEMENT

<u>Figure 38.</u> Seismic section of the W-E line which crosses suggested drilling site 4 at shot point 13920. The southern Ninetyeast Ridge survey area. Both interpreted and uninterpreted sections are shown. Times are in seconds of two-way travel time.



13840-
SHOT
13920-
14000-
2.1
2.2
2.3
2.1
2.2
2.3
5 km
UNIT 1
UNIT 2
UNIT 4
BASEMENT
2.1
2.2
2.3
2.1
2.2
2.3

Figure 39. Composite seismic profile of the central Ninetyeast Ridge site survey. The turns of the track are designated by letters A through S. Precise locations of the turns are designated by arrows. Directions of the straight seismic line segments are on appropriate side of the letters designating turns. Times are in seconds of two-way travel time. Locations on the profile are shown by shot numbers. Sonobuoy locations are also shown. Suggested drilling site areas are outlined by black boxes. This profile is uninterpreted.

<u>Figure 40.</u> The description of this profile is the same as of profile 1A. This profile is interpreted.

Figure 41. Composite seismic profile of the southern Ninetyeast Ridge site survey. The turns of the track are designated by letters A through M. Otherwise markings are the same. This profile is uninterpreted.

Figure 42. The description of this profile is the same as of profile 2A. This profile is interpreted.

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