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STRUCTURE AND SEDIMENTATION IN AN ACTIVE CALDERA, RABAUL, PAPUA NEW GUINEA

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ABSTRACT

Recent seismic and tectonic activities in Rabaul Caldera, Papua New Guinea, suggest that magma is moving beneath this partially submarine structure, and that a new volcano may be developing. Changes in elevation noted onshore over the past 10 years indicate that rapid and large magnitude (up to one meter on south Matupit Island) uplifts are taking place on the seafloor near the center of the caldera. The trend of onshore measurements suggests that even greater uplift may have occurred offshore. The frequency of caldera seismic events has increased in the same period. Within the caldera, seismic epicenters define an elliptical ring, the focal area of which lies in the same general area as the center of this uplift.

A marine geophysical survey undertaken in 1982 by the S.P. Lee in Rabaul Caldera shows the development of a seafloor bulge in the center of the caldera. High-resolution, seismic reflection profiles show that this bulge consists of two domal uplifts bounded and separated by two major north-south trending fault zones. These zones are marked by folded surficial sediments and youthful faults, several of which cut the seafloor. A prominent slump also flanks the upbowed area.

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Five major acoustic units have been identified in the seismic reflection profiles and these consist of an acoustic basement, and sedimentary units of irregularly-layered, cross-layered, contorted and well-layered sequences. The sedimentary units primarily represent ash laid down io different depositional environments. The cross-layered, irregularly-layered, and contorted units appear to have been deposited in a dynamic environment subjected to strong current forces, seismicity and/or mass wasteing while the well-layered sequences were deposited in a passive or quiet-water environment. Locally, an interfingering of well-layered sequences with the other sedimentary units indicated a transitional environment that has alternated between dynamic and passive depositional processes.

A submarine channel cuts through most of all the acoustic units and appears to be the conduit for sediment transport out of the caldera. The channel occupies an older buried channel in the north of the caldera that is presently being exhumed, whereas in the south, active erosion of well-layered sediments is taking place. Several youthful looking volcanic cones also interrupt the depositional layers.

We conclude that the seafloor bulge and fault zones result from emplacement of magma at a shallow depth. The magma has upbowed and displaced sedimentary layers beneath the seafloor. Contorted surficial sediments and slumps adjacent to the bulge are probably the result of uplift and seismic activity. The pattern of seismicity appears to define the accumulation of magma at depth beneath the seafloor bulge. Continuation of this activity will probably culminate in an eruption, possibly with the construction of a new volcano.

INTRODUCTION

The port city of Rabaul is situated in a large volcanic caldera on the north coast of New Britain, Papua New Guinea (Fig. 1). The caldera is open to the sea on the eastern side forming an excellent sheltered harbor. Several extinct or dormant satellite volcanoes are scattered around the northern and eastern rim of the caldera, and small, active volcanoes occur within the caldera itself. Eruptions from these relatively small volcanoes have taken place in historical time. During one eruption in 1937, 505 lives were lost. The population of Rabaul town at that time vas about 6000, but has now risen to about 15,000, and within 15 km of the center of the caldera the total population is about 70,000. A major disaster could occur from the eruption of any of the nearby volcanoes. The Rabaul Volcanological Observatory (RVO), situated on the northern rim of the caldera was established to monitor volcanic activity through a network of seismometers. tiltmeters and other types of surveillance instruments for the specific purpose of warning the populace of impending eruptions.

Over the last ten years, a gentle up-warp has occurred within the caldera. This deformation has been measured in some detail on land by means of optical levelling, tiltmeters, dry tiltmetry, and repeated gravity readings. All measurements have shown consistent trends that indicate uplift of an area around Matupit Harbor (Fig. 2). The largest change exceeds one meter on the south end of Matupit Island. but the pattern of onshore measurements suggests that even greater uplift may have occurred southeast of the island, in Blanche Bay. The frequency of caldera seismic events noted on the Rabaul network has also increased several-fold in the same period, and it has been found that a ring pattern of seismicity occurs within the caldera. The elliptically annular pattern of caldera seismicity has its centroid in the same general area as the focus of this uplift (Fig. 3).

The U.S. Geological Survey's (USGS) Research Vessel S.P. Lee made a port stop at Rabaul while working under a hydrocarbons resource evaluation program for other southwest Pacific countries. This program involved Australia, New Zealand, and the United States (ANZUS), and was coordinated through the UN-sponsored Committee for Coordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC) In response to a request from the Papua New Guinea government through CCOP/SOPAC, the USGS agreed to collect geophysical data in Blanche Bay and Matupit Harbor to assist RVO in delineating the area of suspected uplift.

A marine geophysical study such as undertaken here is unique in the investigation of the development of rubmarine volcanoes. If indeed the bulge believed to be developing on the seafloor of Blanche Bay were to be associated with future volcanism, or if a new volcanic cone is formed in this area, then this type of study would allow geologists to view the sediment deformation and disruption that accompanies the development of a shallow magma chamber prior to eruption. Marine seismic reflection profiling methods give a three-dimensional perspective to sub-seafloor stratigraphy that can be used to observe progressive structural deformation associated with dynamic tectonic events, if monitored on a regular basis. The results reported here provide baseline information that may be used to initiate an offshore monitoring program.

METHOD AND PROCEDURES

Data collected during the 8-hour survey (Fig. 4) consists of precision 12kHz bathymetric profiles, 1,200 joule Uniboom, high-resolution seismic reflection profiles, a sonobuoy refraction profile and single channel air gun seismic reflection profiles; a single large air gun (500 in) was fired throughout the survey to test the local seismic network response from various locations in the harbor (see Tiffin and Vedder, 1982) as well as to provide an acoustic source for the single channel seismic reflection profile. The primary data used in this report are the 12kHz sounding profiles and the high-resolution seismic reflection profiles. The latter were recorded at a 0.25 sec. fire and sweep rate and passed through a 250Hz low cut and 1500Hz high cut filter. The Uniboom system aboard the Lee has four hull-mounted electromagnetic boomer plates as the source and twin short high-resolution hydrophone streamers boomed abeam as the receiver. With the use of this system we were able to obtain good penetration of up to 200 m at a resolution of 1 m in the shallow water depths from 25 to 300 m in the submarine part of the caldera.

Navigational fixes were plotted at approximately 5 minute intervals, as well as at the times of turns, using two high precision navigational RADAR's (each one reading ranges and bearings from separate and independent targets) read simultaneously. Fixes were plotted directly on U.S. Naval Chart No. 82192 at a scale of 1:25,000. Accuracy of positioning is estimated to be better than 80 meters over most of the survey area.

TECTONIC SETTING

The Rabaul Caldera dominates the lowland of northeastern Gazelle Peninsula, New Britain Island (Fig. 1). The caldera, breached by a 5 km gap on the southeast side, forms Blanche Bay, the harbor of Rabaul.

The Rabaul volcano (Fisher, 1939; Fleming, 1974) is a shield volcano of probable Quaternary age (Macnab, 1970). It is situated near the juncture of three crustal plates: the Solomon Sea plate, the Pacific plate, and the South Bismarck plate (Fig. 5), and is only a few kilometers west of the major transform fault between the Pacific and South Bismarck plate, which passes through St. George's Channel (Johnson, 1979).

South of New Britain Island, the New Britain trench marks the active subduction of the Solomon Sea plate under the New Britain arc. The Rabaul volcano is the earternmost element of the arc. Several major active faults cut through the Gazelle Peninsula (Macnab, 1970), St. George's Channel and adjacent southern New Ireland (Hohnen, 1970). The area is often shaken by large earthquakes of intermediate focus depth along a northwest dipping Benioff zone, while shallow large magnitude events occur in St. George's Channel. The region is one of the most seismically active areas of the world.

CALDERA PHYSIOGRAPHY

The Rabaul Caldera is elliptical in shape, measuring 14 km from north to south, and 9 km from east to west (Fig. 2). This collapsed and breached caldera is surrounded by steep walls up to 450 m high. The caldera walls are part of an old ring fracture system that involved the collapse of the summit of the original shield volcano. Vertical movement along the fracture system may have been as much as 600 m.

Several extinct or dormant basaltic and basaltic-andesite satellite cones are situated along the northern and eastern walls of the caldera (Fig. 6). These are named Tovanumbatir (North Daughter), Kabiu (Mother) and Turangunan (South Daughter). The breached cone of Palangiagia straddles the eastern ring fracture with a later smaller cone of Rabalanakaia within it.

Inside the caldera, a narrow coastal plain provides a habitable area for the city of Rabaul, its airport and harbor facilities. The active volcanic cones of Tavurvur on the east side, and Vulcan on the west, rise from the margins of the caldera. The active fissure of Sulphur Creek is present on the east side near Palangiagia. Remnants of other volcanic centers including the oddly shaped rocks of the Dawapia Rocks (Beehives) and Matupit Island are also found within the caldera.

Offshore, but within the caldera, several bays are formed from the modification of the primary caldera by post–collapse volcanic events (Fig. 7). The present day seafloor topography and morphology reflect the complex development of the bays; the primary topographic elements are basins, shoals, and cones. In the northern part of the caldera two relatively narrow bays, elongated along a north–south axis, are separated from each other by a peninsula at the southern end of which is Matupit Island. The larger bay lies to the west and is known as Simpson Harbor while the smaller one to the east is known as Matupit Harbor (Greet Harbor). A relatively broad embayment known as Karavia Bays forms the southern part of the caldera. All of the harbors and embayments open to the central and largest bay, Blanche Bay, which in turn is open to the sea along its eastern margin, the breached wall of the caldera.

Simpson Harbor, in the northern part of the caldera, is a broad, flattened trough sloping southward into Blanche Bay. A submarine channel, herein called Simpson Channel (Pigs. 2 & 7), heads adjacent to the Dawapia Rocks approximately three–fourths of the way south from the head of the embayment and may extend even further into the bay. North of this area, the harbor floor is relatively flat, sloping gently upward and northward from a depth of 85 m to about 20 m. Depths in the entrance to Simpson Harbor reach 150 m in the center of the submarine channel where it enters Blanche Bay. Dawapia Rocks appear to be the exposed and eroded remnants of a volcanic cone that was built up from the harbor floor.

The floor of Blanche Bay generally slopes to the south toward Karavia

Bay, although it is interrupted near its center by a subtle bathymetric terrace that extends due east from Vulcan volcano. This terrace is bifurcated by an easterly–trending, poorly developed rubmarine channel that connects with Simpson Channel, and which continues along its southerly trend into Karavia Bay. The bay opens to St. George's Channel through a 5 km gap in the southeastern caldera wall. Two shoal areas occur in the mouth of the bay marking the line of the breached caldera wall. Mackenzie Shoal, the more northerly shoal, comes to within 5 m of the sea surface about 0.5 km offshore immediately south of Turangunan. An unnamed knob in the center of the breach rises steeply from the floor of the bay to within about 80 m of the surface.

Karavia Bay forms the southern part of the caldera. It is a well developed basin reaching a depth of 275 m and shaped like a half–bowl with steep sides to the south. Simpson Channel enters the basin from the north, then follows the thalweg of the basin eastward into a deep channel north of Raluana Point, here called Karavia Channel, which connects the basin with St. George's Channel outside the harbor through the breached sill or remnant of the southeast caldera wall.

Matupit Harbor is very shallow and saucer–shaped, with a flat–floor at about 60 m depth. It lies between Tavurvur cone and Matupit Island. A shallow sill extends eastward from Matupit Island and separates the harbor from Blanche Bay, making it a physiographically enclosed basin below the sill depth of 25 m.

VOLCANIC EVENTS

Two major explosive events, the first 3500 years B.P. and the second 1400 years B.P., led to the development of the present caldera, and covered the surrounding countryside by a thick mantle of Airfall pumice and ash, and ignimbrite (Heming, 1974; Heming and Carmichael, 1973; Peterman and Heming, 1974; Walker, et al., 1981). The primitive cone of the original volcano foundered during these events along a ring fracture at the caldera walls. dropping the caldera floor approximately 600 m or more to its present elevation below sea level. One of the ancient volcanic events may have taken place in the Karavia Bay area of the southern caldera and another was probably in the northern section (Heming, 1974). Between these major eruptions, additional volcanic events occurred and are recorded in the stratigraphic column. The seismicity pattern of Figure 3 probably outlines the ring-fault developed during the last caldera forming eruption (McKee, et al., 1983).

Of the four youngest volcanic structures. only Rabalanakaia has not definitely been active within historical time (Fisher, 1939); a report by a French navigator, Philip Carteret, in 1767 suggests that some type of eruption may have been in progress then at either Rabalanakaia or Tavurvur. Rabalanakaia has a well-preserved crater surrounded by an ash rampart. Youthful-looking lava flows extend from the crater along the lowland as far as the shore of Matupit Harbour north of Tavurvur.

Sulphur Creek fissures were active in about 1850. Tavurvur erupted explosively in 1791, 1878, 1937 and intermittently from 1941 to 1943. Vulcan, which in earliest historical times was a submarine bank, erupted in 1878 to form an island of low relief. The island was welded to the western shoreline during the 1937 eruption of Vulcan in which 505 people died.

Both Vulcan and Tavurvur were active simultaneously in 1878, even though they are located on opposite sides of the harbor (Fisher, 1939). In 1937, they were both active at the same time again, with Tavurvur erupting sympathetically for one day during the Vulcan eruption (Joycey, undated; Thomas, 1937; McKee et al., 1983). On both occasions when the two were active, disturbances of the sea or clouds of vapor rising from the bay were

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GENERAL GEOLOGY OF THE CALDERA

Four informal units (Fig. 6) in the Rabaul volcanic series were distinguished by Heming (1974). Be termed these (1) the pre-Caldera unit, (2) the Karavia Bay unit, (3) the Caldera unit, and (4) the post–Caldera unit. The basal part of the seismic stratigraphy defined in our work is composed of these units. Briefly, they are as follows:

Pre-Caldera Unit

As described by Heming (1974), lava flows and pyroclastic rocks make up the pre-Caldera unit, which outcrops on the eastern and northern caldera walls, and in an area about 8 km south of the caldera. The early volcanism produced mainly basaltic lava flows and scoria with later eruptions composed predominantly of andesite and dacite pyroclastics. The basalt and basaltic–andesite outcrops are massive flows up to 20 m thick, interbedded with thin tuffs. Pyroclastic flows were erupted during the first caldera collapse 3500 years B.P., an event that may have ranked with Krakatau in magnitude and deposited several tens of cubic kilometres of tephra over the surrounding country side. The satellite volcanoes Tovanumbatir, Kabiu and Turangunan, which consist of basalt and basaltic-andesite flows and scoria interbeds, are part of this unit.

Karavia Bay Unit

Andesite lava flows and pyroclastic rocks from a source in the southern part of the caldera formed after the first caldera collapse, according to Heming (1974). Andesite lava flows crop out on the western caldera wall south of Vulcan while pyroclastic rocks appear in outcrop mainly along the south shore of Karavia Bay. These include tuffs, ash beds, paleosols and breccias. The breccias progressively increase in quantity in the upper part of the section and eventually dominate the lithology at the top of the section. The ash beds dip up to 40' to the south-southvest. The unit is unconformably overlain by pyroclastic rocks of the Caldera unit.

Caldera Unit

The Caldera unit is made up of pyroclastic beds ranging in lithologies from basalt to rhyolite (Heming, 1974). The lover beds in the unit are mainly ash-flow deposits unconformably overlying the Karavia Bay and pre-Caldera units. A thick, widely distributed paleosol separates the lover and upper beds and denotes a period of inactive volcanism prior to the second caldera collapse 1400 years B.P. This event ejected a volume of tephra exceeding eleven cubic kilometres (Walker, et al., 1981). The upper beds of the Caldera Unit are all pumiceous ash deposits mantling most of the caldera walls and the surrounding countryside. The lowest upper bed is a graded dacitic pumice lapilli and fine ash deposit. Unconformably overlying this are two pumiceous ash-flow deposits, both of which attain a thickness of up to 30 m where deposited in valleys; they are separated by an intervening breccia whose origin is uncertain. At one locality on the south shore of Karavia Bay, the intervening breccia is replaced by a welded tuff over 6m thick. Like the lover beds of this unit, the upper beds also rest unconformably over the Karavia Bay and pre-Caldera units in places.

Post-Caldera Unit

The post-Caldera unit is represented by the cones of Rabalanakaia, Sulphur Creek, Tavurvur and Vulcan. Dawapia Rocks and Hatupit Island are also part of the post–Caldera unit (Heming, 1974).

Rabalanakaia is made up of pre-historical lava flows and ash. Sulphur Creek consists of pre-historical lava flows and ash, and has historically erupted andesitic pyroclastics. Historically, Tavurvur has explosively ejected bombs and ash, but produced no lava flows; however, lava flows are present in older parts of the cone. Vulcan, also historically active, is a pumice and ash cone of considerable volume. An estimated 0.3 km of material was erupted in the four–day eruption of 1937. Dawapia Rock and Matupit Island, whose time of activity are unknown, are of similar composition to Vulcan.

DEFORMATION AND SEISMICITY

Onland Deformation

Remarkable deformation in the Sulphur Creek–Matupit Island area has been monitored closely since 1973, principally by optical levelling and gravity techniques (McKee, 1982). Between 1973 and 1982, the southern end of Matupit Island vas uplifted by almost one meter. Figure 8 shows the results of optical levelling surveys carried out since 1973 along a line from a stable bench mark near RVO to Matupit Island. McKee et al. (1983) give the following description of deformation: the levelling data on stations immediately north and 1–2km east and southeast of Hatupit Harbor indicate that over the same time interval elevation changes, although positive, have been probably less than 10 cm. However, significant uplift (about 30 cm or more) is believed to have taken place at the southwestern coast of Tavurvur volcano. Partial contours of these changes indicate that the focus of uplift probably lies immediately south of the entrance to Hatupit Harbor. Results from dry tiltmetry around Matupit Harbor since early 1981 and measurements from a spirit level tiltmeter at TAV seismometer site (Fig. 8) since early 1972 confirm the existence of an uplifting source in this area. Dry tilt data from a station on the southern end of Matupit Inland indicates a current rate of uplift (July, 1983) of 4-8 microradians per month (to southeast).

Changes in Bathymetry, 1962 - 1982

Published bathymetric charts of Rabaul Harbor (US82192, and AUS 680) provide insufficient detail for useful comparison with traverses made by the S.P. Lee in 1982. However, a detailed Royal Australian Navy (R.A.N.) collector sheet (0452/10, 19/10/0) with mainly parallel, north–south traverses at about 20 m intervals covering Matupit Harbor (from which part of chart AUS 680 was prepared) is publicly available. This detailed coverage, surveyed in 1962, extends to almost 1 km south of the entrance to Hatupit Harbor.

Two lines of the S.P. Lee's track, entering and leaving Hatupit Barbor (Lines R-6 & R-7), were selected for comparison with the detailed 1962 data of this area. Before comparison could be made, a number of navigational and tidal corrections to both sets of data were required to bring them to the same datum level. Figures 9 and 10 show the comparison of 1962 and 1982 bathymetry after corrections were applied. Although these data show the sea floor to generally be between 3 to 5 m shallower, discrepancies noted below suggest that more offshore data is needed to properly evaluate the long term seafloor changes.

Comparison of depths within the flat floored central part of Hatupit Harbor shows a difference of about 0.5 m. This amount of uplift is in good agreement with onshore measurements nearby. This tends to confirm the validity of the corrections applied. The comparison shows that outside of Matupit Barbor, there is a progressive divergence southwards of the 1982 and 1962 profiles. Significant uplift of the sea–floor south of Matupit Harbor is thus indicated between these times. The greatest shown on the profiles compared is

5–8 m. For the 20 year period, this would translate into a rate of uplift of 25–40 cm per year, considerably higher than that recorded from the onshore data.

Several other discrepancies also are evident, however. The match of 1962 and 1982 data over the northern side of the sill at the entrance to Matupit Harbor is poor. This may be due to the steepness of this side of the sill, from which diffractive effects on sound waves could be expected. No migration of the data has been carried out. Pair match of 1962 and 1982 bathymetry is found at the peak of the sill, but in general, the 1982 profiles show the sill to be deeper than it was in 1962. This result is anomalous in the light of evidence of uplift during the time between the two surveys. Closely spaced fixes near the sill in the 1982 survey have a depth difference of about 1 m. Corresponding points in the 1962 survey show a difference of about 5 m. This may reflect uncertainty in positioning rather than actual differences in soundings. However, deposition and erosion could have had some effect over the 20 year period, particularly in the shallow sill area and could account for some of the changes noted.

The results of tiltmetry indicate that the center of uplift is about 1 km south–southwest of Matupit Island. Determination of parameters of the source of deformation, following the methods of Mogi (1958) and Eaton (1962) for a point source model, yield a focal depth of about 2 km and a volume of about 0.04 km. Calculations indicate that the maximum uplift is about 2 m. This value is significantly less than the changes in bathymetry. This discrepency could result from slumping of material on the southern flank of Matupit Island (see below) which would add a component of <u>apparent</u> uplift.

Seismicity

Seismic surveillance began in Rabaul in 1940, but vas improved in 1967 by the establishment of a network of seismic stations around the northern part of Blanche Bay (Simpson Harbor). In the early 1970's. the seismic network was extended southward to cover the whole of Blanche Bay and now consists of nine stations (Fig. 3). The improved network shows that, at least since 1970, the seismicity of Rabaul caldera has consisted essentially of shallow, short-period, volcano-tectonic earthquakes originating from depths of 10 kms and less. Since 1977, and possibly earlier, earthquake foci have been predominantly in the depth range of 0-2 km (McKee, et al., 1983).

Between 1967 and 1971 seismicity of the caldera was quite low and stable and the rate of occurrence of local earthquakes varied from about 20 to 100 events per month (McKee, et al., 1983). Since late 1971, distinctly higher rates of earthquake occurrence have been noted (Fig. 11). The highest monthly earthquake total registered up to early 1983 vas 1,170, recorded in January 1982. The strongest caldera earthquakes recorded to early 1983 were magnitude (ML) 5.2 and 5.1 events in 1980 and 1982, respectively (McKee, et al., 1983).

The seismically active area in Rabaul is seen to consist essentially of two inward-facing arcuate zones forming an elliptically annular pattern within the caldera (Fig. 3). The shape of the main zones could be linked to the caldera-modifying eruption about 1400 years B.P.; that is, the seismicity may define the faults along which deepening or widening of the former caldera took place. In addition, there appears to be an intimate relationship between the most recently active volcanoes in the caldera and some of the concentrations of seismicity indicating that conduits for the intra-caldera volcanoes developed along the caldera faults; this is shown on Figure 3 with the volcanoes lying within the elliptical pattern of recent seismicity. Apart from these relationships there appears to be a spatial, and perhaps temporal, connection between the seismicity and the uplift at Matupit Island. Indeed, the center of uplift seems to be located near the centroid of seismic activity in Blanche Bay. about 1 km south-southeast of Matupit Island.

Volcanic activity is usually presaged by increased shallow seismicity, commonly in the depth range 20 km to near surface. This seismicity often climbs to shallower depths as magmatic material rises towards the surface, thus stimulating harmonic tremors. The results of geophysical surveillance in Rabaul Caldera since 1971, particularly the results of seismic and deformation studies, have been forming an intriguing scenario which can be interpreted as the prelude to an impending eruption.

SEISMIC–REFLECTION STRATIGRAPHY

The high–resolution seismic reflection profiles collected within Rabaul Caldera are of good quality and indicate a considerable thickness of well-layered sediments and/or sedimentary rocks beneath the harbors and bays. A maximum penetration of 200 m in the central part of the caldera was obtained; we are able to resolve features as small as 1 m in these profiles. Generally, the seismic reflection profiles show rhythmically bedded, well–layered reflectors.

Five major acoustic units are identified in the seismic reflection profiles: (1) acoustic basement, (2) an irregularly–layered sequence, (3) a cross–layered sequence, (4) a contorted sequence, and (5) a well–layered sequence. Two caldera–wide unconformities are identified: an angular unconformity separating acoustic basement from the overlying sedimentary units and another unconformity, locally a disconformity, which separates the well-layered sequence from the underlying irregular or contorted units.

Acoustic Basement

Acoustic basement is normally opaque to acoustic waves or is characterized by the lack of correlatable reflectors; it is not identified everywhere within the survey area as the seismic system used in the survey was not sufficiently powerful to reach deeply buried basement. Generally, acoustic basement in the Rabaul Caldera consists of volcanic rocks: basaltic and andesitic lava flows, intrusives, breccias, thick scoria and well-solidified agglomerates of the Pre-Caldera, Karavia Bay, Caldera and Post-Caldera units described previously from onshore exposures. The andesitic lava flows of the Karavia Bay unit almost certainly are the acoustic basement observed near the end of line R-2 and along line R-3 (Figs. 12 & 13), near the western and southwestern caldera wall. Acoustic basement observed on the northern part of line R-2 and along line R-8 (Figs. 12 & 14) probably are composed of andesite, dacite, and minor basaltic rocks of the Post-Caldera unit. Post-Caldera rocks associated with Tavurvur and Palangiagia volcanoes are also found as acoustic basement rimming Matupit Harbor. On one line, an acoustical basement projection above the caldera floor just north of Vulcan volcano may represent a separate volcanic cone or formed along a north-south trending rift (Fig. 14). It is difficult to determine the lithology and age of the shoals that are the remnant of the eastern wall of the caldera, but it is speculated that acoustic basement in this area is composed of rocks of the Pre-Caldera and Caldera units.

Acoustic basement crops out along the seaward opening to Blanche Bay, along the southern and vestern margin of Karavia Bay, in northern Matupit Harbor, and offshore from Vulcan volcano. Everywhere else in Rabaul Caldera acoustic basement is unconformably covered with sedimentary deposits.

Irregularly-layered Unit

This unit is characterized by irregular, discontinuous reflectors that commonly exhibit gentle folding (Fig. 12). In Blanche Bay, Karavia Bay, Simpson Harbor, and along the upper parts of the shoals beneath the approach to Blanche Bay from the east this unit appears to everywhere lie unconformably upon the acoustic basement. It ranges in thickness from 10 to 35 m. These deposits may represent water-laid ash deposited during the latest stage of the deposition of the Caldera unit. Folding and faulting of this unit occurred after deposition from volcanic and tectonic activities and mass downslope movement. The age of the unit is difficult to determine, but is believed to be the oldest identifiable submarine sedimentary unit in Rabaul Caldera. On the other hand, there may be older units that were not detected by our survey.

Cross-layered unit

Distinctly, cross-bedded reflectors, well defined and continuous, are identified in seismic reflection profiles R-6 and R-7 (Figs. 15 & 16) south of Hatupit Island as well as underlying the sill at the mouth of Hatupit Barbor. They appear to consist of water-laid material deposited in a complex and dynamic marine environment. The age of this unit is difficult to determine as its basal relationship to the underlying rocks is not seen in the profiles. However, it is older than the well-layered sedimentary deposits found in Hatupit Harbor and northern Blanche Bay. The thickness of this unit varies from at least 30 m to at least 200 m.

Contorted Unit

Well defined to hashy, discontinuous reflectors associated with zones of acoustic semi-transparency characterize this unit. Associated surface topography is irregular and hummocky while internal folding and deformation of reflectors is common. This unit consists of deposits of water-laid ash and other unconsolidated material that have undergone, or are undergoing, mass downslope movement. This is well exhibited in Figure 16 where the unit is 40 m thick and appears to represent a slumped upper part of the cross-layered unit. The slump has slid southwestward off the south flank of the sill of Matupit Harbor. Age of slumping is not shown although it may be associated with the recent seismicity and uplift. No sediments cover the hummocky topography in this region.

Another area where this unit is identified is at the start of line R-2 (Fig. 12) where folded and hashy reflectors cover the eastern and southern flanks of Vulcan volcano. Here sedimentary deposits of unknown lithology appear to have moved downslope and now overlie the well-layered deposits in Karavia Bay. This sequence is contemporaneous and interfingers with the uppermost reflectors of the well-layered unit. It is possible that this sequence represents the latest pyroclastic deposits from Vulcan.

Well-lavered unit

This unit is characterized by well defined, rhythmically layered, continuous reflectors that are flat-lying or gently dipping (homoclinal). In most areas where it occurs this unit unconformably overlies the older irregularly layered unit or acoustic basement. It is thickest in Karavia Bay where it is 115 m thick (Fig. 12). It is thinner in Blanche Bay, ranging from 15 m to 40 m (Fig. 13) and in Simpson Harbor where it ranges from 20 m to 80 m in thickness (Fig. 17). This unit also obtains a sizable thickness in Matupit Harbor where it is over 105 m thick (Fig. 15). It is the youngest submarine sedimentary unit found in Rabaul Caldera and probably is composed of water-laid material from the most recent Post-Caldera volcanic eruptions.

STRUCTURE

Interpretation of the seismic reflection profiles show that generally structure within Rabaul Caldera is simple, except for an area in Blanche Bay just south of Matupit Island and Harbor (Figs. 18 & 19). Here the seafloor is upbowed and hummocky, whereas elsewhere the caldera floor is either flat or gently sloping. In Simpson Harbor, Karavia Bay, Matupit Harbor and most of Blanche Bay the seafloor and subsurface sedimentary layers represent depositional environments that are relatively undisturbed from tectonic movements. In two locations on the caldera floor, southern Simpson Harbor and central Blanche Bay, the sediments are pierced and overlain by volcanic cones and around the walls surficial slumping have locally taken place. Nowhere. except within the area of upbowing, here called the bulge, is faulting identified.

The Bulge - Our data indicates a prominent seafloor bulge in the area that has been shown from onshore levelling to be the point of maximumuplift (McKee, 1982). The bulge appears to be composed of two distinct, en echelon, dome–like ridges that exhibit anticlinally folded strata (Fig. 18), which are believed to trend generally in a north–south direction and are separated by a series of normal, stepped faults (Fig. 19). Only two tracklines (R-7 and R-8) of the 1982 & survey cross the area of the bulge, but a later survey by the Lee in 1984 also crossed the area and preliminary onboard interpretation of this data suggest a general north–south trend for the structures. Unfortunately, these latest collected data are not processed and not available for inclusion in this paper.

On the two dome–like features the western one is the largest being over 0.5 km vide. It is gently upbowed with maximum folding of strata along its eastern boundary well defined by a fault. This feature appears to extend beneath Matupit Island and may be directly responsible for the increase in elevation taking place there. The second dome-like feature lies to the east of the first. is much smaller. being only about 200 m vide. However, the surface of this feature is very hummocky and may be severely slivered by faulting. Both the vest and east sides are faulted. Separating the two dome-like features are three well defined faults and more may be present. Both features appear to plunge to the south.

Faults - As mentioned above, the dome-like features are bounded by faults (Fig. 19). Four faults have been identified in the seismic reflection profiles and more may be present (Fig. 18). These faults are concentrated in the area of the bulge and trend north-south. They are all normal faults, downthrown on the east and all have seafloor expression with scarps ranging in height from 5-20 m. Because these faults displace the seafloor, offsetting recently deposited sediments, it is believed that these are active faults that are developing from tension associated with uplift. It is even possible that gases and steams seen arising in Blanche Bay between Vulcan and Tavurvur volcanoes during their 1937 eruption (Fisher, 1959; Johnson, 1981) occurred along one or more of these faults. Because the crossings of the faults are limited to one or two tracklines it is difficult to precisely define the orientation and further work in the area may show a different trend.

Volcanic Cones - Two volcanic cones are shown to exist on the floor of Rabaul Caldera (Fig. 19). One cone is located just north of Vulcan volcano and may be associated with a north-south trending rift or may even be part of a volcanic spur extending out from the volcano. The second cone lies in the central part of Blanche Bay and vas discovered in 1972 by the HMS Hydra (Crick, 1973, p. 3). This cone, 70 m high with 15 m high crater walls in water depth of 90 m, lies at the southern terminus of the bulge along the southward extension of the eastern most fault mapped in the area (Fig. 19). Crick

(1973) suggests that this cone and an adjacent ridge are co-linear with the 1878 Vulcan Island crater and may be associated with an east–west trending fault. However. we speculate that this cone is associated with north–south trending faults of the present developing bulge system.

DEPOSITIONAL ENVIRONMENTS

Based on seismic stratigraphy the marine sediments in Rabaul Caldera can be divided into three distinct depositional environments which reflect the manner in which the sediments were deposited and the processes that affected them since deposition: (1) a dynamic environment, (2) a passive or quiet water environment, and (3) transitional environment. We assume that the marine sediments in the caldera are primarily ash ejected from the volcanoes within the caldera. Once these sediments reach the seafloor they are affected by several major processes: waves and currents, gravity and tectonism. In areas where tidal or storm generated waves and currents are absent then only gravity and tectonic forces will affect the depositional configuration.

Volcanic eruptions cause episodic high influxes of sediments into Rabaul Caldera (Fig. 20). These have considerable impact on the sedimentary budget during, and for a time after, eruptions when the erupted material is washed into the sea from the limited drainage area of the caldera. The caldera is a nearly enclosed marine basin, and much of the volcanic material is retained in it. During times of volcanic quiescence. normal sedimentation rates are low, and sea floor sediments are either undisturbed or eroded and redeposited by dynamic bottom processes.

Dynamic Environment

The seismic reflection profiles in Blanche Bay off the mouth of Matupit Harbor exhibit cross–stratification, faulting, and submarine slumps in the sedimentary units (Pigs. 16 & 18). This suggests that sediments deposited in this region not only were laid down in a dynamic marine environment, but also in a relatively active tectonic environment.

The presence of cross-bedding near Matupit Island indicates that while deposition was taking place the sediments were subjected to strong currents. Tidal and storm currents would influence, disturb or rearrange any normal or quiet-water sedimentary structures. As this area is located near the breach of the caldera, open to the sea, it is subject to considerable wave and tidal energy from St. George's Channel.

The presence of slump structures suggest that sediment deposition in this area has been rapid, and on slopes of sufficient gradient that downslope mass movement from the force of gravity has resulted. This has probably been encouraged by external stimuli such as wave loading and earthquakes. In addition, continuing uplift in Blanche Bay, as indicated by the measured uplift of Matupit Island, and by the changes in bathymetry, as well as inferred movement along shallow faults that on our profiles appear to cut recent deposits, has assisted the slumping. The area of slumping is near the focus of the suspected uplift indicated by the seismicity pattern and uplift contours (Figs. 3 & 8).

<u>Passive or Quiet-Water Environment</u>

Sediments of the well-layered unit in both Karavia Bay and Matupit Harbor exhibit characteristics of quiet-water deposition (Figs. 12 & 15) and with the exception of erosion in Karavia Bay there is no evidence in our seismic reflection profiles of disturbance or displacement of these sediments. In Matupit Harbor the flat-lying sediments onlap the confining edges of the basin and are neither deformed nor tilted. In Karavia Bay an erosional channel (Karavia Channel) running through the south central part of the bay may be actively carrying sediments out of Rabaul Caldera (Figs. 13 & 15).

Simpson Channel in the northern part of Rabaul Caldera in the southern most part of Simpson Harbor is morphologically a relatively narrow (less than 500 m wide) flat–floored, rounded–edged feature that occupies the course of an older, filled channel which is eroded into the irregularly–layered unit (Pig. 17). The present day channel broadens to over 1 km wide near the southern limits of Blanche Bay where it appears to contain very little sediment fill and exhibits steep, erosional side scarps (Fig. 12). The channel (Karavia Channel) becomes narrower (less than 0.5 km wide) and V-shaped near it's exit point along the eastern boundary of the caldera. Based on the morphology of Simpson and Karavia Channels it appears that sediment transport alternated with minor amounts of deposition along the present day Simpson Channel, in Simpson Harbor. Unconsolidated sediments are thereby transported by the bottom currents through the channel from Simpson Harbor to Blanche Bay where they are either deposited or carried out of the caldera through Karavia Channel. Whether the sediments carried into Blanche Bay are deposited, transported or even remobilized, depends upon the current dynamics and sediment type at any one moment in time. Because the channel changes from a filled feature in the north to a distinct erosional feature in the south we suspect that exhumation of the channel fill is actively underway. Also, since the older channel in the northern part of the caldera appears to cut the caldera stratigraphic unit, we would date the origin of the channel at younger than 1400 years B.C.

Transitional Environment

The sedimentary deposits that are found in this environment exhibit structures that show effects of both dynamic and passive depositional processes. These deposits, composed of interfingering, contorted and well-layered strata, are primarily located in Simpson Harbor and extend into

Blanche Bay (Figs. 14 & 17). Deposition in this area is affected by tidal currents which, during periods of rapid sedimentation associated with volcanic eruptions, resulted in cross-bedding. Between eruptive events, well-layered beds were deposited. In areas of sloping bottom topography, localized gravity sliding took place forming the packages of contorted and disturbed sedimentary strata.

SUMMARY AND CONCLUSIONS

Seafloor physiography and subsurface geology indicate that Rabaul Caldera has evolved in a complex way. Four major basins have been defined (Fig. 7) in which thick sedimentary sequences of tephra have been deposited. In Matupit Harbor, Karavia Bay and the southern part of Blanche Bay, sedimentation appears to have been of a normal, quiet water type with localized slumping near the edges. In Simpson Harbor a more confused sedimentary regime exists, with a combination of quiet-water deposition and current-effected bedding. The northern part of Blanche Bay exhibits the most complex picture of sedimentation with contorted and chaotically bedded sediments.

Sediment transport within Rabaul Caldera appears to take place mainly along a submarine channel system (Simpson and Karavia Channels) that extend from the head of Simpson Harbor southward through Blanche Bay to Karavia Bay where it loops east to northeast and leaves the caldera through the eastern breach. This channel system starts in Simpson Harbor as an obscure depression overlying an older filled channel (Simpson Channel) and becomes more distinct as it enters Blanche Bay. It is a well developed, almost canyon-like feature in Karavia Bay (Karavia Channel) where it appears to be actively eroding its walls. At times of volcanism the headward region of the canyon is choked by ash fill, while at times of little or no volcanism sediment is exhumed from the channel and current transportable sediments entering the caldera are carried out to sea along this channel (Fig. 2). Three sediment depot areas (Simpson Harbor, Blanche Bay, and Matupit Harbor) are present. Matupit Harbor is a restricted basin with only deposition taking place, whereas Simpson Harbor and Blanche Bay are connected by Simpson and Karavia Channels, a sediment conduit redistributing sediments from the northern part to the southern part of the caldera.

Geologic structure of the caldera floor is generally simple with well defined faults occurring primarily around the periphery of the caldera. An exception to this is in the northern part of Blanche Bay where a major fracture zone consisting of a series of recent faults exist on the floor of the bay. This zone trends N-S and is marked by folded surficial sediments and several faults that cut the sea floor. It passes through a broad dome or bulge of upbowed sediments south of Matupit Island. Nearby to the north, at the entrance to Hatupit Barbor, a well developed submarine slump appears to be in the process of sliding off the southern flank of the sill that separates Hatupit Harbor from Blanche Bay.

Recent elevation changes noted on shore indicate that rapid and large increases of elevation are taking place south of Matupit Island. The contours of elevation change determined from levelling surveys onland show 100 cm of uplift parallel to the southeastern shoreline of Matupit Island (Fig. 8). The seafloor bulge discovered during the Lee investigation, lies in the same area. The bathymetric changes noted between 1962 and 1982 amount to about 5-8 m about 1 km south of the island giving a mean rate of uplift of 25–40 cm/yr.

In comparing the location of the bulge with the pattern of seismicity in Rabaul Caldera (Fig. 21) it is seen that the seismicity surrounds the bulge in an elliptical shape with the long axis extending nearly north–south. The focus of the bulge and the fracture zone on its northern flank lie within the a seismic area.

We conclude that the sea floor bulge south of Matupit Island is the result of emplacement of a magma body at shallow depth, which has upbowed sedimentary layers beneath the seafloor. The fracture zone may be associated with the bulge and may have been the feature along which the reported disturbances of the sea or clouds of vapor rising from the bay were seen between Vulcan and Tavurvur during their 1878 and 1937 eruptions. The contorted surficial sediments in the general area of the bulge are interpreted as slumps. The slumping may have been stimulated by seismic events associated with the development of the bulge. However, the cross-stratified sediments in the area are the result of current effects from tidal flow in and out of the caldera.

We believe that the pattern of seismicity defines activity along ring faults of the caldera. This activity probably results from stresses applied by the accumulation of magma at shallow depth below the apex of the seafloor bulge. Continuation of this activity will almost certainly culminate in an eruption, possibly with the construction of a new volcano.

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FIGURE CAPTIONS

Figure 1. Index map shoving location of study area.

Figure 2. Bathymetric map of Rabaul Caldera shoving location of Simpson and Karavia Channels and major onshore geomorphic features. Onland contours in meters, isobaths in fathoms (about 36 m intervals). Bathymetry from Australian Department of National Development Map (1970). Seismic data from Denham (1969). Plate boundaries and relative motions of crustal plates from Taylor (1979) and Johnson (1979).

Figure 3. Pattern of seismicity in Rabaul Caldera from February 1977 to June 1982. Modified after McKee (1982).

Figure 4. Tracklines of the S.P. Lee 1982 geophysical survey in Rabaul Caldera.

Figure 5. Tectonic structure map of the Papua New Guinea region. Bathymetric contours in meters. Modified after Heming (1974).

Figure 6. Geological map of Rabaul Caldera. Modified after Heming (1974).

Figure 7. Oblique map of Rabaul Caldera showing submarine physiography. After Alpha and Greene (1985).

Figure 8. Elevation changes between 1973 and 1983 determined from stations of the Rabaul Caldera gravity network from Bench Mark (BM) 21 to Matupit Island. Filled circles refer to gravity network stations that arc also used as levelling sites. Dashed lines are contours of elevation changes relative to BM 21. Modified after McKee et al. (1983).

Figure 9. Bathymetric profiles constructed from the Royal Australian Navy collector sheet 0425/10, 19/10/0 (dot in circle) developed from a 1962 bathymetric survey of Matupit Harbor and constructed from the 1982 S.P. Lee Survey (solid line) Line R-6 in the same area. Along the outer (southern) flank of the Matupit Harbor sill there is a 3-5 m difference in depths that may relate to the present uplift.

Figure 10. Bathymetric profiles constructed from the Royal Australian Navy Collector sheet 0425/10, 19/10/0 (dot in circle) and developed from a 1962 hydrographic survey in the Matupit Harbor area compared with the 1982 S.P. Lee Survey (solid line) Line R-7 in the same area. Similar amounts of uplift to Lee Line R-6 are seen here.

Figure 11. Seismicity of Rabaul Caldera showing monthly number of earthquakes between 1967 and 1982. Modified after McKee (1982).

Figure 12. Seismic–reflection (Uniboom) profile taken along a part of S.P. Lee Line R-2 and shoving the well–layered sequence in Blanche Bay. Vertical Exaggeration 5.86x.

Figure 13. Seismic–reflection (Uniboom) profile taken along S.P. Lee Line R-3 shoving the well-layered sequence in Karavia Bay. Vertical Exaggeration 2.8x.

Figure 14. Seismic reflection (Uniboom) profile taken along a portion of S.P. Lee Line R-8 shoving the volcanic cone or extension of a volcanic ridge northeast of Vulcan in Simpson Harbor. Vertical Exaggeration 5.25x.

Figure 15. Seismic reflection (Uniboom) profile along S.P. Lee Line R-6 shoving well layered unit in Matupit Harbor, cross–stratified unit, and Simpson Channel in Blanche Bay. Vertical Exaggeration 4x.

Figure 16. Seismic reflection (Uniboom) profile along a part of S.P. Lee Line R-7 shoving cross-stratified unit and slump near sill to Matupit Harbor. Vertical Exaggeration 3.2x.

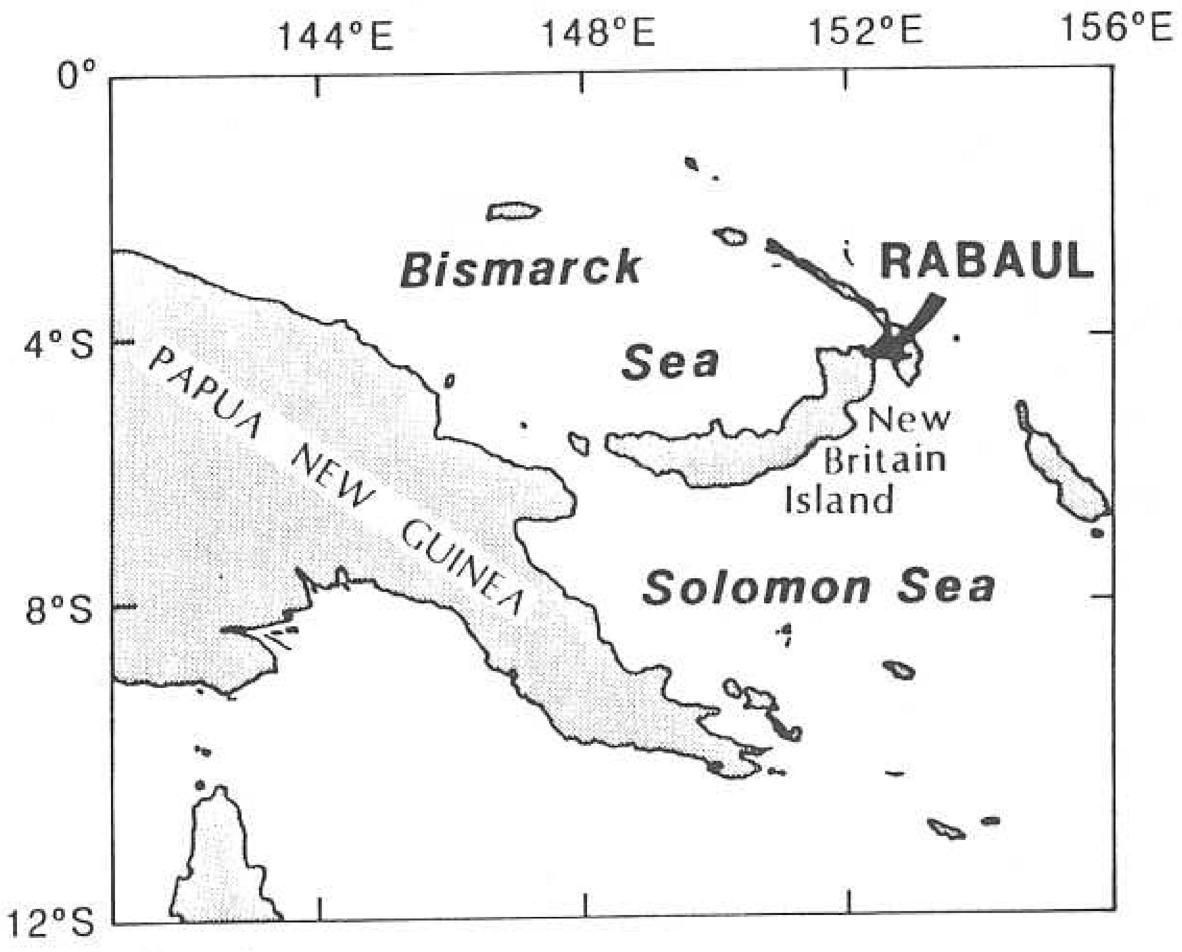
Figure 17. Seismic reflection (Uniboom) profile along S.P. Lee Line R-9 showing irregularly layered unit and Simpson Channel (in buried channel) in Simpson Harbor. Vertical Exaggeration 6.4x.

Figure 18. Seismic reflection (Uniboom) profile along a part of S.P. Lee Line R-8 showing faulting and sediment upbowing in Blanche Bay just south of Matupit Island. Vertical Exaggeration 3.46x.

Figure 19. Offshore geologic structure sketch map of the central part of Rabaul Caldera. Map constructed from seismic reflection (Uniboom) profiles collected by the S.P. Lee during the 1982 geophysical survey.

Figure 20. Photo of damage created from ash fall during the 1937 eruption of Vulcan volcano. (a) view of Vulcan from the north, (b) the S.S. Durour in Karavia Bay, and (c) a partially buried automobile. Photos courtesy of the Australian Bureau of Mineral Resources.

Figure 21. Offshore geologic structure superimposed on the seismicity pattern to show that the greatest amount of sediment disruption and seafloor distrurbance is taking place within the eleptical pattern, in the aseismic region.


144°E
148°E
152°E
156°E
0°
4°S
8°S
12°S
Bismarck Sea
RABAUL
PAPUA NEW GUINEA
New Britain Island
Solomon Sea


BISMARCK SEA
ST GEORGE'S CHANNEL
0 3 KM
Onland contours in meters
Offshore isobaths in fathoms
N
Tovanumbatir
Rabaul
Palangiagia
Kabiu
Sulphur Creek
Rabalanakaia
Simpson Harbor
Dawapia Rocks
Matupit Harbor
Matupit Island
Tavurvur
Turangunan
Vulcan
Vulcan Island
BLANCHE BAY
100
200
300
400
10
50
60
90
110
150
170

Fig. 2

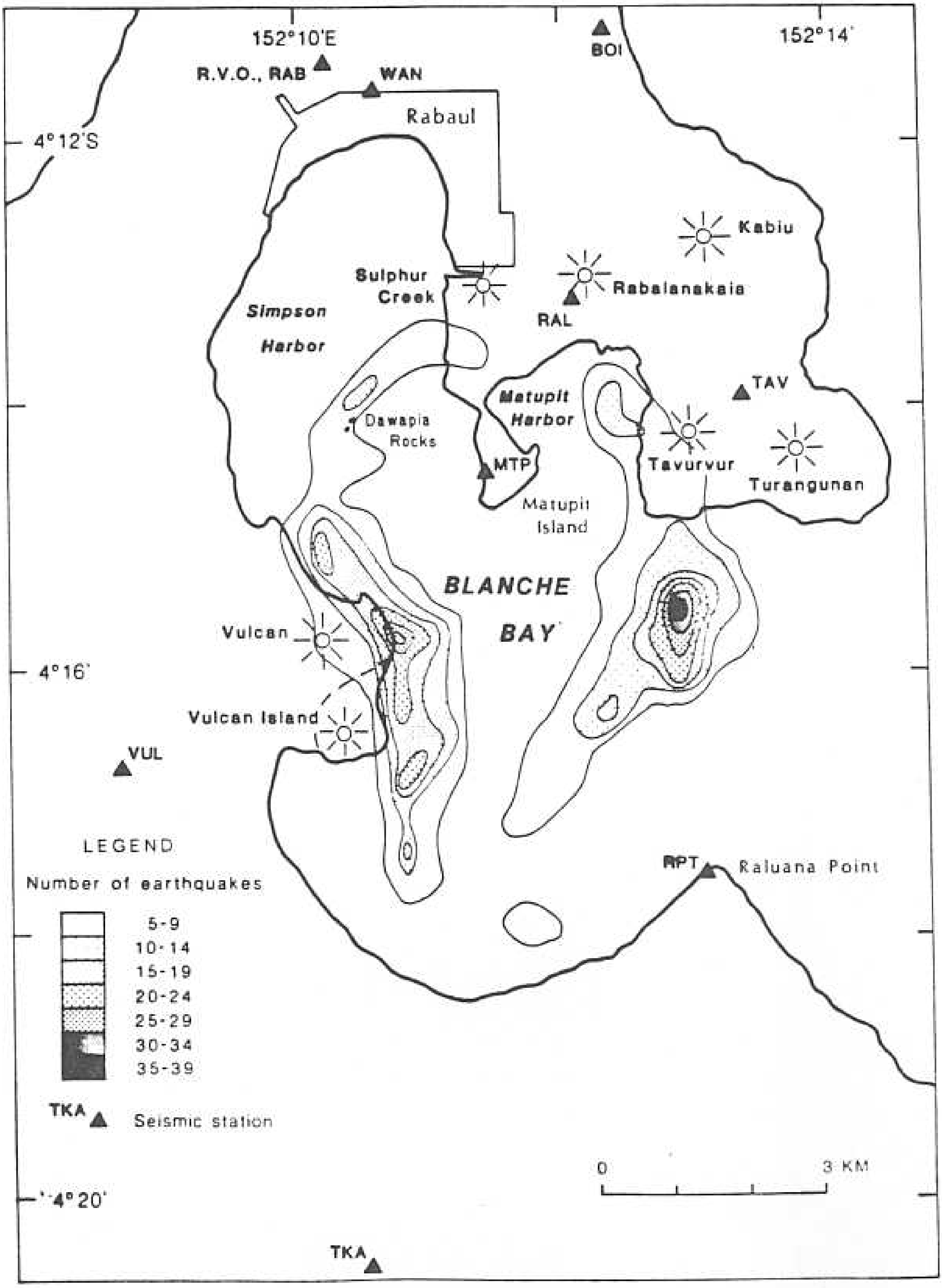

152°10'E
152°14'
4°12'S
4°16'
4°20'
R.V.O., RAB
WAN
BOI
Rabaul
Kabiu
Sulphur Creek
Rabalanakaia
RAL
Simpson Harbor
Matupit Harbor
TAV
Dawapia Rocks
MTP
Tavurvur
Turangunan
Matupit Island
BLANCHE BAY
Vulcan
Vulcan Island
VUL
LEGEND
Number of earthquakes
5-9
10-14
15-19
20-24
25-29
30-34
35-39
TKA
Seismic station
RPT
Raluana Point
0
3 KM
TKA

Fig. 3

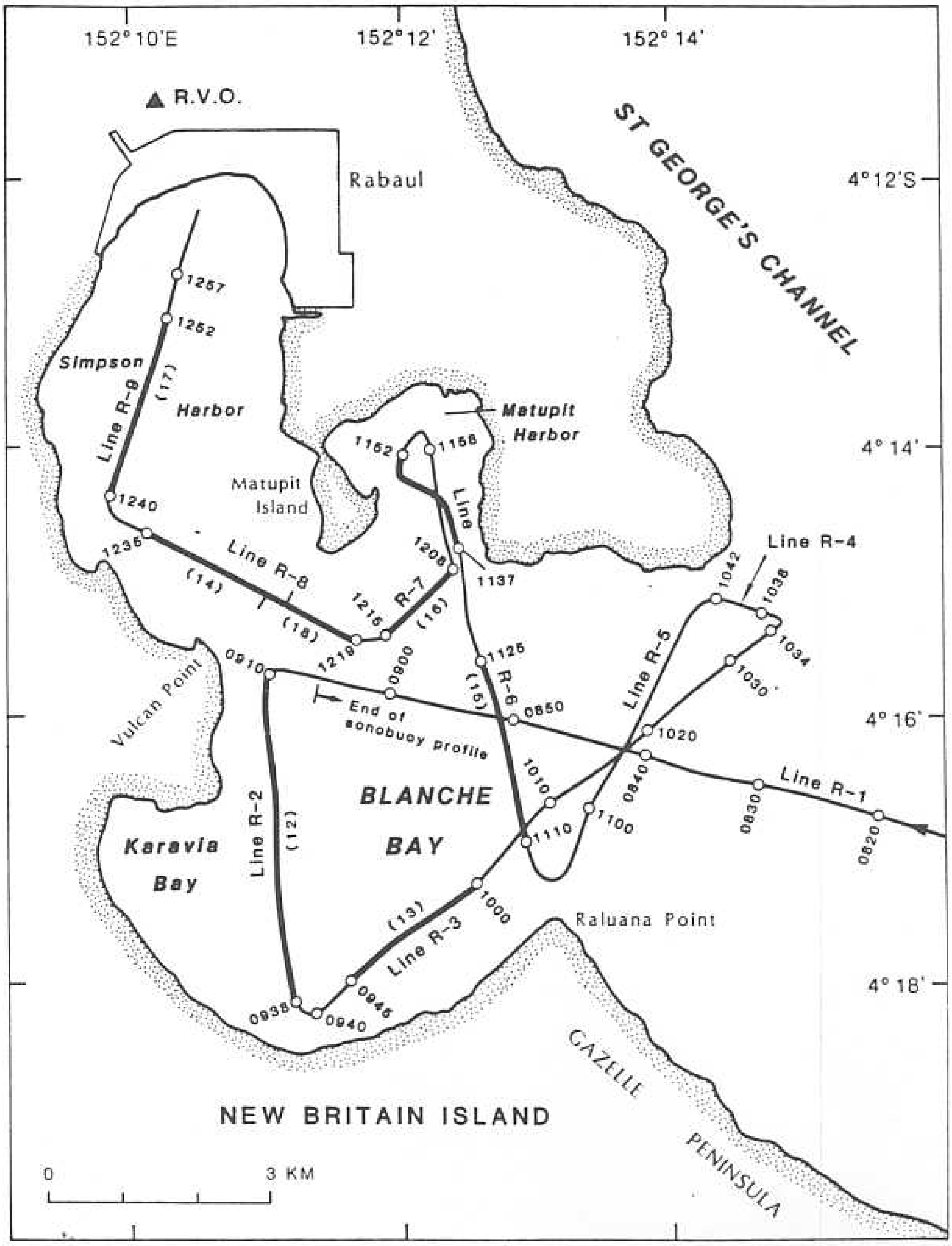

152° 10'E
152° 12'
152° 14'
4° 12'S
4° 14'
4° 16'
4° 18'
R.V.O.
Rabaul
ST GEORGE'S CHANNEL
Simpson
Harbor
Line R-9
(17)
1257
1252
1240
1236
Line R-8
(14)
(18)
1219
1215
R-7
(16)
1208
Matupit
Island
Matupit
Harbor
1152
1158
Line
1137
1125
R-6
(15)
0850
0900
0910
End of
sonobuoy profile
Vulcan Point
Line R-2
(12)
Karavia
Bay
BLANCHE
BAY
0938
0940
0946
(13)
Line R-3
1000
1010
1110
1100
Line R-5
1020
0840
0830
0820
Line R-1
1030
1034
1038
1042
Line R-4
Raluana Point
GAZELLE
PENINSULA
NEW BRITAIN ISLAND
0
3 KM

Fig 4

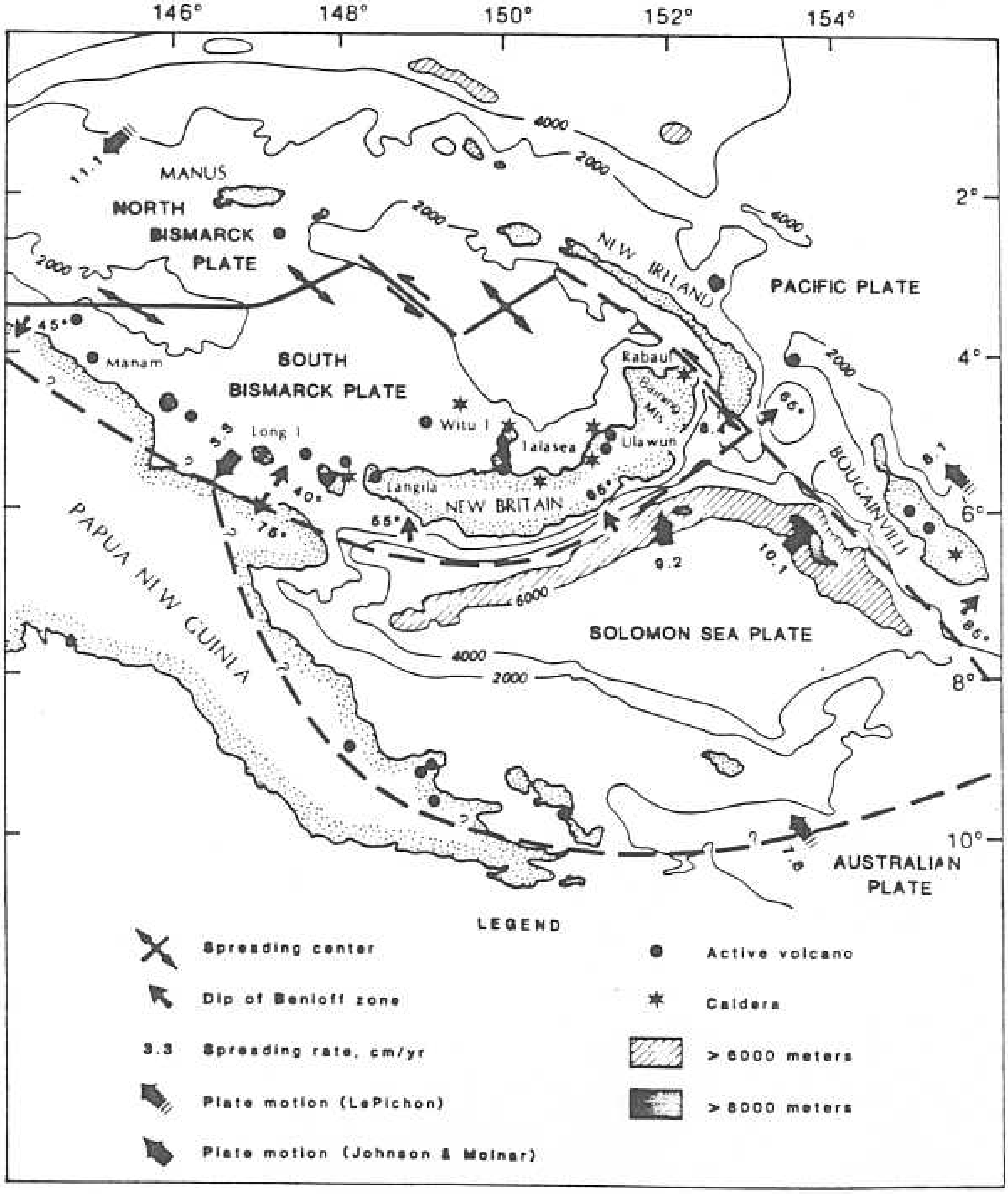

146°
148°
150°
152°
154°
2°
4°
6°
8°
10°
4000
2000
6000
11.1
MANUS
NORTH BISMARCK PLATE
PACIFIC PLATE
NEW IRELAND
SOUTH BISMARCK PLATE
45°
Manam
Rabaul
Baining Mts
66°
8.4
3.5
Long I
Witu I
Talasea
Ulawun
40°
Langila
NEW BRITAIN
65°
55°
75°
9.2
10.1
BOUGAINVILLE
8.1
85°
PAPUA NEW GUINIA
SOLOMON SEA PLATE
7.6
AUSTRALIAN PLATE
LEGEND
Spreading center
Dip of Benioff zone
3.3 Spreading rate, cm/yr
Plate motion (LePichon)
Plate motion (Johnson & Molnar)
Active volcano
Caldera
> 6000 meters
> 8000 meters

Fig. 5

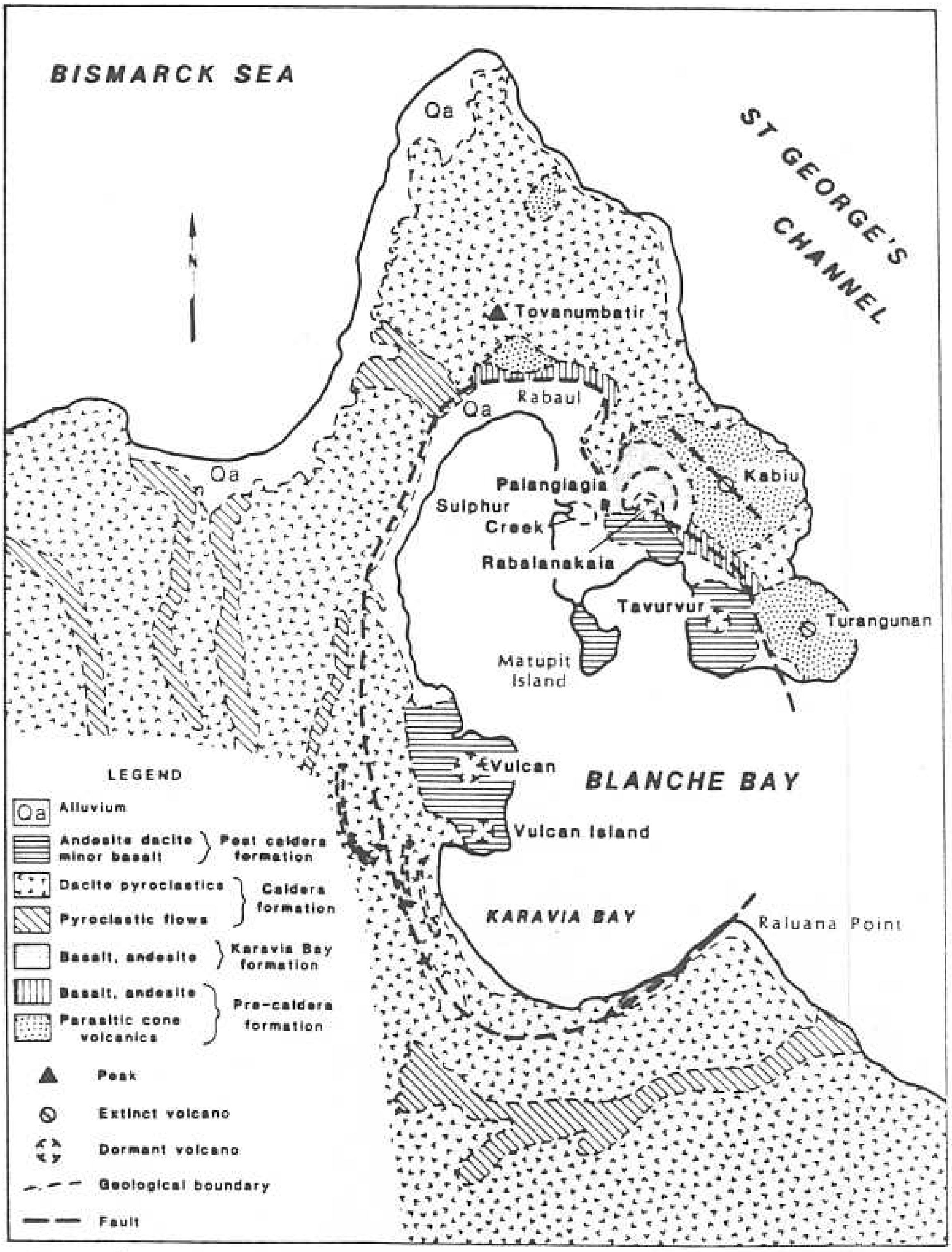
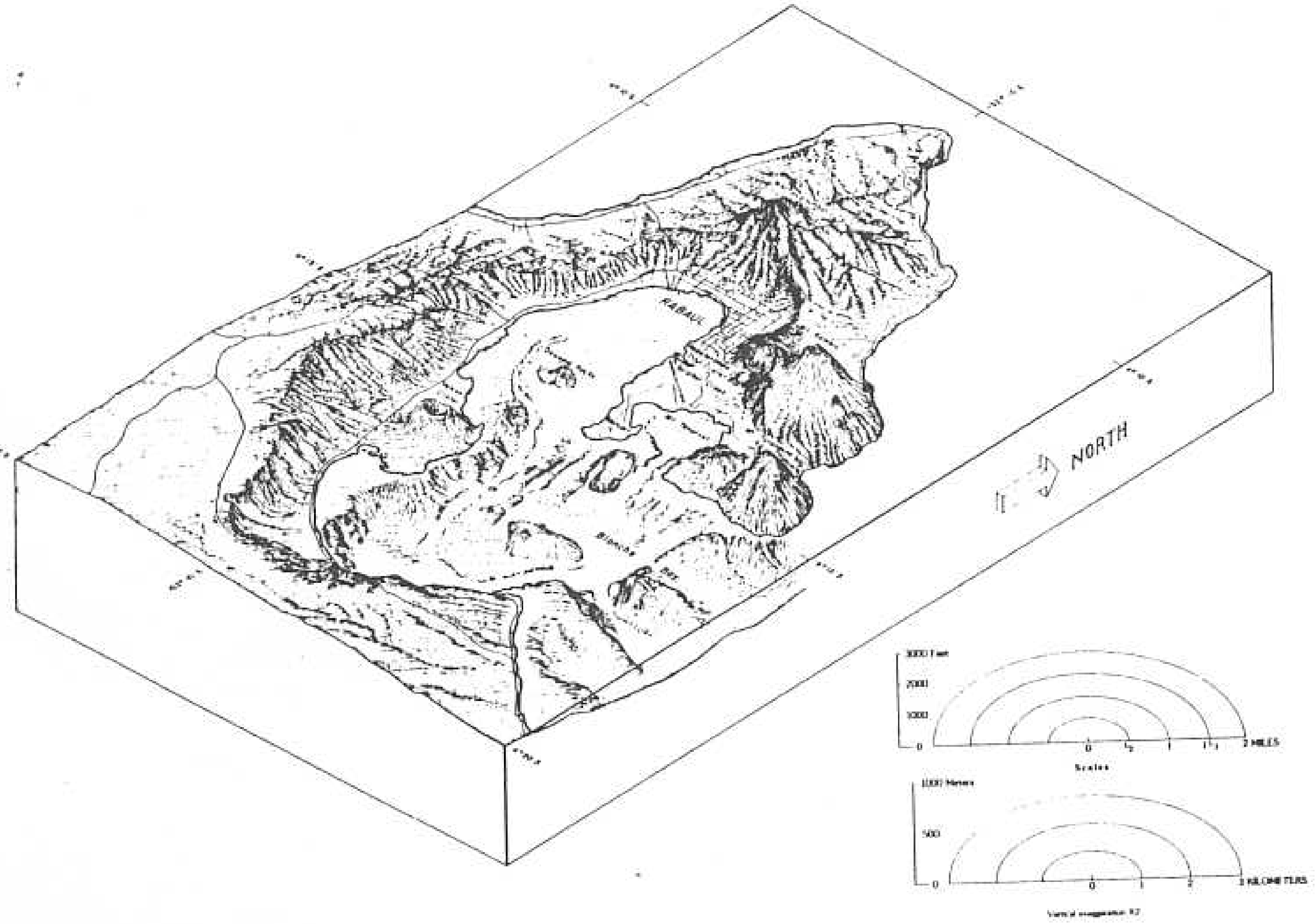
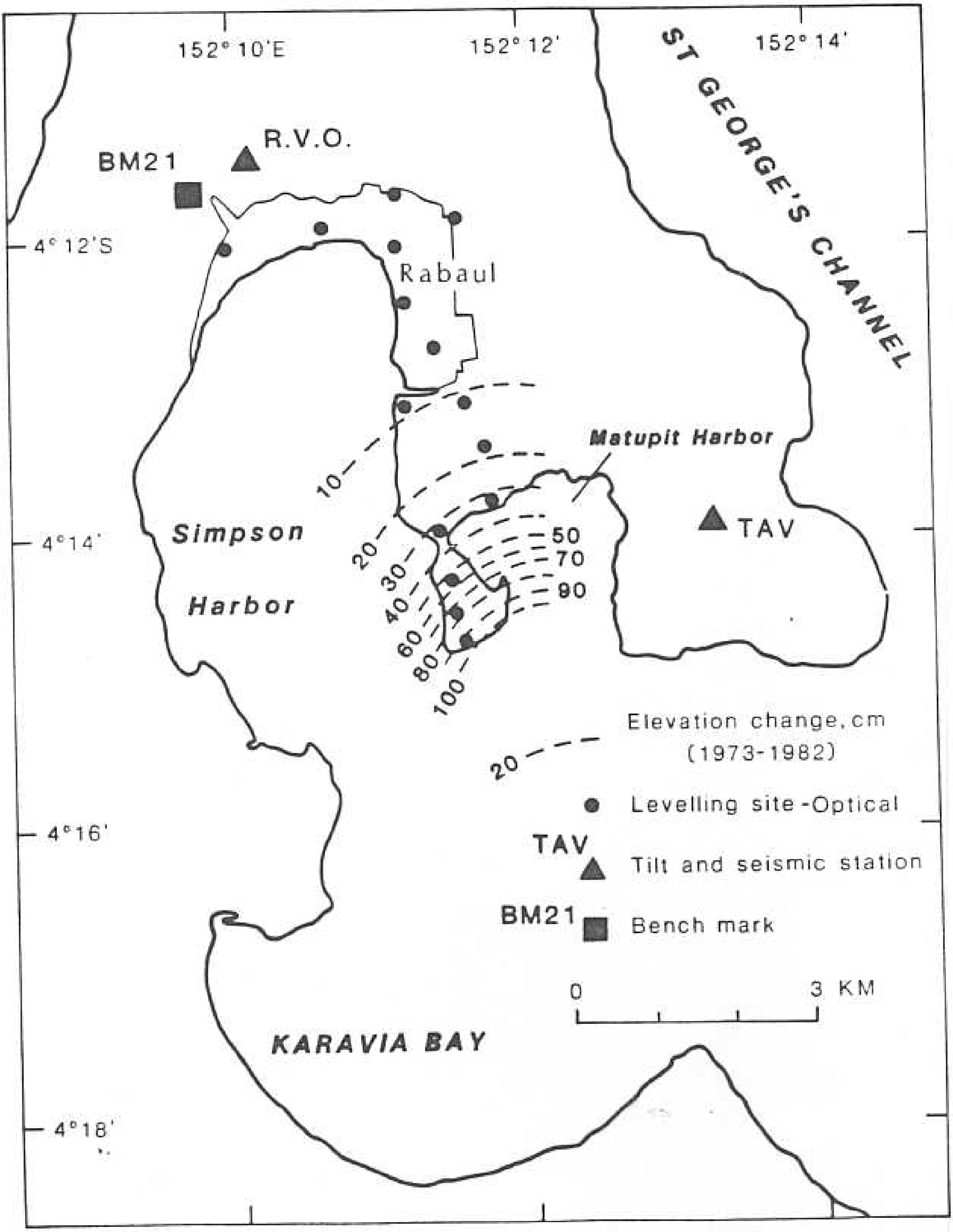

BISMARCK SEA
ST GEORGE'S CHANNEL
N
Qa
Tovanumbatir
Rabaul
Qa
Qa
Kabiu
Palangiagia
Sulphur Creek
Rabalanakaia
Tavurvur
Turangunan
Matupit Island
Vulcan
BLANCHE BAY
Vulcan Island
KARAVIA BAY
Raluana Point
LEGEND
Qa Alluvium
Andesite dacite minor basalt } Post caldera formation
Dacite pyroclastics } Caldera formation
Pyroclastic flows
Basalt, andesite } Karavia Bay formation
Basalt, andesite } Pre-caldera formation
Parasitic cone volcanics
Peak
Extinct volcano
Dormant volcano
Geological boundary
Fault

Fig : 6


RABAUL
Blanche
Bay
NORTH
3000 Feet
2000
1000
0
0
½
1
1½
2 MILES
Scales
1000 Meters
500
0
0
1
2
3 KILOMETERS
Vertical exaggeration X2

7


152° 10'E
152° 12'
152° 14'
ST GEORGE'S CHANNEL
R.V.O.
BM21
4° 12'S
Rabaul
Matupit Harbor
TAV
Simpson
Harbor
4°14'
10
20
30
40
60
80
100
50
70
90
Elevation change, cm
(1973-1982)
20
● Levelling site -Optical
TAV
▲ Tilt and seismic station
BM21
■ Bench mark
0
3 KM
4°16'
KARAVIA BAY
4°18'

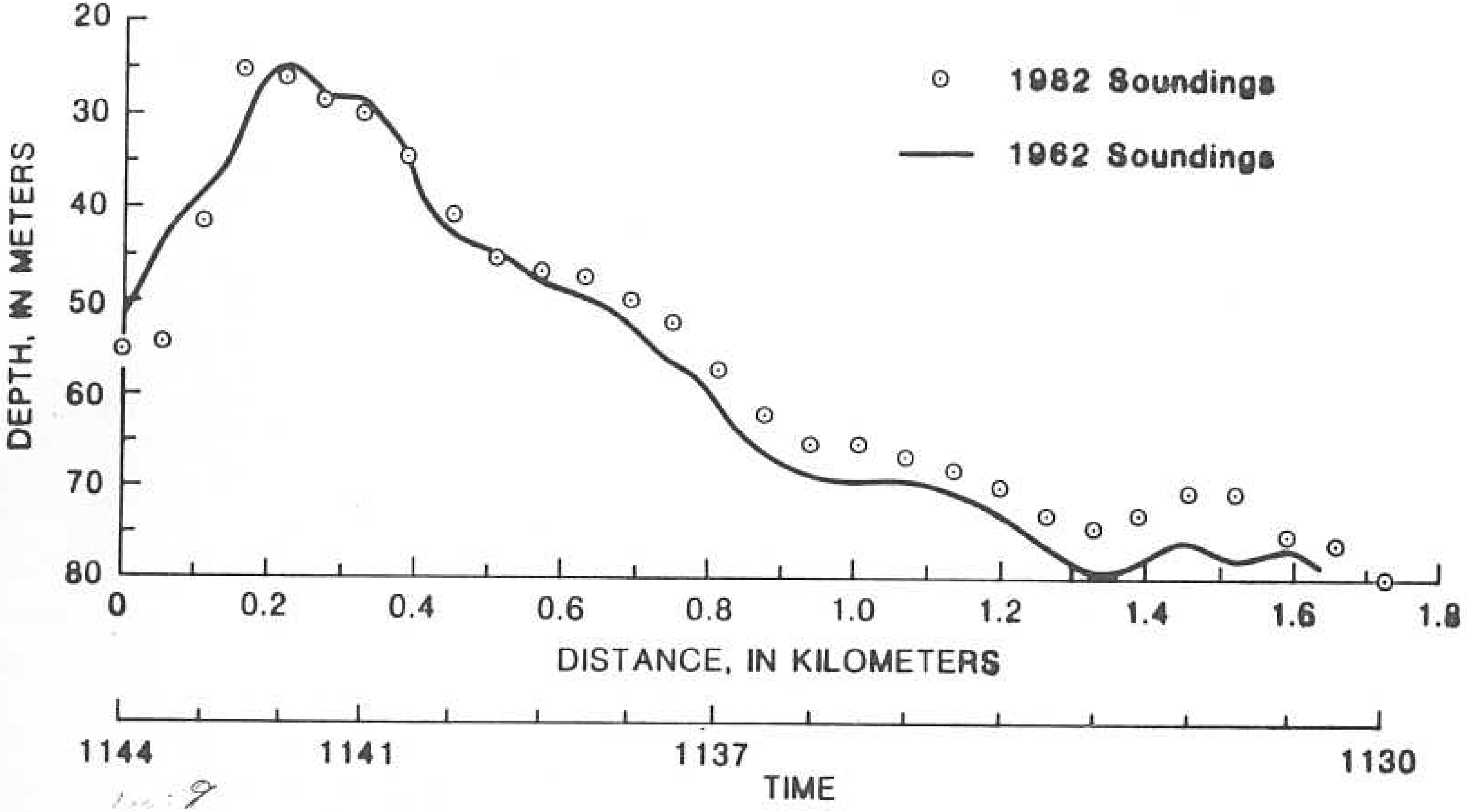
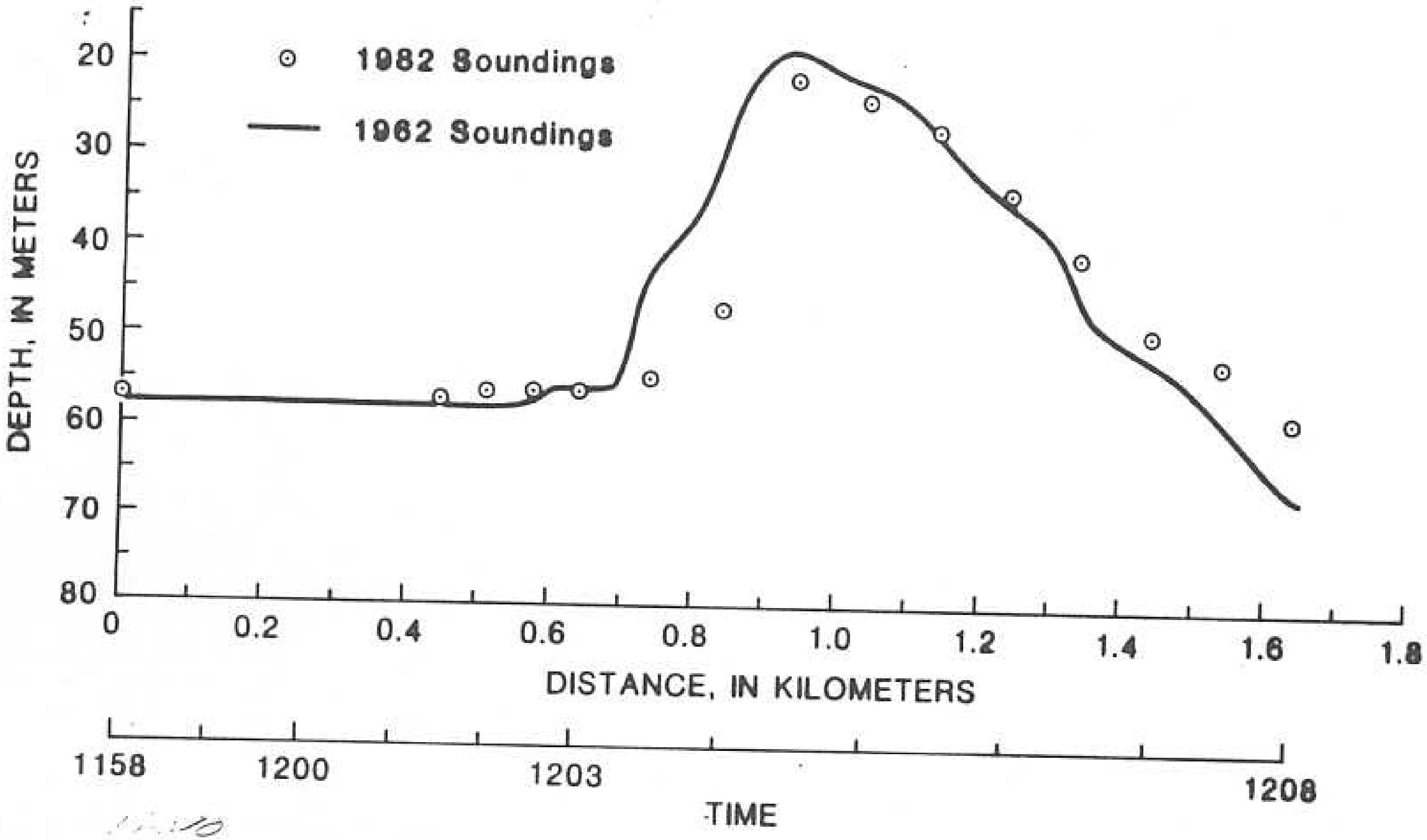
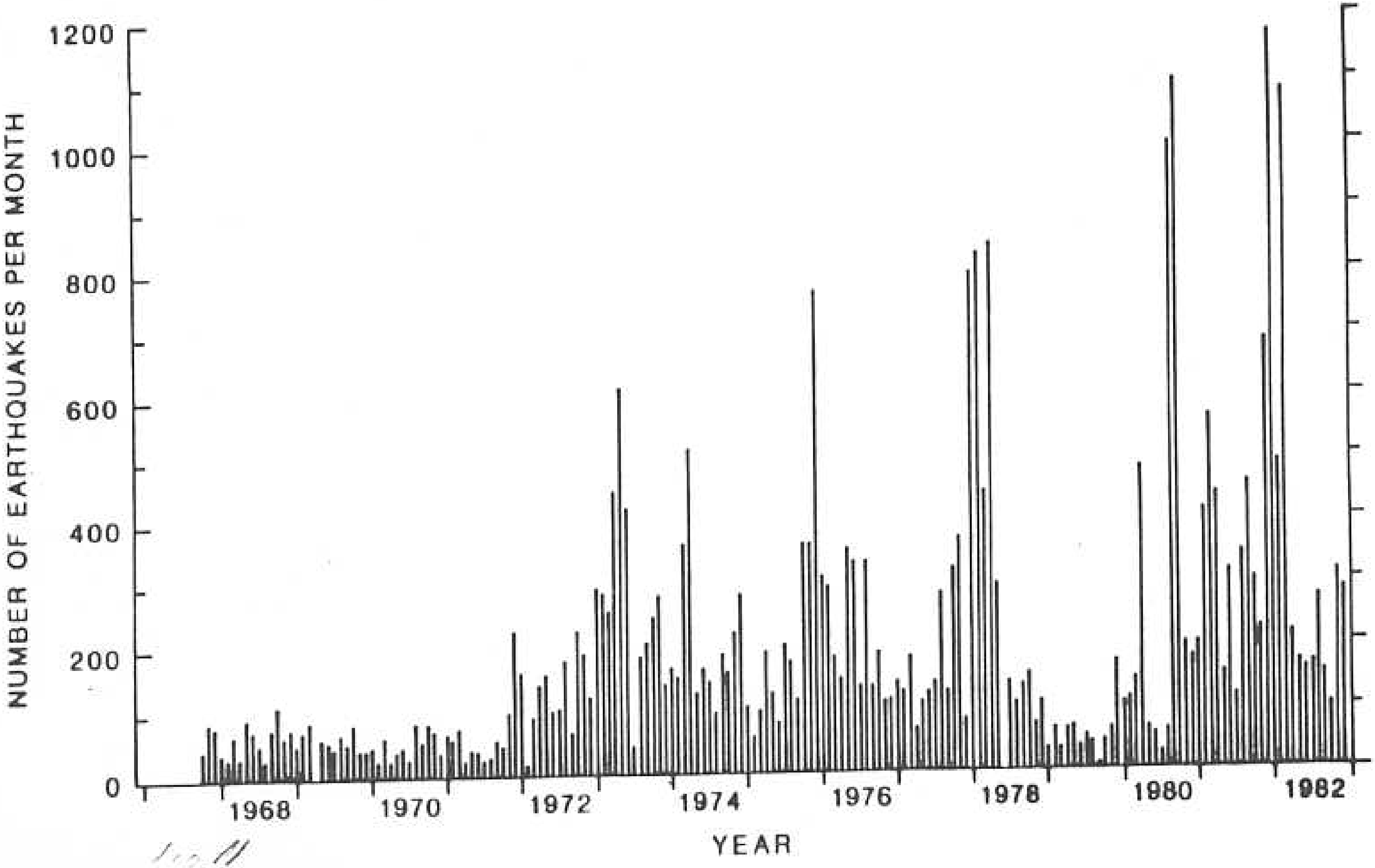
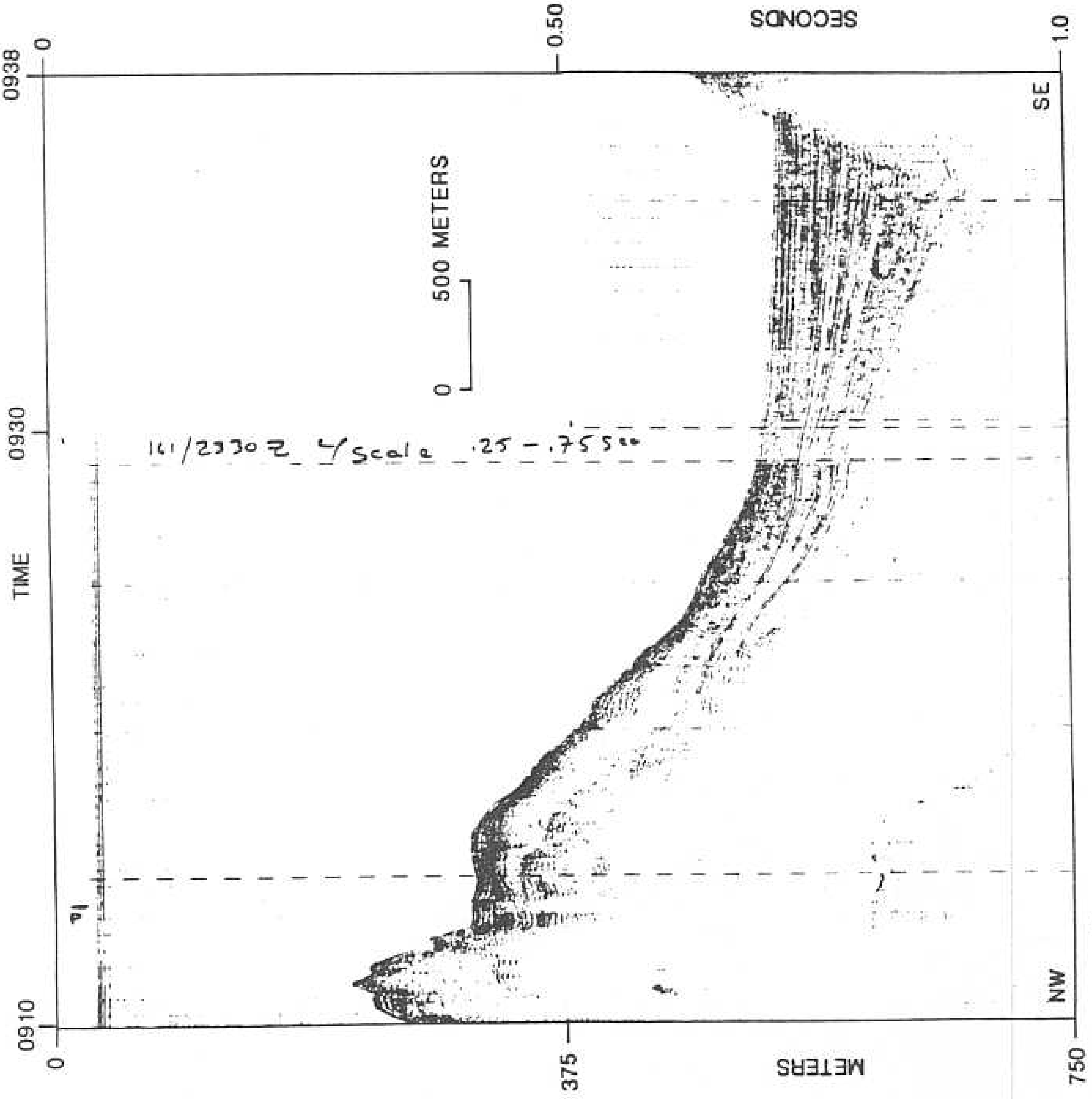

20
30
40
50
60
70
80
DEPTH, IN METERS
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DISTANCE, IN KILOMETERS
1144
1141
1137
1130
TIME
1982 Soundings
1962 Soundings

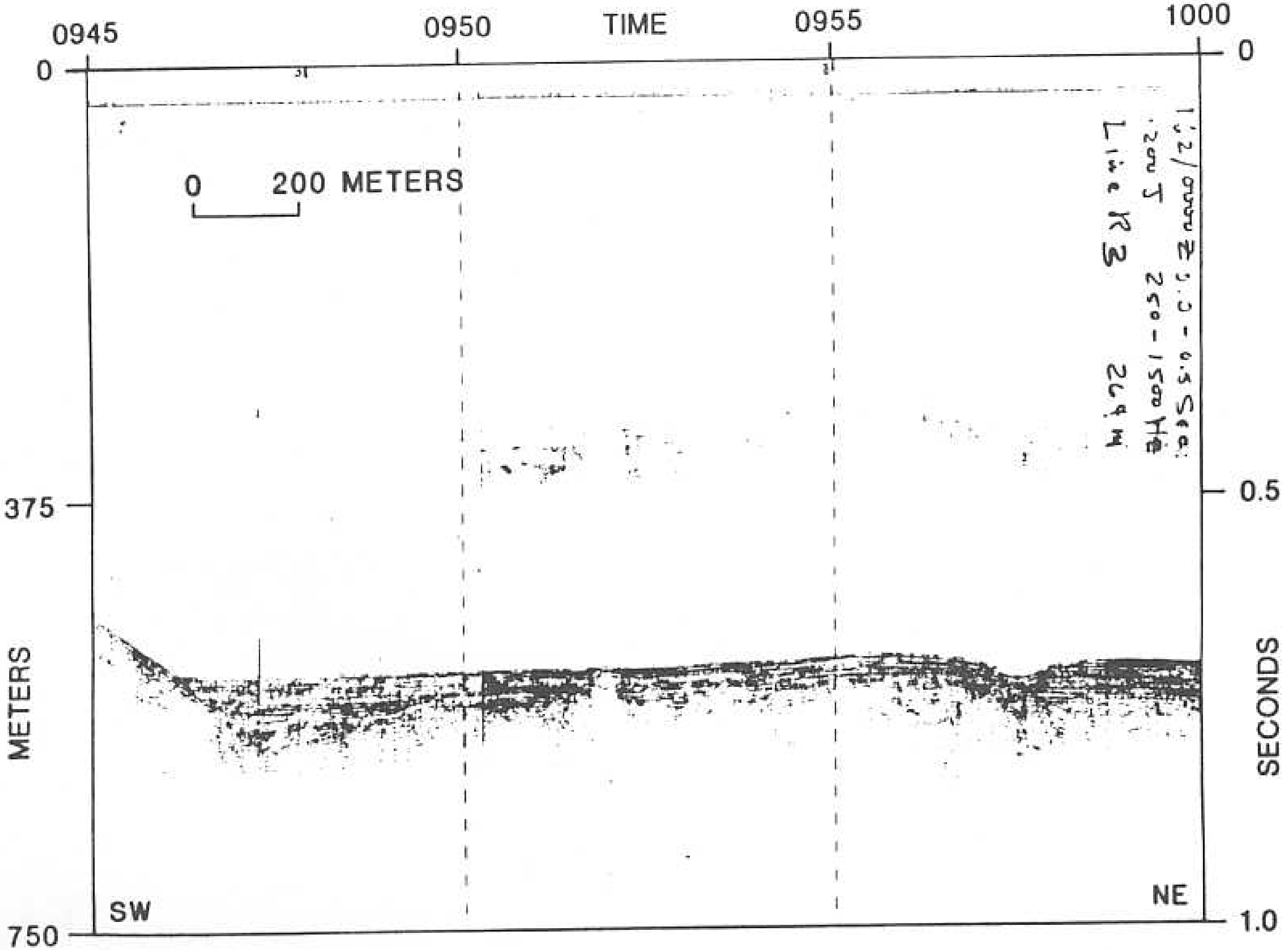
Fig. 9


1982 Soundings
1962 Soundings
DEPTH, IN METERS
20
30
40
50
60
70
80
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DISTANCE, IN KILOMETERS
1158
1200
1203
1208
TIME

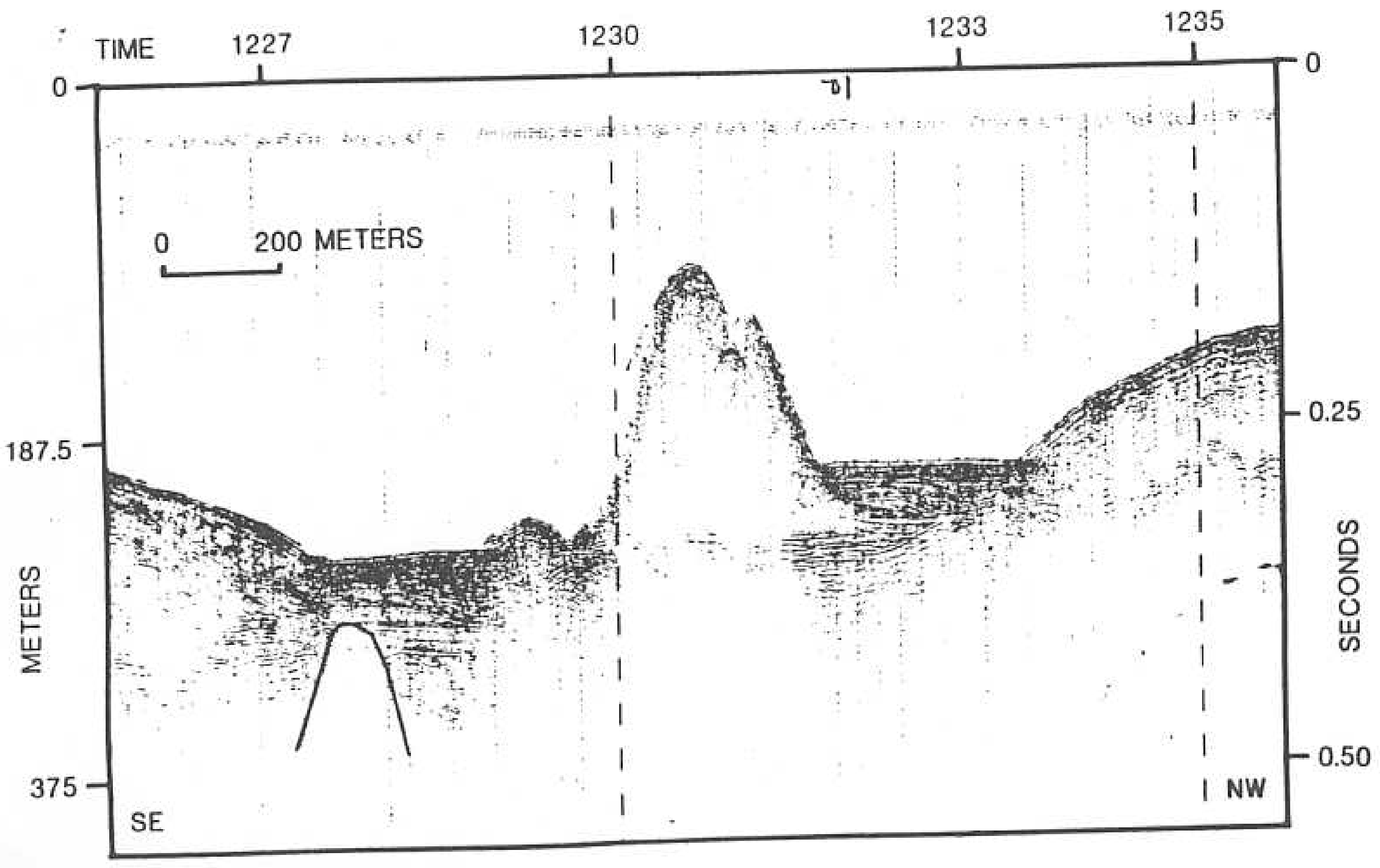
10


NUMBER OF EARTHQUAKES PER MONTH
0
200
400
600
800
1000
1200
1968
1970
1972
1974
1976
1978
1980
1982
YEAR

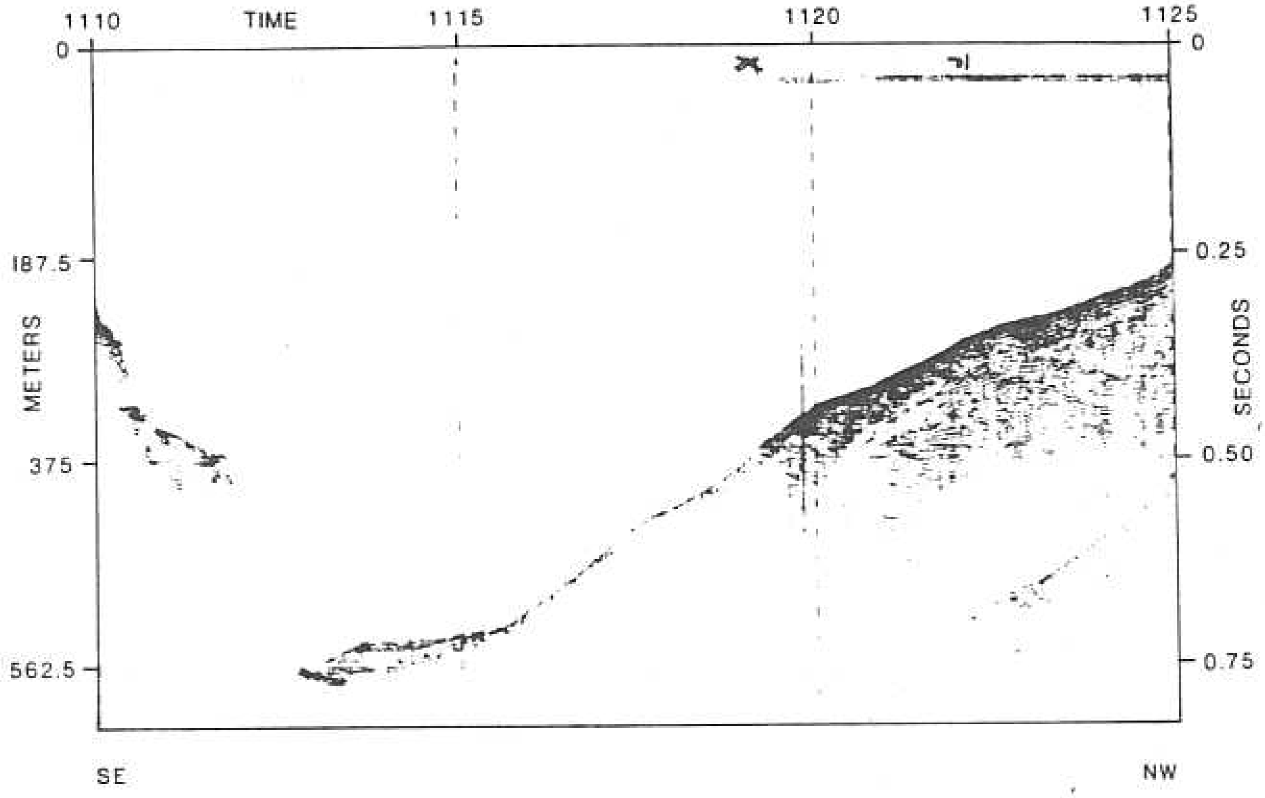

TIME
0910
0930
0938
SECONDS
0
0.50
1.0
METERS
0
375
750
500 METERS
0
NW
SE
161/2330Z ¼ Scale .25 - .75 sec

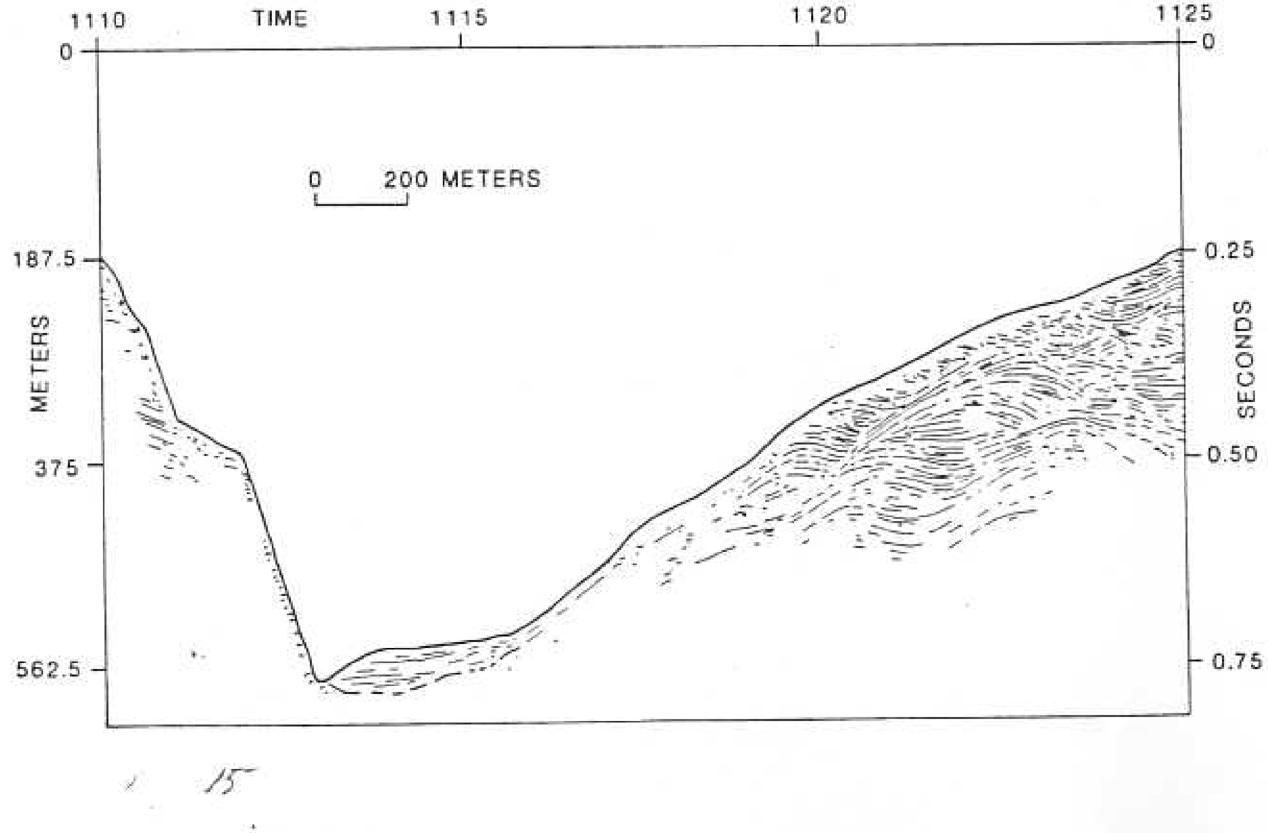

TIME
0945
0950
0955
1000
METERS
0
375
750
SECONDS
0
0.5
1.0
0
200 METERS
SW
NE
1.2/0000Z 0.0 - 0.5 Sec;
·200 J
250-1500 Hz
Line R3
269 m

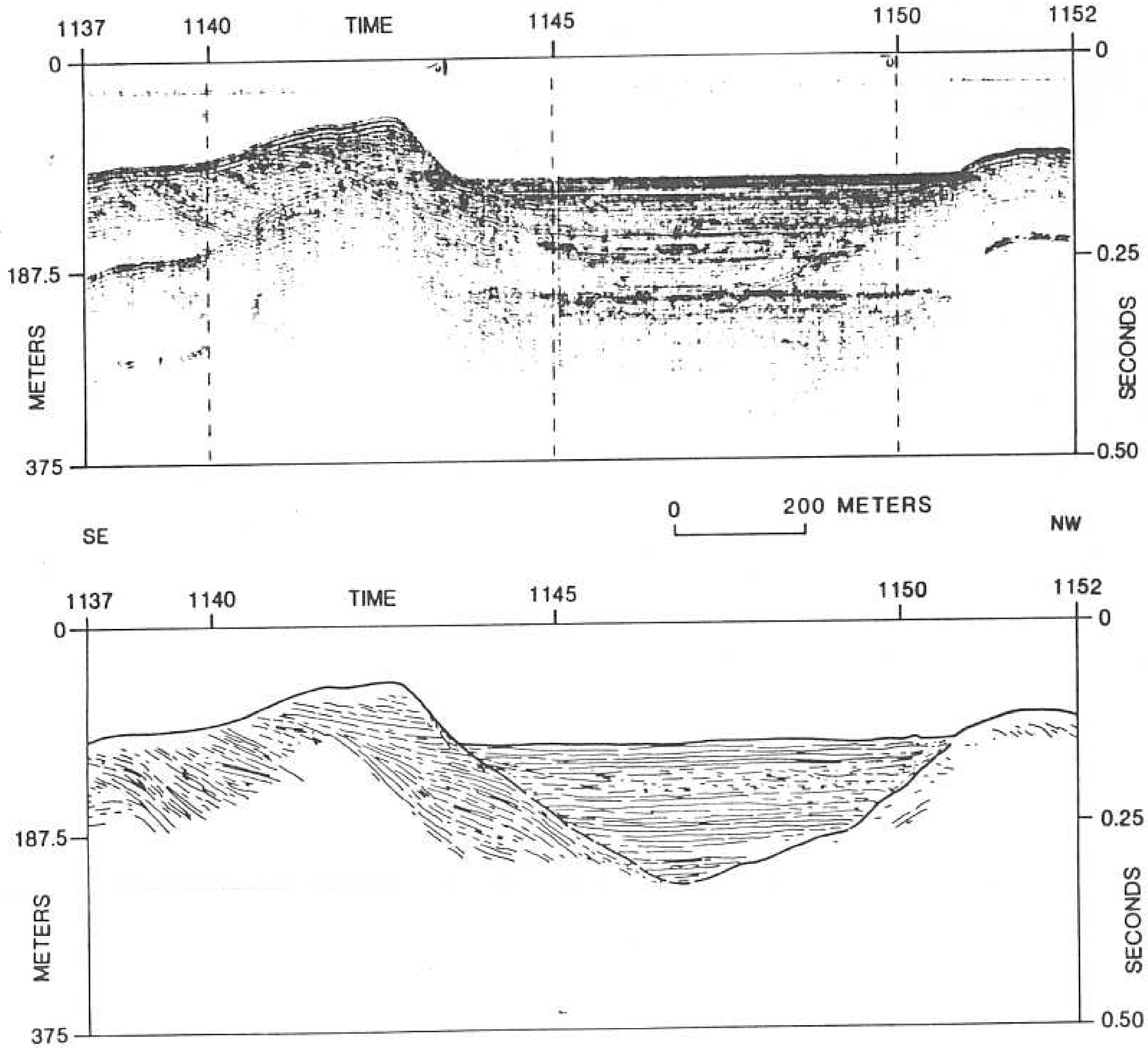
13

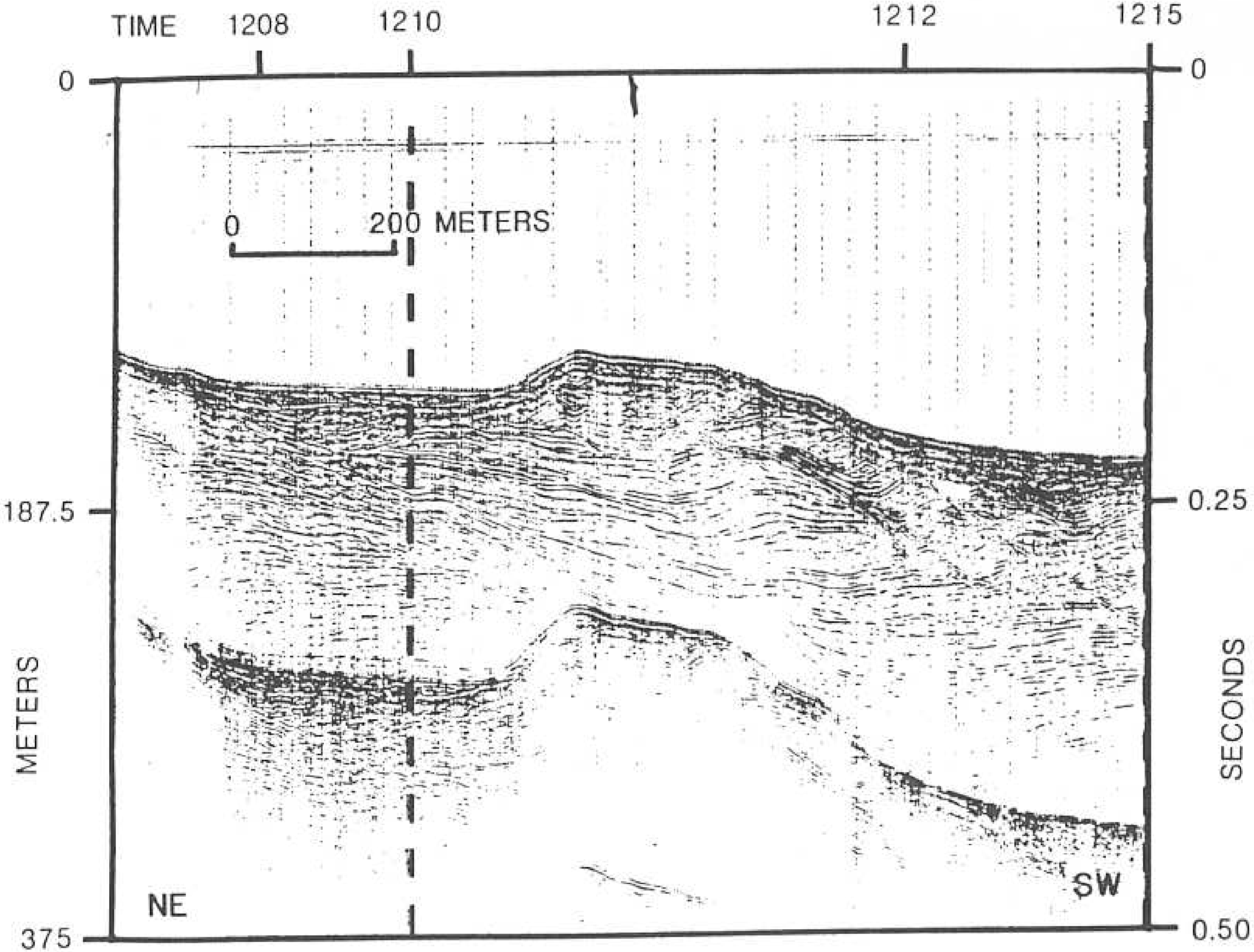

TIME
1227
1230
1233
1235
0
0.25
0.50
SECONDS
0
187.5
375
METERS
0
200 METERS
SE
NW

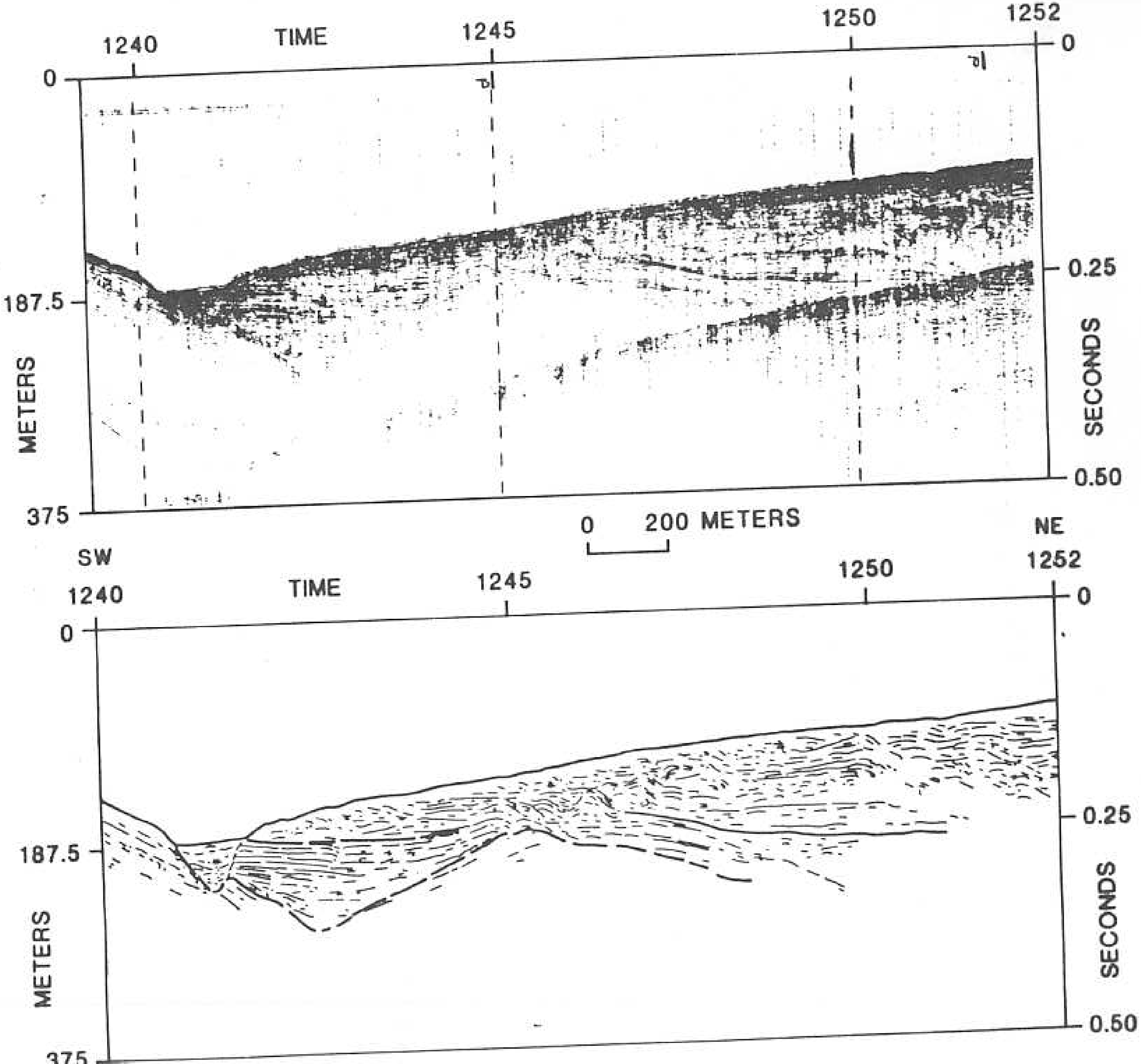
14


1110
TIME
1115
1120
1125
0
187.5
375
562.5
METERS
0
0.25
0.50
0.75
SECONDS
SE
NW


1110
TIME
1115
1120
1125
0
0 200 METERS
187.5
375
562.5
METERS
0
0.25
0.50
0.75
SECONDS


1137
1140
TIME
1145
1150
1152
0
187.5
375
METERS
0
0.25
0.50
SECONDS
0
200 METERS
SE
NW
1137
1140
TIME
1145
1150
1152
0
187.5
375
METERS
0
0.25
0.50
SECONDS


TIME
1208
1210
1212
1215
0
200 METERS
METERS
0
187.5
375
SECONDS
0
0.25
0.50
NE
SW


1240
TIME
1245
1250
1252
0
187.5
375
METERS
0
0.25
0.50
SECONDS
0 200 METERS
SW
NE
1240
TIME
1245
1250
1252
0
187.5
METERS
375
0
0.25
0.50
SECONDS