# A SCIENCE PLAN FOR DRILLING IN WESTERN PACIFIC ARC, TRENCH, BACKARC SYSTEMS

REPORT OF A PLANNING CONFERENCE HELD AT SCRIPPS INSTITUTION OF OCEANOGRAPHY, 25 - 28 JUNE, 1985

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REPORT OF PLANNING CONFERENCE-WESTERN PACIFIC ARC-TRENCH-BACKARC BASIN SYSTEMS

I. INTRODUCTION

A planning conference was convened at Scripps Institution of Oceanography on 25-27 June 1985 to develop a science plan for the study of the active arc - trench - backarc systems of the Western Pacific. The meeting was advertised in EOS and was open to all interested in attending. In addition to about 35 US participants, there were guests from France, Japan and New Zealand who had expressed an interest in the meeting. The purpose of the meeting was to consider scientific objectives, and to propose possible study sites, that could be addressed by the Ocean Drilling Program.

The conference proceeded in three phases; first, we discussed the general nature of the geological evolution of intra-oceanic arc - trench - backarc systems and drew up a list of problems that need further study in order to improve our understanding of crustal evolution in these systems. Models for the tectonic - petrologic development of arc - trench - backarc systems, most of them developed by the participants as a result of previous work, were summarized, new problems and concepts were discussed, and important unsolved problems were identified. Some specific problems were also discussed such as the significance and origin of the uplifted blocks of oceanic crust, and the diapirs of serpentinized peridotite, found in the forearcs of the Mariana and Bonin systems. Other specific topics included the petrologic charavteristics of backarc basin basalts and their similarities/differences to MORB or to arc magmas; the nature of the Valu Fa ridge (Tonga Arc) "magma chamber", and sedimentologic - tectonic problems related to accretion and vertical tectonism in forearcs. The ophiolite problem was reviewed and we discussed the importance of developing a better understanding of the structure, composition, and physical properties of the crust/upper mantle in intra-oceanic arc - trench - backarc systems in order to be able to distinguish between ophiolites derived from deepsea oceanic lithosphere versus lithosphere originally formed in other settings such as backarc basins. The conferees agreed that there is good evidence in support of the long-standing assumption that ophiolites are fragments of oceanic lithosphere but there was considerable doubt among participants at this meeting that the rocks of ophiolites necessarily represent lithosphere formed at mid-ocean ridge spreading centers. Other settings such as backarc basins or even island arcs may have been the site of formation of many of the ophiolites. The difficulty in recognizing petrologic-geochemical signatures sufficient to distinguish between mid-ocean ridge basalts and some backarc basin basalts requires data more extensive than can be obtained by dredging of seafloor exposures.

The second phase of the meeting was devoted to considering various regions where the major problems could be studied. Four regions were selected as being the most promising in terms of the problems needing further study and in view of the extensive geologic data that exists. These were the Izu-Bonin, Mariana, Lau-Tonga, and Banda-Sulu arc systems. At this time we did not attempt to rank any of these in terms of priority; each has special merits and offers insight to different aspects of the common theme of crustal evolution at convergent plate margins in intra-oceanic settings.

The final phase of the meeting resulted in compilation of a list of proposed drill sites, in each of the four regions, that would provide very important data to help answer some of the fundamental problems we discussed. The conferees also agreed that the proposed ODP drill sites would be important not only in retrieving the stratigraphic record at these sites but would be important for long term studies involving logging of physical properties, study of hydrothermal circulation, pore fluid chemistry and its changes with time, and seismic experiments. We recognized that drilling is but one part of what should be a continuing multi-disciplinary project. We endorse the continued survey of arc systems both on land and at sea using "conventional" geologic and geophysical techniques, the use of manned and remote controlled undersea vehicles and platforms, and the drilling of deep crustal holes on islands of the forearc such as Guam, Saipan, Eua or in the Bonins.

## II. The Backarc Basin - Island Arc Ophiolite Analog: A Problem for Deep Drilling?

Although ophiolites have traditionally been regarded as the model of typical oceanic crust recent detailed chemical and mineralogical studies of both ophiolite and island-arc rocks strongly suggest that many classic ophiolites are more closely related to an arc or near-arc setting rather than to a typical ocean ridge spreading center. The latter vary typically from "normal" depleted or "tholeiitic" MORB, to relatively alkaline basalts, approaching typical ocean island basalt in composition. In contrast, many ophiolites may include some MORB-like tholeiitic pillow lavas, but these grade into mildly calc-alkaline to highly calcic andesitic, arc tholeiitic, or boninitic rocks typical of intra-oceanic island arcs such as Tonga or the Marianas. These arc affinities were recognized in the Troodos ophiolite by Miyashiro (1973) mainly in terms of major element characteristics of the pillow lavas, but he also noted that the overall structure ans stratigraphy of Troodos could be equated with an island-arc setting. Ewart and Bryan (1972) emphasized the geochemical similarity of the early-stage basaltic andesites of the Tonga island arc to some ocean-ridge basalts, as well as to pillow lavas reported from some ophiolites. They interpreted the pillow lava/sheeted dike/gabbro complex exposed on Eua Island as the top of an underlying ophiolite complex, which was presumed also to be the source of periodotites dredged from the lower forearc slope. Studies of the Zambales Range ophiolite (Philippines) led Hawkins and Evans (1983) to propose that it compresses remnants of arc and backarc basin crust. Bloomer and Hawkins (1983) proposed that rocks exposed on the slopes and forearc of the Mariana Trench constituted an ophiolite suite although most of the rocks indicate an origin in an arc setting. Recent studies of peridotites from ophiolites and oceanic fracture zones confirm that there are consistent differences in spinel and pyroxene compositions between typical abyssal peridotites and those of many ophiolites (Dick and Bullen, 1984; Dick and Fisher, 1984). Hickey and Frey (1982) demonstrated that similarity in rare earth patterns between boninites from several west Pacific island arcs and the lower pillow lavas from the Betts Cove ophiolite complex; similar relations are seen in the arch-derived ophiolite of the Zambales Range (Hawkins and Evans, 1983). Much more detailed analysis of fresh, glassy pillow rims from the Troodos Ophiolite (Robinson et al, 1983) have confirmed the earlier suspicions that these are island-arc related; specifically, it is suggested that all of the Troodos ophiolite was created in a setting similar to the Bonin or Marianas arc.

Although the chemical and mineralogical evidence are persuasive, the classic ophiolite definition is based on stratigraphy and overall lithologic associations. To date, these are not well-defined either in the deep ocean basins or the island-arc environment. Hopefully, one or more deep holes in oceanic crust will be successfully completed during the ODP program. Similar consideration should be given to one or more deep holes in a island arc setting, for comparison both to the oceanic crustal section and to typical ophiolite stratigraphy.

Compared to deep ocean crust, the site selection for this hole (or holes) poses greater problems in the arc environment. "Arc-ophiolites" may well be composite sections made up of fragments of oceanic crust, fore-arc crust, and back arc basin crust which have been tectonically shuffled and superimposed on one another. Hopefully, the "oceanic" part of any such composite ophiolite can be deduced from drilling already planned on or near the mid-ocean ridges. Remaining questions which must be addressed, then, seem to be the following:

1. What portion of the island arc stratigraphic section can be deduced from field studies on land?

2. To what extent can deep drilling in the forearc clarify relations between "tholeiitic" arc basals, sheeted dikes, andesitic or boninitic lavas, and ultramafic rocks?

3. What elements of "arc-ophiolite" stratigraphy may be defined by drilling on or near a back-arc spreading center?

4. Can any details of tectonic evolution of the arc be deduced from deep drilling in fore-arc or back-arc regions?

5. What down-hole experiments can be used to help define major stratigraphic units, structural boundaries, and the lateral continuity of these features?

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## III. SUMMARY OF SPECIFIC PROBLEMS FOR STUDY

### A. Major Scientific Problems in Intra-Oceanic Forearcs

The forearc regions of the intra-oceanic arc-trench systems of the western Pacific provide an opportunity to study several major problems of importance to understanding the evolutions of convergent plate margins. These problems may be separated into those pertaining to the accretion - underplating - or erosional processes on the inner trench slope and to those bearing on the history of the forearc basin and its sedimentologic-tectonic history.

The forearc regions of the intra oceanic arc systems have proven to be very complex and are much less well understood than those of arcs in which thick sections of sediment are being accreted or consumed. A very different mode and distribution of deformation is also suggested by the available data. Typically, little or no sediment appears to be accreted to the trench slopes of oceanic forearcs, exposures on the trench slope are comprised largely of igneous rocks. Despite this lack of accreted sediment, oceanic forearcs show a general increase in width with age. The great water depth, paucity of seismically imageable sediments and the apparent complexity of these forearcs has combined to leave us with a very unsettled state of affairs. Recent reconsideration of drilling and other marine data have even called into question some of the initial interpretations which led to the conslusion that there arcs were loci of persistent tectonic erosion.

One of the most startling discoveries, in the Mariana forearc, was that igneous rocks, of arc origin occurred very close to, and on, the trench slope (for discussion see Bloomer, Appendix of this report). This observation, coupled with recognition of normal faulting in the forearc and interpretation of large scale subsidence, was cited as the basis for the lateral and vertical removal of forearc material since the late Eocene by tectonic erosion. Subsequently it was noted, that the present distribution of upper Eocene arc volcanics outlined a 200 km wide volcanic arc comprised of arc tholeiite and boninites, which is quite unlike any present day young oceanic arc system. Reanalysis of the paleodepths indicated by the core data together with indication of progression outbuilding of the upper slope apron pointed toward uplift, or at least lack of subsidence, in the forearc as well as a lack of forearc truncation. Together these observations cast doubt on the role of tectonic erosion since the late Eocene and suggest a very anomalous situation in the early (upper Eocene) phase of arc development.

Tectonism since this early phase has been suggested by Seabeam and sidescan (SeaMARC II) studies to be primarily an internal disruption of the forearc basement by such processes as serpentine diapirism and block faulting induced by seamount collision. To what extent these processes dominate the evolution of the Mariana forearc, let alone oceanic forearcs in general, remains topics of speculation.

Studies of the sediments and the stratigraphic record of forearcs are critical to the development of our ideas about their evolution and structure (for discussion see Haggerty in Appendix of this report). Detailed sedimentological and paleontological studies can help determine the history of vertical motion in oceanic forearc regions. This information is essential because the magnitude of the movements, whether these be uplift, subsidence, or more likely a combination, places constraints on thermal and mechanical models for the evolution of active margins. Determination of the vertical history is therefore important to an integrated drilling program dealing with the processes, structure, and petrology of active margins. Drilling is the most appropriate means for obtaining a complete stratigraphic data set for interpretation of the vertical history compared to dredging or other sampling techniques.

Studies of sediments for unraveling vertical tectonics of an area require an interdisciplinary approach. Data from paleontological and sedimentological studies are combined to provide time-stratigraphic information. Paleontological studies provide us with a chronologic framework for ordering the sequence of depositional (and/or redepositional) events and changes in the ecologic environment and paleodepth. The effects of global sea level change and sediment loading must be accounted for in order to adequately estimate the vertical tectonic motion as the consequence of mechanical effects, such as underplating or thermal effects from the subducting, cold slab.

In contrast to Karig and Ranken's (1983) proposition that some uplift has occurred in the Mariana forearc, several other reports cite tectonic erosion and subsidence of the same forearc (La Traille and Hussong, 1980; Mrozowski and Hayes, 1980; and von Huene and Uyeda, 1981), or even a change in response along the arc or across the arc. The question of intermittent accretion and tectonic erosion in the forearc region has never been properly addressed with an appropriate suite of samples from an intra-oceanic convergent margin.

Studies of the sediments from the forearc for vertical motion also lend themselves to addressing other problems such as the timing of volcanic or intrusive activity in the forearc region. The biostratigraphic age of the sediment can yield minimum age of volcanism or a maximum age of intrusion. This will also be important for comparative purposes with tephrochronology. If radiometric dating of igneous material proves to be unsuitable because of a high degree of alteration, then the biostratigraphic (or paleomagnetic) data are necessary. If hydrothermal circulation is associated with intrusive activity, there may be a diagenetic signature in the nearby and/or overlying sedimentary strata. Diagenesis can be governed by the chemical composition of the pore waters which can change their composition during migration through the rocks. Studies of the interstitial waters retrieved from these sediments will also be valuable because they may reveal chemical changes that were undetected in the solid phase geochemistry of the sediments. The question of a diapiric origin of seamounts in the forearc region (Fryer et al. in press) may also be addressed by studying the history of the vertical motion of the strata immediately overlying the bathymetric high and comparing it to the history of an adjacent region.

The tectonic setting in which new trenches and oceanic arcs originate also remains a major problem. Do these arcs originate within oceanic plates randomly or along transform zones, or do they evolve from earlier, perhaps continental margin arcs? Associated with the problem of the origin of these arcs is the possible relationship of arc crust to ophiolites. Do arcs build on ophiolitic substrates or might certain ophiolites actually develop within oceanic forearcs?

Studies that we feel could best address these major problems about the origin and evolution of oceanic forearcs include: (1) the spatial and temporal distribution of vertical displacements across the forearc; (2) the nature of igenous and metamorphic activity in the forearc; (3) the character of deformation in the forearc as functions of space and time. If these specific objectives can be reached, the more fundamental processes that control the origin and evolution can be much more tightly constrained, or perhaps even yet unperceived processes will be uncovered.

1) Vertical Displacement

Vertical displacement should be determined in forearc systems from the volcanic chain to the trench and during the evolution of the arc system. These determinations would be easiest where there is a thick, relatively undeformed sediment section in which relative displacement can be seen in tilted and offset horizons, and displacements with respect to sea level can be determined using the various paleodepth criteria. The techniques of backstripping can be used to reconstruct vertical profiles over the history of the arc. Thick sediment sections in oceanic forearcs occur primarily in upper slope aprons, but frontal arc platforms, which are occasionally uplifted so far as to form islands, also preserve a moderate sediment cap. The lower trench slope, with a very thin, irregular sediment cover, which often is displaced by slumping or other gravitational processes, and which may even occasionally originate by accretion from the oceanic plate, can provide valuable information, but only if very carefully analyzed.

Features of subducting oceanic plate that may affect a vertical response in the arc must also be investigated. These include the paleodepth or the decending plate, the effects of seamounts and other colliding entities, as well as of the normal faults that develop on the outer slope. Vertical motions of the forearc caused by features of the descending plate might be tested by a comparison of forearcs in which distinctly different tectonic crust is being subducted; e.g., very young versus old, smooth versus rough.

A prime candidata for studying vertical motion in an intra-oceanic forearc is the Mariana convergent margin because it is the region with the best data collection to date from numerous dredging operations as well as a previous DSDP cruise resulting in six drill holes. The recommended study location is at 15°N in a more equatorial location than the previous 18°N Mariana transect because there may be better preservation of calcareous microfossils owing to a supressed equatorial CCD. The drill holes associated with a submarine canyon will yield the younger sediments in the upper flank of the canyon whereas a drill hole in the base of a canyon would obtain older exposed strata and perhaps igneous basement in the forearc. Other recommended drill holes are into and offset from bathymetric highs such as an outer arc high (Izu-Bonin region) or a forearc seamount (Mariana reegion and/or Izu-Bonin region). These bathymetric highs, if above the CCD, may have better preservation of importance calcareous microfossils. Turbidites shed from these bathymetric highs may also contain better preserved carbonate sediments in adjacent depositional depths below the CCD. A drill site in the southern region of the Mariana forearc is advantageous because the data can be combined with a shore-based drilling program or a geologic field program on the island of Guam or Saipan. The importance of such combined data sets from the island tnd the drill site(s) can not be understated because it will yield information about the history of the vertical motion across the forearc.

Additional problems that may be addressed are associated with structure of the forearc and its response to the subduction of seamount chains, such as the Magellan Seamounts to the east of the Mariana forearc, and ridges, such as the Louisville Ridge associated with the Tonga forearc. How does the subduction of these features change the structure of the forearc? Does this increase the horizontal strain across the forearc, change the distribution of the strain or fracture the forearc? From the internal structure of the forearc, what is the deformational style as a consequence of the subduction of such large and small bathymetric and tectonic features? Drill sites located in the forearc region associated with forearc basins, forearc terrace, and the upper trench slope will yield data to address such questions. Studies pertaining to the physical properties of the sediments, seismic reflection data, and seismic velocity structure of the forearc will be important for solving these problems.

2) The Nature of Igneous and Metamorphic Activity

Igneous rocks in oceanic forearcs carry information not only concerning the behavior of the arc but also of the descending plate. In situ igneous rocks of the forearc help constrain the location of past volcanic arcs, back-arc spreading, and possible forearc spreading. This clearly is of major importance in addressing the question of arc-derived ophiolites. It also addresses the problem of the nature of the basement beneath the arc. The relative contribution of seamounts and other fragments of oceanic crust to the forearc are largely determined by the nature of the igneous rocks in the forearc. In short, a much better knowledge of the chemistry, petrology, and "stratigraphy" of igneous rocks in the forearcs is required. One particular aspect of magmatism that must be better known is the variation in intensity of arc volcanism over time and the correlation of these variations with parameters such as subduction rate and back-arc spreading.

Magmatic and hydrothermal heat sources generate metamorphism in the forearc; the metamorphic facies distribution is determined by pressure-temperature conditions (for discussion see Rideout and Guth in Appendix of this report). These conditions may be very important in causing hydration of ultramafic rocks that subsequently form diapirs. Moreover, displaced or nonequilibrium metamorphic facies may reveal mass movements of rock with the forearc and/or changes in the thermal regime as the arc evolves. Much more information about heat flow, pore fluid chemistry and pressure gradients is needed to adequately understand the thermodynamics of oceanic forearcs.

## 3) Internal Deformation within Oceanic Forearcs

Although there is abundant evidence for deformation in forearcs, very little is known quantitatively about the displacement fields and overall effects of the observed structural features. High angle faults are common on islands of the frontal arc and in the upper slope apron but whether those are a response to significant horizontal extension or more to a vertical "jostling" is uncertain. Micro-normal faults in drill cores from forearcs have been associated with these faults but have also been interpreted as effects of shallow downslope creep. The morphology of the lower trench slope has similarly been viewed as reflecting massive normal faultinging and tectonic erosion. On the other hand, emergent complexes though to represent oceanic forearcs display widely spaced shortening structures. The intensity of faulting across the arc, and over time, is also very poorly calibrated, as in the correlation of forearc deformation with collision events.

A second mode of deformation that has been proposed for the forearc is diapirism, driven by serpentinization of ultramafic rocks and producing cone-like structures in the forearc. How these bodies circulate material, where and when they are active, and how they are created are important not only for the determination of forearc structure but also because of insights they provide concerning physical conditions at depth.

Some form of internal disruption, without significant addition or subtraction of material across the plate interface, is almost certainly occurring in the best studied oceanic forearcs. Diapirism is the most attractive process at this time, but such processes as channelized recirculation and shear driven flow within the forearc wedge might also be entertained. The contribution to deformation of accreted masses also cannot be dismissed.

Large horizontal motions within the forearc have not been given much consideration but recent paleomagnetic data indicate rotations of more than $60^{\circ}$ and large latitudinal shifts in rocks of some arcs. How these motions occur and their relationship to the overall structural evolution of forearcs are not understood.

## 4) Methodologies for Study in Oceanic Forearcs

The major objectives outlined above must be approached by a multiplicity of techniques, applied in arc systems where the particular objectives are best expressed, and where the chances of success are best. Ocean drilling will be an indispensable component of study but, more than ever before, drilling must be preceded by and associated with other approaches. Some of these additional types of study include seismic profiling, multichannel bathymetry, sidescan profiling, deep submersible investigations, and island mapping and drilling.

5) Seismic Profiling

There is a pressing need for better seismic profiling in oceanic forearcs, in particular for grids of profiles over the upper slope aprons to adequately delineate patterns of faulting and of basement relief beneath the sediments. Such networks are also needed for the correlation of stratigraphic horizons between drill sites for interpolation of vertical displacement. These surveys would also serve as pre-site investigations of prospective drill sites. Because sediment aprons are usually less than 1500 m thick, state of the art, digital single channel profiles would be sufficient. Simple deconvolution and migration at assumed velocities might significantly enhance data quality. Similar profiling, in conjunction with multibeam bathymetry and for sidescan profiling on the outer trench slope would also be very useful in studying the normal faults and other structures that might affect the behavior of the inner slope.

6) Multichannel Bathymetry

Multichannel bathymetry, such as that provided by Seabeam and SeaMARC II, would be a primary technique for exploration of the deeper sections of both inner and outer trench slopes, where the morphology is complex and the sediment cover is thin to absent. The great water depths reduce the resolution of this technique and in specific instances use of deep-towed acoustic sources might be considered. Multichannel bathymetry was instrumental in delineating the circular diapirs on the inner slope and differentiating them from ridges. Although the technique is much less useful in shallow water and over the smooth sediments of the upper slope, it would be valuable for the mapping of the submarine canyons that cross the upper slope.

7) Sidescan Profiles

Sidescan techniques have proven very valuable in the study of volcanic terranes and of recent structural features. In oceanic areas it would be most valuable in studies of the rough lower trench slopes, but might also help to determine the orientation and correlation of faults in the upper slope apron. On the lower slopes, sidescan images could best outline slump features and small channel systems.

8) Deep Subsersible Investigations

Deep diving submersibles, such as DSRV's Alvin and SeaCliff, have a limited but extremely valuable role in the investigation of oceanic forearcs. Only with this synergistic technique can the detailed characteristics of the diapirs, of recent structure, and of sediment transport processes be obtained. To some degree submersibles might be supplemented by camera and remote video systems but at present these provide no opportunity to pursue interesting observations in realtime. SeaClif, with a 6000 m capability would be able to investigate at least the upper part of the sparsely sedimented lower inner trench slope.

9) Island Mapping and Drilling

The few non-volcanic islands on oceanic arcs provide platforms for various intensive investigations. Most such islands have been at least rudimentarily mapped, but few if any studies oriented toward the critical objectives outlined earlier have been made. Outcrop studies of paleodepth and environment could be coupled with measured sections to produce vertical displacement curves. Outcrops would also permit detailed structural studies, including the geometry and ages of faulting. More paleomagntic data is urgently needed. There is also need for more geochemical and petrologic studies of the igneous rocks on the islands, but perhaps the greatest opportunity in this area is for deep basement penetration into the arc crust. Land based core drilling would be relatively inexpensive and would take advantage of the erosion of most or all of the sediment cover. Basement penetration depths of 1.5 km would be a modest objective and would explore igneous stratigraphy of the early arc and perhaps even its substrate. Holes through the sedimentary section might also be considered as these would give a more complete and better preserved section than would outcrops.

10) Ocean Drilling

All the major objectives in oceanic forearcs have some elements that can only be approached by deep drill holes into the sedimentary section and igneous substrate. The history of vertical displacement across the forearc must be acquired from drill cores, which provide accurate stratal thicknesses and porosities as well as age and paleodepth indicators. Small scale structures, and changes in deformation with age and depth, can also be best obtained from the drill cores. In addition to the primary stratigraphic data, a good record of relative intensities of arc volcanism can be derived from tephrachronologic studies of drill cores, especially those in the thicker, near-arc parts of the upper slope apron. The nature of the igneous basement beneath the large section of the forearc covered by this sediment apron can only be obtained by drilling. Drill holes into the serpentine diapirs or into the flanking sediments may also be the best way to understand this deformation process.

Adequate elucidation of forearc behavior will require 3 or 4 data sites across the arc, only one or two of which could be represented by islands or by non-drilling techniqes (as on the lowermost slope). Such a transect must be knit together with a detailed net of seismic profiles. Some idea of the three-dimendional variability of oceanic forearcs should be sought by investigating several transects within an arc system or among several systems that represent differences in age or differences between "normal subduction" and "collision".

11) <u>Oceanic Arc Systems Proposed for Study</u>

Although a number of methods of study of oceanic forearcs have been reviewed, the emphasis here is on arc systems that could best be studied by ocean drilling. Consideration should include expression of the problem or objective, technical and logistic feasibility, and existing data base. Arcs that received the most attention, principally because of the available data base, were the Mariana, Bonin, and Tonga arcs. The appreciable interest in the Malanesian arcs (New Hebrides through West Melanesian) was tempered by a lack of data as well as the recognition that most of these have sparsely sedimented, very young forearcs.

The Mariana Arc has the advantages of islands on the frontal arc (e.g. Guam, Saipan), a good data base, and good logistics. The proposed objectives are well-posed and there is strong support for a site or pair of sites on the inner part of the upper slope apron. Penetration of this thick sediment section (~1-1.5 sec) as well as deep penetration into the underlying igneous basement could be accomplished by one hole through the sediment apron near 16°N and a second nearby hole in a large submarine canyon where much of the sediment section has been eroded away.

The Bonin arc appears similar in many respects to the Mariana arc. Its linearity and fewer seamounts on the outer trench slope are points of difference, although there is good evidence for a collision near 25°30'N where the Ogasawara plateau is impinging on the subduction zone. The Bonin islands represent available study sites on the outer arc high. No drill data are available from this are but a virtual plethora of seismic and multibeam bathymetric data have been collected.

Drilling in the Tonga arc has not been proposed as a substitute for that in the Mariana or Bonin arcs but to investigate variations, in particular to see if the Mariana-Bonin system has an anomalous early history or if rather we are missing major processes of arc development.

## B. Major Scientific Problems in the Intra-Oceanic Volcanic Arc Systems

A number of significant problems concerning the evolution of the earth's crust and mantle require a better understanding of magmatic processes at convergent plate boundaries. These include:

1) Growth rates of arc magmatic systems. What are the predominant controls on the production rates of arc magmas? What is the effect of varying convergence rates on igneous production rates and compositions?

2) Fate of subducted sediments and oceanic crust: Are these recycled into the mantle or are they stripped from the slab by melting to form arc volcanoes? (e.g., Karig and Kay 1981; Brown et al., 1982; Kay, 1985)

3) Sources of convergent margin magmas: To what extent can we identify the various contributions of subducted oceanic lithosphere, subducted sediments, mantle wedge, and arc crust to arc melts? (e.g., Perfit et al., 1980; Gill, 1981)

4) Magmatic vs. Off-scraped contributions to the growth of arcs. How much of an arc is composed of magmatic additions as opposed to material that has been tectonically accreted to the arc (e.g., Kay 1985)? What proportion of the magmatic contribution is extrusive, and what proportion is either intrusive or results from magmatic underplating? (e.g., Hawkins et al., 1984; Natland, 1981; Fig. 1).

5) Compositional variation of arc magmas through time: Are there any systematic variations in the composition of magmas generated as a given arc matures? If so, what processes control magmatic evolution in arcs?

6) Petrologic relationships between arc and back-arc basin magmas: What petrogenic relationship exists between the magmas of the arc itself and those of associated back-arc basins (Wood et al., 1981; Gill et al.,

1984; Stern et al., 1984)? How does this relationship change as a given arc/back-arc basin system matures?

7) Modes and rates of formation of the continental crust: Models for the evolution of continental crust depend heavily on the coalescence of arcs through time (e.g., Reymer and Schubert, 1984).

The answers to these questions are of fundamental importance to our understanding of how arcs and back-arc basins form and evolve now, how the continental crust developed in the past, and what sorts of chemical communication exist between crust and mantle. We have only recently begun to systematically address these problems. While it is important in our quest to study all magmatic arcs, it is especially critical to study arcs built on oceanic crust. The magmas of these "intra-oceanic" arcs are relatively unmodified during their ascent to the surface, either by crystal fractionation or crustal anatexis (Leeman, 1983), thus allowing us to better define the composition of primary arc magmas and so less ambiguously address the seven questions above.

Studies of recent igneous rocks from active subaerial volcanoes of intra-oceanic arcs are becoming increasingly important (e.g., Ewart et al., 1973; Dixon and Batiza, 1979; Morris and Hart, 1983). Unfortunately, studies of arc volcanism in these settings suffer from the fact that most of the active arc is submerged. For example, if we take the width of the active arc as 50 km (Fig. 2), and take a typical intra-oceanic arc such as the Mariana with an active arc ~ 900 km long, then the active arc covers an area of $4.5 \times 10^4$ $km^2$. Along this length of the Mariana Arc, the recent and active volcanic islands occupy less than 200 $km^2$, so that less than 0.5% of the active arc is on dry land (Fig. 3). This degree of subaerial exposure is typical for intra-oceanic arcs.

The bias to our understanding of intra-oceanic arc magmatism resulting from only the tops of the largest volcanoes being exposed can best be appreciated if we imagine what we would know about arcs that are totally constructed on continental crust, such as the Cascade Arc, if we limited ourselves to studies of the top 1000 m. of Mt. Rainier, Mt. Shasta, Mt. Hood, and a few other of the largest stratovolcanoes. We would be largely ignorant of the eruptive styles, volumes and compositions of lavas extruded on the flanks of these volcanoes as well as the nature of synchronous igneous activity between the stratovolcanoes. As a result of geologic studies of the Cascade Arc, we know that there is abundant volcanic activity on the lower flanks of the stratovolcanoes as well as in the lowlands between the central volcanoes. The latter especially have a different eruptive style, being largely fissure-fed "aa" flows, as well as different compositions, being largely basaltic, as compared to the largely fragmental, andesitic to dacitic eruptions from central vents of the stratovolcanoes (e.g., McBirney, 1978; White & McBirney, 1978). Thus, reasoning from analogy with the Cascade Arc, it is certain that if we base our understanding of intra-oceanic arcs on the volcanic islands alone, our models are wrong. This has implications not only for the resolution of the seven questions above, but also for the interpretation of ancient metavolcanic sequences in orogenic belts. Many of these assemblages and some ophiolites have been interpreted as being the roots of island arcs (e.g., Miyashiro, 1973; Shervais and Kimbrough, 1985). Since these are predominantly submarine assemblages as shown by the abundance of pillowed basalts and marine sediments, such metavolcanic and ophiolitic arc-related sequences must somehow represent submerged portions of arcs. If we are to understand not only modern processes of arc evolution but also the tectonic evolution of ancient orogenic belts (and the mineral deposits these host) we must develop a better understanding of the submerged portions of active arcs.

To a certain extent, we can attack this problem by a combined program of a) geologic studies of older arcs now subaerially exposed as part of the frontal arc, such as Guam or Eua, b) dredging and piston coring studies on submarine arc volcanoes, c) detailed swath-mapping studies of arcs; and d) submersible diving on the active arc. A number of other questions can only be addressed by deeper coring, of the sort that only a marine drilling platform can perform. For example, studies of lower Teriary volcanic rocks in the Mariana frontal arc has led to a refined understanding of the timing of arc volcanism as well as the composition of the volcanic products associated with the initiation of a new arc (e.g., Meijer et al., 1983). However, studies of older volcanic rocks cannot give much information on the spatial relationships between the different components of an arc. Uplift of the older volcanic succession is controlled by the fore-arc tectonic regime, thus it is unlikely that the limited exposures of the older volcanic succession is representative of that arc at the time it was active. Furthermore, since we know so little about the various igneous and sedimentary environments that exist in submarine portion of active arcs, it is difficult to determine where in an active arc the older volcanic succession formed. Again, without a proper understanding of all portions of modern intra-oceanic arcs, it is impossible to reconstruct spatial variations in older ones.

Sampling bias in the intra-oceanic arcs can be overcome to a certain extent by dredging and submersible diving on submarine arc volcanoes. Studying rocks recovered by dredging the smaller arc volcanoes can shed light on the earliest stages in the evolution of the central volcanoes. Such studies have been carried out only over the past 5 years (Garcia et al., 1979; Dixon and Stern, 1983; Stern and Bibee, 1984) but already have led to a substantial revision of models for the magmatic evolution of arc volcanoes (Meijer and Reagan, 1983). A dredging program would also be useful for studying the variation of volcanic products along the submerged flanks of volcanic islands, but has thus far not been carried out.

In order to get a detailed understanding of the morphology of and distribution of flows on individual volcanoes, it will be necessary to undertake detailed swath-mapping studies of individual edifices (Hussong and Fryer, 1983) accompanied by a submersible diving program. The quantity and quality of morphologic and morphotectonic data that results from Sea MARC II and related swath-mapping techniques promises to lead to an order-of-magnitude improvement in our understanding of arc/back-arc basin tectonics and distribution of lava flows, especially in those instances where the features are studied and sampled in subsequent submersible investigations.

The results of dredging, mapping, and submersible diving of submerged arc features will be a much better understanding of the spatial variations in the tectonic and magmatic styles of the active arc at present. To document temporal variations in style, as well as to understand igneous and sedimentary processes between the subaerial and submarine volcanic edifices, it will be necessary to drill and core several hundred meters deep into the active arc. Problems that only a drilling platform such as the D/V Resolution can help us address include the following:

1) Igneous, sedimentary, and metallogenic processes between active volcanic edifices: As already discussed, we know very little about the composition of the smaller volcanic arc edifices and nothing regarding the arc between the central volcanoes. It is essential that we begin to address the question of what processes, both igneous and sedimentary, dominate in this region. For example, is there abundant fissure-fed basaltic volcanism between the central volcanoes? If so, are these abyssal arc volcanics similar to that of arc-like ophiolites? Or is the geology of these regions dominated by deposition of pyroclastic and reworked volcaniclastics from the larger edifices? Alternatively, are the central volcanoes built on an older arc basement similar to that exposed in the fore-arc, with little igenous activity except at the central volcanoes and little sedimentation except towards the back-arc and fore-arc? Finally, what potential exists in the deepest portions of the arc for base-metal mineralization, such as Kuroko-type (volcanic-hosted) or Besshi-type (sediment-hosted) massive sulphide deposits?

2) Temporal and spatial relationships between arc and back-arc basin

magmatism: The major features of Karig's (1971) model for the formation of back-arc basin by the longitudinal splitting of the active are more satisfying tectonically than petrologically. Initially, and for an indeterminant period afterwards, the sources of back-arc and active arc magmas must either be superimposed within the upper mantle or be one and the same. As the back-arc basin widens, arc and back-arc basin magma sources become increasingly separated in space (Fig. 4). Island arc and back-arc basin magmas are compositionally and isotopically distinct, implying distinct magma sources (e.g., Stern, 1982). The juxtaposition of these sources early in the development of a back-arc basin has proven very difficult to satisfactorily conceptualize. In order to further address the early stages in the evolution of arc-back-arc basin magmatic systems, we need to recover igneous rocks that formed at the earliest stages of back-arc basin development. This can be done by drilling in the back-arc close to the active arcs, such as was attempted during DSDP leg 60. Alternatively, it may be technically simpler to identify a region in the earliest stages of rifting, such as the northernmost Mariana Trough (Stern et al., 1984), and drill there. In any case, only a deep coring program can satisfactorily address the problem of the relationship between island arc and back-arc magmatism at the earliest stages in the development of the system.

3) Temporal variations in the evolution of a single arc edifice: Models for the evolution of arc volcanism in the past assumed that compositional differences between arc systems of different age were primarily a function of their age difference (Jakes & White, 1972). With the new information on submarine arc volcanoes, this approach has changed, and newer models assume that the submarine edifices are earlier evolutionary stages as compared to the larger, subaerial edifices (Meijer and Reagan, 1983). Both approaches suffer from the fact that these premises are not readily testable. In order to build sounder models for arc evolution, we need to understand the long-term variations in the composition of a

single arc volcano. What are the initial products of an evolving central edifice, and how do subsequent magmatic pulses vary? What are the controls on these variations: crystal fractionation, partial melting, and/or assimilation? If we can understand the long-term temporal variations in the composition of volcanic products from a single volcano and if we can understand the processes responsible, we will have a much sounder basis for understanding the processes responsible for the longer term evolution of arc systems. This, in turn, would lead to a refined understanding of the evolution of the continental crust. The only way in which we can understand the evolution of a single arc edifice, from the time it began on the seafloor through its evolution as a large, subaerial edifice, would be to drill 1-3 km deep on the flanks of one.

We are aware that a previous attempt to drill on the active arc was a failure. DSDP site 457, between the volcanoes of Pagan and Alamaga in the Mariana Arc,, was drilled with the objective of determining the structure and nature of the arc upon which the present volcanoes are built, but was abandoned after 61 m because it could not penetrate through poorly lithified pyroclastic and volcaniclastic materials. The failure of this hole has led to, we feel, an unnecessarily pessimistic opinion regarding the likelihood of successful drilling on active arcs. We believe that DSDP site 457 failed because it was drilled too close to large, subaerial volcanoes that are subject to high rates of erosion and that produce large amounts of pyroclastic material. A significant fraction of this material comes to rest between the larger volcanoes, resulting in the very high sedimentation rates determined for this hole (minimum rate = 57m/m.y.; Shipboard Scientific Party, 1981). We predict that if sites are chosen along the active arc away from the larger volcanoes, the sedimentation rates will be much lower and will include a higher proportion of finer clastic and biogenic material. If sites are chosen between submarine edifices, erosion of adjacent highlands would be minimized, as would be the production of coarse pyroclastic material. In the former case, the absence of rainfall and wave action means the submarine edifices should "erode" at a much lower rate than the subaerial edifices, while in the latter case, hydrostatic pressure and the lower degrees of fractionation should make the explosive eruption and distribution of pyroclastic material from submarine vents a rare occurrence. Thus sediments between the submarine volcanoes should be finer-grained, more thinly bedded, and better lithified than sediments deposited between the subaerial volcanoes. If true, then the prospect for successfully attaining the objective of DSDP site 457 by drilling between submarine volcanoes would be greatly enhanced.

In summary, studies of active intra-oceanic arcs are giving us an increasingly detailed perspective on these essential components of crustal evolution. We are beginning to study the 99.5% of the active arcs that is hidden beneath sea level, using dredging, swath-mapping, and submersible diving. Drilling on the active portion of these arcs is the only way in which we can address certain critical questions regarding the evolution of these arcs. There are risks involved in scientific drilling of active arcs, but with careful site surveys and site selection, the technical difficulties can be overcome. Results from studies of cores recovered from active arcs would lead to a substantially improved perspective of arc evolution, and would be of interest to a broad spectrum of earth scientists.

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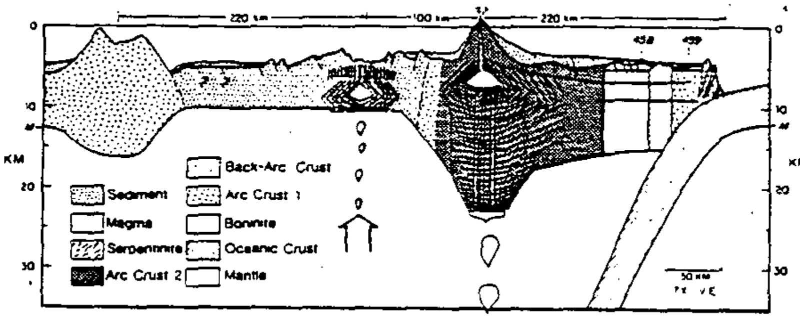
# Figure Captions

Figure 1. Cross-section through arc-back-arc basin systems such as the Lau-Tonga and Mariana arc region. A spreading back-arc basin separates a remnant arc from an active volcanic arc which has been superimposed on part of the back-arc crust. Tectonic erosion has removed fore-arc material exposing roots of older arc components on the trench slope. (from Hawkins *et al.*, 1984.)

Figure 2. Perspective section showing the principal bathymetric features, tectonic elements, and crustal profiles in the Mariana Arc-Back-Arc System. Numbered localities refer to DSDP Leg 60 sites. Note the active Mariana Arc is about 50 km wide. (from Hussong *et al.*, 1981.)

Figure 3. Profile along the highest points of the active Mariana Arc, from 18°N to 25°N. Seamounts denoted "(A)" refer to recently active volcanoes. Note how little of the arc is exposed above sea level. Vertical Exaggeration = 75X. After Stern *et al.*, 1984.

Figure 4. Petro-tectonic cartoon showing possible relationships between the sources of island arc and back-arc basin magmas in the early stages of rifting (A) and in a mature arc-back-arc basin system (B).


220 km
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458
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KM
Back-Arc Crust
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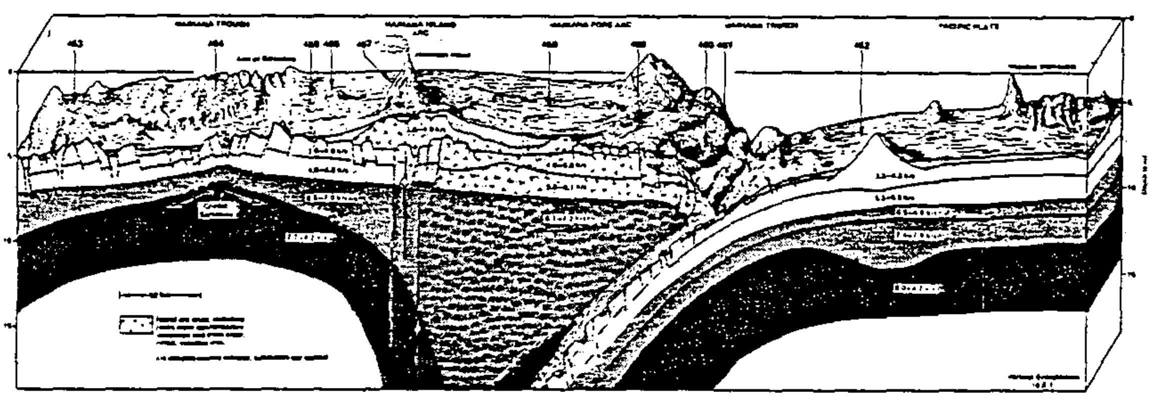
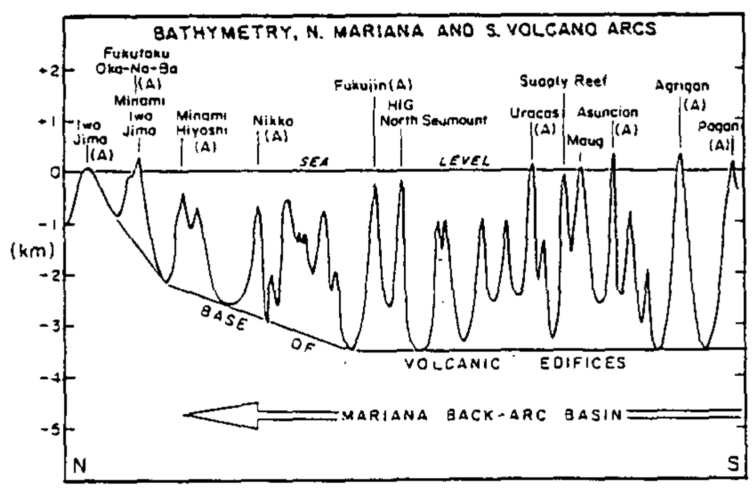
Arc Crust 1
Magma
Boninite
Serpentinite
Oceanic Crust
Arc Crust 2
Mantle

Fig 1




BATHYMETRY, N. MARIANA AND S. VOLCANO ARCS
+2
+1
0
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(km)
-2
-3
-4
-5
Iwo Jima (A)
Fukutoku Oka-No-Ba (A)
Minami Iwo Jima
Minami Hiyoshi (A)
Nikko (A)
Fukujin (A)
HIG North Seamount
Supply Reef
Uracas (A)
Maug
Asuncion (A)
Agrigan (A)
Pagan (A)
SEA LEVEL
BASE OF VOLCANIC EDIFICES
MARIANA BACK-ARC BASIN
N
S

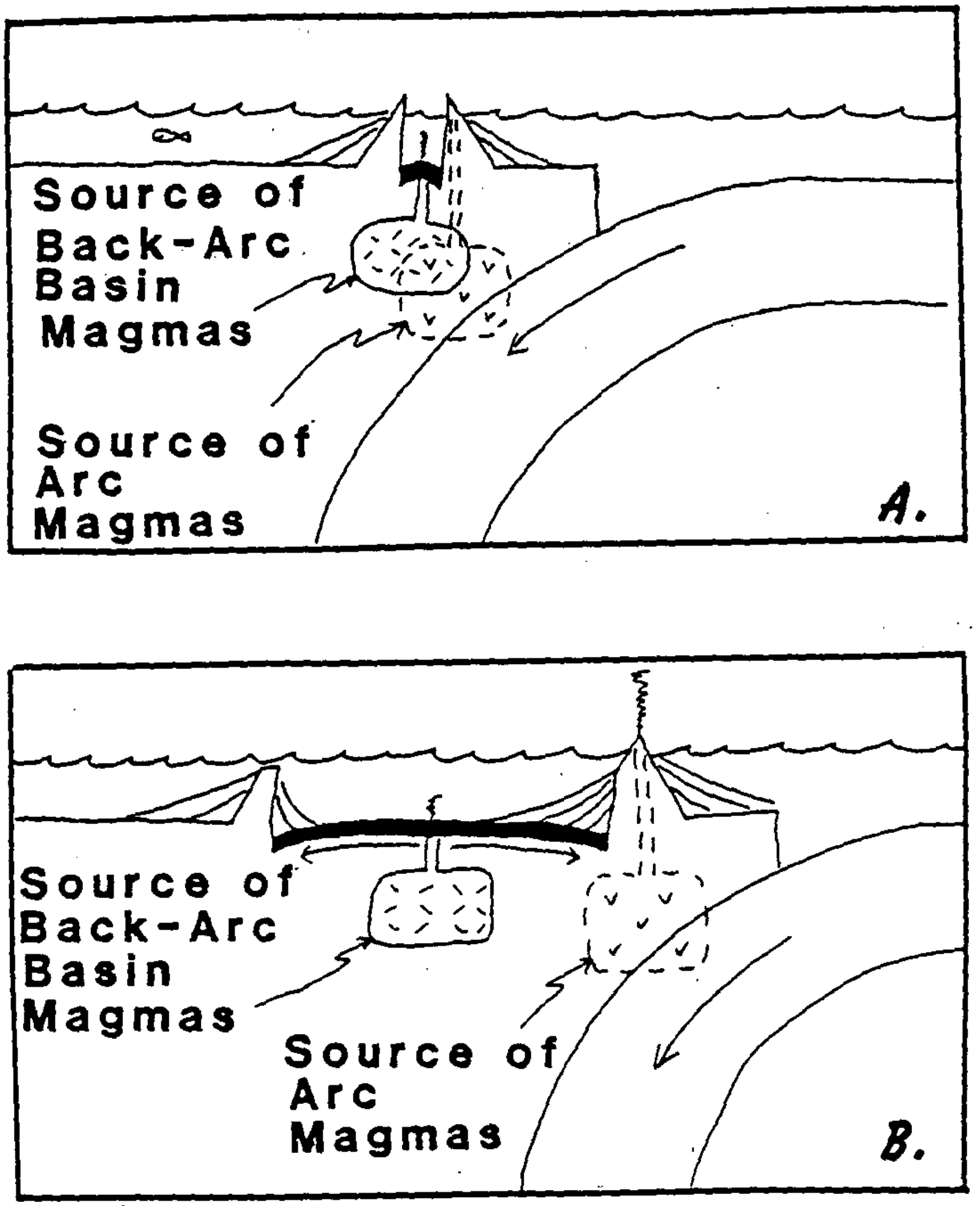
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Fig 4

## C. Major Scientific Problems; Backarc Basins

There are at least four major problems for study in backarc basins. These include definition of the chemical-petrologic character of backarc basin basalts and an assessment of their differences or similarity to MORB or island arc volcanic rocks; the tectonic evolution of backarc basins and the dynamic aspects of their initial opening; the relationship between basalt crust formation, the sedimentary infilling and hydrothermal circulation; and an evaluation of the possible relationships between backarc basin lithosphere and the oceanic rock assemblages known from ophiolites.

Data from many backarc basins are available and clearly establish that the main rock type formed during the spreading process is tholeiitic basalt that, in most aspects, shows a close similarity to basalt types collected from mid-ocean ridges (e.g. Hart et al, 1972; Hawkins 1974, 1976, 1977; Hawkins and Melchior, 1985; Fryer et al, 1981; Dick, 1982; Saunders and Tarney, 1979). In spite of the overall similarity to MORB, there is subtle, but significant, variability in the abundances of alkalies, alkali metals, LREE, water and some isotope ratios such as $^{87}Sr/^{86}Sr$ and $^{3}He/^{4}He$ that point to differences in the mantle source beneath backarc basin and to the possible effects of "volatile" components derived from previously subducted oceanic lithosphere (Hawkins and Melchior, 1985; Poreda, 1985; see also discussion by Poreda in Appendix of this report). These chemical differences are expressed not only as distinctive characteristics for different backarc basins but as compositional zonation within individual backarc basins e.g. Lau Basin (Hawkins and Melchior, 1985) and the Scotia Sea (Saunders and Tarney, 1979). A possible explanation for this, presented by Hawkins et al, 1984 and Hawkins and Melchior, 1985 is that as backarc basins develop they progressively tap mantle material that is less enriched in "slab derived" components and more like the source that forms "N-MORB" (See Fig. 5 ).

There are additional complications about the petrology of backarc basins that suggests that in some there is an interlayering with arc tholeiitic or calc-alkaline lavas e.g. in the Mariana Trough DSDP hole 452A (Wood et al, 1981). Lonsdale and Hawkins (1985) interpreted the presence of small rhyodacite mounds in the Mariana Trough as the expression of fractional melting of arc-derived sediment trapped between basaltic lava flows on the seafloor. Dacite vitrophyre dredged from Zephyr Shoal in the Lau Basin (Hawkins, 1976) is another example of anomalous silicic rock exposures on otherwise "normal" oceanic crust. The most striking evidence for silicic magmatism within the confines of a backarc basin is the extrusion of rhyodacite vitrophyre at the Valu Fa magma chamber site in the Lau Basin (see discussion by Morton in the Appendix of this report). Whether or not this silicic magmatism is a reflection of the Tonga arc magmatic system (the bulk of the evidence suggests that it is) or is a variant of backarc magmatism is not yet agreed on. Nevertheless, the presence of this rock type points to the importance of backarc settings as a probable site of origin for ophiolites and to the need for detailed petrologic studies of backarc basins.

These data show that there are good reasons to postulate that there is considerable three-dimensional heterogeneity in the crust of young backarc basins and that the earliest stages of their opening may yield a spectrum of rock types even though MORB-like basalt is the main product in most stages of this evolution. Drilling, especially on the flanks of young backarc basins, is the best way to study this heterogenity.

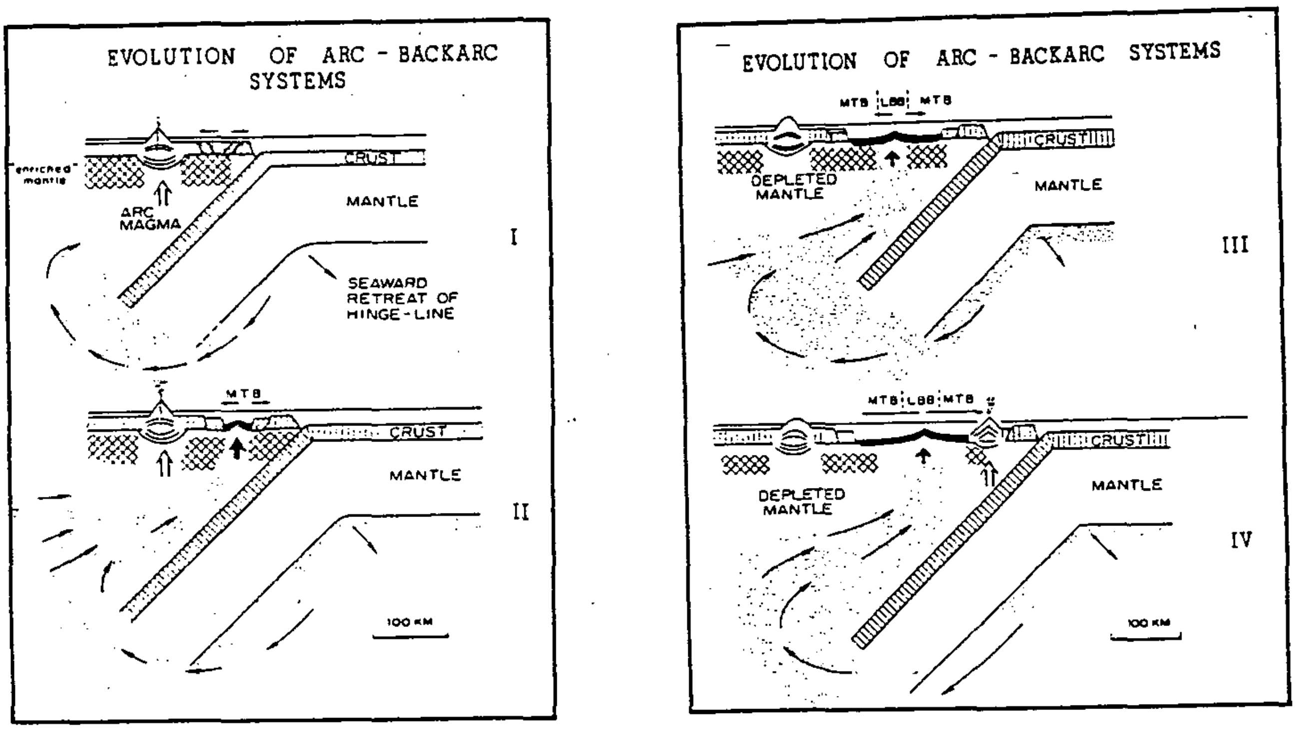


Fig. 2.

Model to explain the evolution of back arc basins and the compositional zonation of back arc basin crust. (I) Initial stage of evolution showing the convergent plate margin, the active volcanic arc, and the forearc. The forearc is under extensional stress due to the "rollback" of the trench hingeline. The cross-hatched area under the arc and forearc represents mantle that has been partly depleted in its "basaltic" components but variably enriched in water and large ionic-radius lithophile (LIL) elements derived from subducted oceanic crust. The stippled pattern and the curved arrows represent deep mantle convective flow driven by the seaward retreat of the subducted plate. The mantle counterflow causes thermal upwelling in the forearc and causes the forearc extension. Heavy lines in the forearc crust represent normal fault planes that form half-grabens as the forearc is dilated. (II) This view represents a more advanced stage of forearc extension. Rising mantle diapirs (solid arrow) have partly melted to form MORB-like basalt in the rifted region. These melts have been modified by zone-refining processes that enrich them in water and LIL components derived from the enriched upper mantle. The basalt is comparable to the Mariana Trough-type basalt (MTB). (III) Continued extension of the forearc causes new ocean crust to form due to fractional melting of the rising mantle diapir. Inflow of "new" mantle, and eruption of basalt through upper mantle and deep crust depleted in the enriched material, allows eruption of basalt more like normal MORB, e.g., Lau Basin-type basalt (LBB). The volcanic island arc has become inactive because the geometry of the subduction system has been changed due to the seaward retreat of the subduction zone. Note that this model requires that there is a break in arc volcanism during the early stages of "back arc" basin evolution. (IV) A new volcanic arc has formed on the outer edges of the zone of extension. It is superposed on, or replaces, part of the back arc basin crust. The active arc is not a fragment split off from the older (remnant) arc. The configuration shown here is similar to the Lau Basin in which the back arc crust is zoned from MTB to LBB basalt. In the Mariana Trough the new arc formed at a stage equivalent to stage II above. The geometric arrangement of arcs and the new oceanic crust make the latter a true "back arc" basin. A more detailed explanation of the model for tectonic evolution shown here, and the field evidence to support it, is given by *Hawkins et al.* (1984).

from Hawkins and Melchior, 1985.

The evolution of the basins by spreading seems to be well established but the details of the spreading mechanism and fabric of spreading, especially in the earliest stages, is not well known. Karig (1971) proposed a general model for their evolution that followed conventional rigid plate models for ocean ridge spreading. Support for this type of process comes from the recognition of symmetric magnetic stripes in some backarc basins such as the Scotia Sea. There is some support for this symmetry in the Mariana Trough. However, Lawver and Hawkins (1978) pointed out that in the Lau Basin although the magnetic lineations were symmetric in some areas generally the symmetric patterns rarely extended for more than 50 km before being desrupted. Also, they noted that there were abundant seamounts that disrupted the symmetric patterns. They proposed that the Lau Basin spreading fabric may be characterized by numerous point sources, by ridge jumps and by continual reorganization of the spreading fabric. While drilling is not the most effective tool to study the spreading geometry of backarc basins, it will be an important help in unraveling crustal ages (through the sedimentary record) and to test models for the mechanisms of basin opening.

The geometry and kinematic characteristics of the initial rifting of backarc basins is speculative. The conventional idea has been that the original volcanic arc was rifted, an active segment was carried seaward and new ocean crust was generated in the rift zone. This intuitively satisfying model was questioned by Hawkins et al (1984) who proposed that in some settings the initial rift may have been in the forearc and that the earliest stages of backarc spreading actually were in the forearc. The outer, active, volcanic arc in some systems is younger than the earliest "backarc" crust. This model can be tested by drilling on the older parts of backarc crust and interpreting the sedimentologic history of the basin filling.

Other models needing testing include the proposal that propagating rifts may play an important role. This process may actually be occurring today in the Lau Basin and at the north end of the Mariana Trough (see discussions by Stern, by Flower and Rudolfo and by Ito et al in the Appendix of this report).

The ophiolite problem may not ever be solved by use of petrologic-geochemical discriminants alone in view of the marked similarity between MORB and backarc basin basalts. This is especially true when effects of metamorphism are considered. The most significant variables are the elements most likely to be mobilized during hydrous subsolidus reactions whereas the immobile trace elements are those that commonly show the closest affinity for the MORB and backarc basin basalts. Apart from the apparent abundance of silicic rocks in some backarc basins, the sedimentologic record appears to offer the most promise for recognizing remnants of backarc crust.

Backarc basins may have sediments characteristic of restricted circulation, high silica activity (e.g. favorable for radiolarites if other oceanographic conditions permit), clastic sediments derived from adjacent island arcs may be interbedded with basalt, the clastic material amy be virtually the same age as the underlying basaltic crust, and stratiform metalliferous deposits may be favored along the arc-basin margin.

The hydrothermal circulation system in backarc basins may also show distinctive characteristics because of the clastic sedimentary blanket that may bury young crust.

Collectively all of these studies will have bearing on the ophiolite problem. Recognition of crust derived from backarc or arc material is critical in making paleotectonic interpretations of the suture zones represented by ophiolites. The sense of convergence polarity is obviously wrong if backarc remnants are mistakenly interpreted as fragments of obducted deep sea floor.

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## IV. SUMMARY OF PROPOSED DRILL SITES

We have selected four geographic areas in which there are well defined problems, extensive background information, and excellent prospects for finding answers to many of the important problems concerning crustal evolution in arc-trench-backarc systems. These are the Banda-Sulu, Lau-Tonga, Mariana and Izu-Bonin systems. In addition there are important problems to be solved in other systems such as the Sea of Japan and d'Entrecasteaux-Vanuatu Trench. The Banda-Sulu area has been proposed to the Western Pacific Panel and only a summary of this drilling plan is presented here. The Sea of Japan and d'Entrecasteaux-Vanuatu areas also have been proposed by other groups and were not extensively discussed at our meeting. Copies of these proposals are included for reference. The main focus of our plans was on the three active intra-oceanic systems listed below. These are:

1. Lau Basin-Tonga Trench system

We propose 12 sites (Fig. 6). Five are on the Tonga Ridge and upper slopes of the Tonga Trench. One site is on the west side of the Lau Ridge (remnant arc). Three sites are on the west side of the Lau Basin adjacent to the Lau Ridge and three sites are in the Lau Basin

2. Mariana Arc system

We propose 12 sites to complement the DSDP transect at 18°N (Fig 7). Three sites are in the forearc; 4 sites are on the trend of the arc volcanoes and 5 sites are in the Mariana Trough (backarc basin) or its northern extension.

3. Izu Bonin system

We propose 11 sites (Fig. 8). Two sites would have two holes - 9 holes are proposed. Two holes are in the outer forearc, four holes are on the inner forearc and three holes are on the island arc and area undergoing rifting (to form a backarc basin?).

We have not ranked the importance of the geographic localities as each offers critical insights to the evolution of arc systems. The priority within each system is as follows:

Tonga-Lau

First priority sites: TT-1, TS-1, L-7, L-9, L-11 (not in rank order)

Back-up sites: TT-2, TS-2, L-5, LAU-1, LAU-2, L-8, L-10 (not in rank order)

Mariana

First priority sites: NM-1, NM-2, MA-5, MF-4, M-8 (not in rank order)

Back-up sites: MF-1,2,3; NM-3, NM-4, M-9, M-10 (not in rank order)

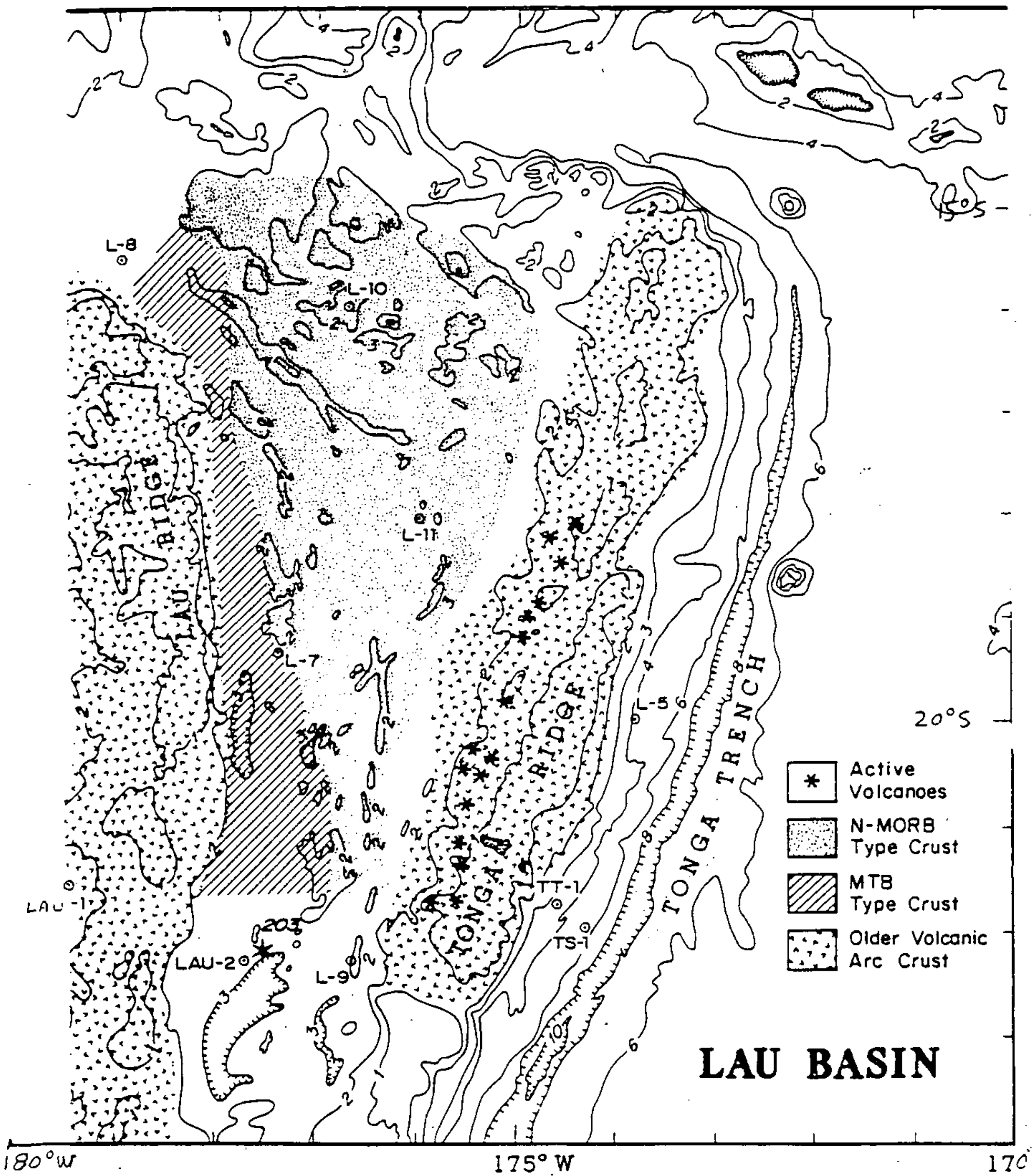
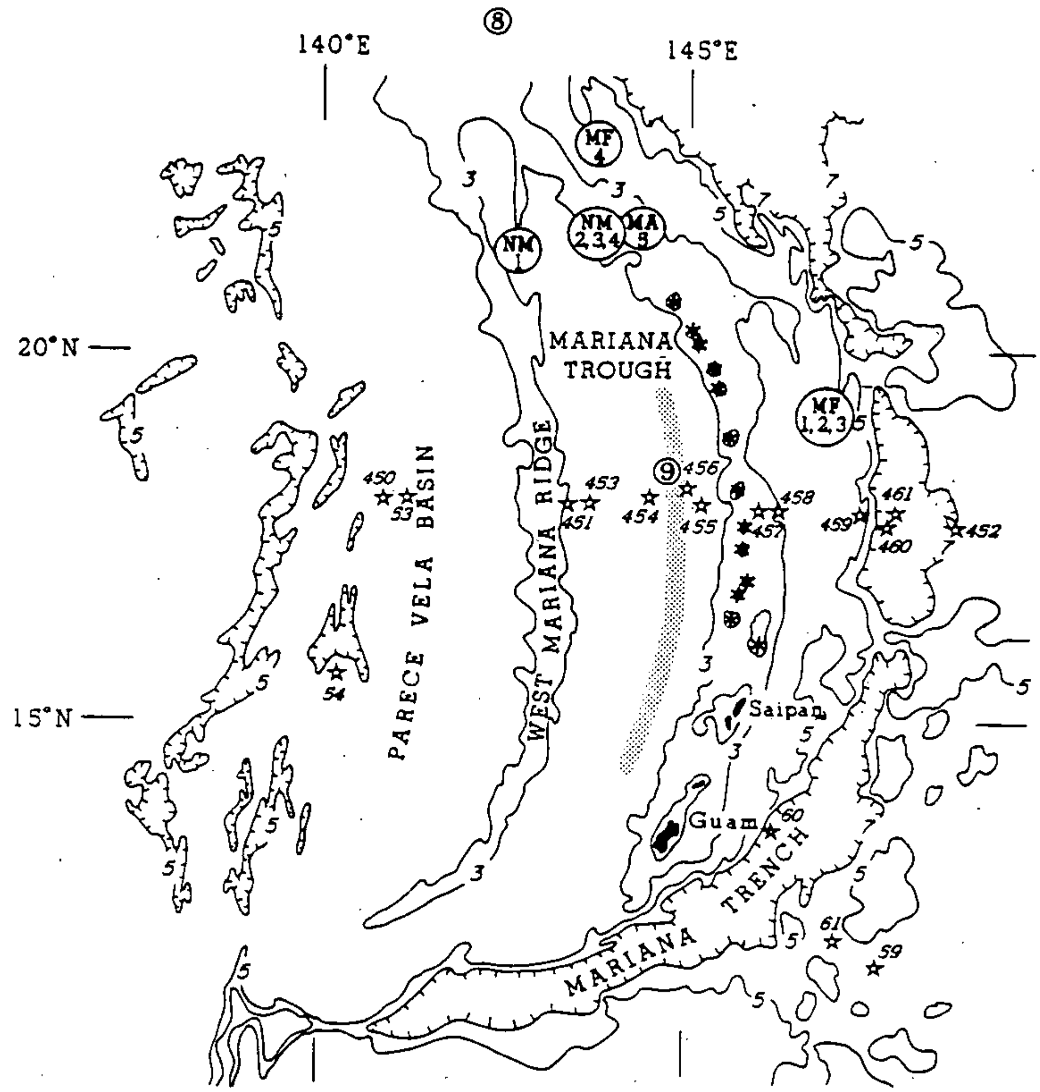



Figure 5: Sites proposed for the Lau Basin - Tonga Trench system. Site designations as discussed in the text. Depths are in km. Patterns and symbols designate active volcanoes, area underlain by MORB (mid-ocean ridge basalt) MTB (Mariana Trough type basalt) and volcanic rocks of the island arcs.




MARIANA ARC & TROUGH

Figure 7: Sites proposed for the Mariana Arc system. Site designations as dicussed in text. Depth are in km. Stars with numbers, eg 460, are DSDP sites. Active volcanoes of the Mariana arc are shown as asterisks. Stippled pattern in Mariana Trough is approximate location of the spreading axis.

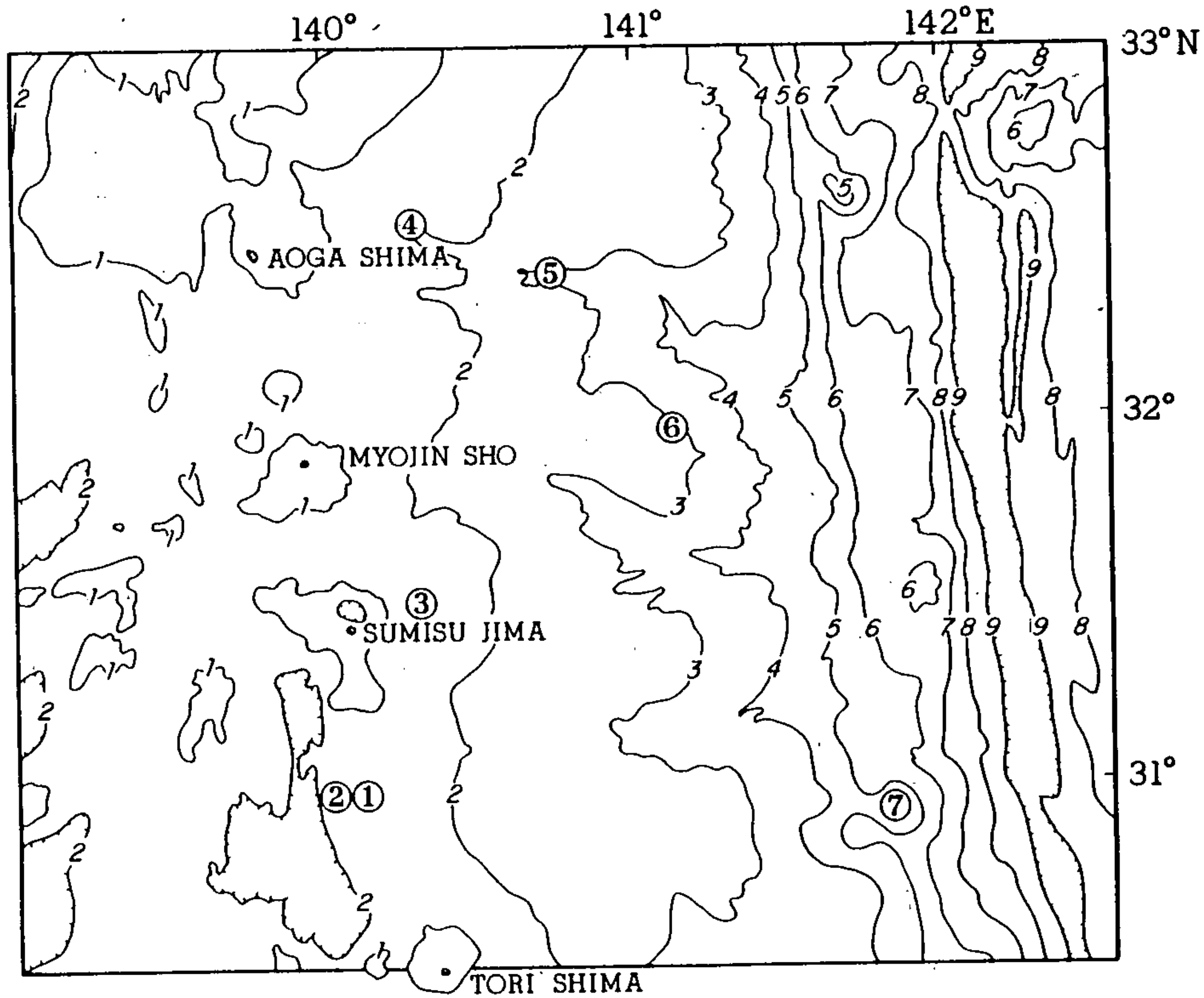



Figure 6: Sites proposed for the Izu - Bonin arc system. Site designations are discussed in text. Depths are in km.

Izu-Bonin

not ranked

The participants were unanimous in recommending that all of the proposed ODP sites be considered as but one important element in a multi-disciplinary effort to understand arc systems. This work should be completed by additional land and marine geological-geophysical work, sampling and observations with manned and remote vehicles and platforms, and should make use of the excellent opportunity to use deep drilling on islands as a means of obtaining additional samples as well as making deep crustal down hole measurements.

## V. TONGA ARC-LAU BASIN STUDIES

The Tonga Arc system comprises the Tonga trench, an outer arc ridge formed of an uplifted limestone platform that in part is known to overlie Eocene (and older?) igneous rocks, an active volcanic arc (Tofua arc) the Lau Basin (backarc basin) and the Lau Ridge (Remnant arc). The Lau Basin probably is less than 3 m.y. old and the age of the active volcanic arc is not known but may be much younger than the Lau Basin, e.g. <1 m.y. (Hawkins et al, 1984). The Lau Ridge remnant arc was active from 14 to 5 Ma and the volcanic arc is built on an Eocene to Oligocene basement (Gill et al, 1984; Whelan et al, 1985; Kroencke and Rodda, 1985).

There are two main reasons for proposing an intensive program of drilling in the Tonga Arc system. (1) The regional geology is well known from previous land and marine geologic studies, there is a good chronologic record of tectonic and volcanic events known from these studies; the region has been studied intensively in the last few years and additional work is funded for 1985-1986. Specifically this includes extensive SEABEAM charting and geochemical-geophysical surveys of the Lau Basin. (2) To date the only arc system that has received such extensive study plus deep drilling is the Mariana Arc system. A study of the Tonga system, which is known to have some fundamentally different characteristics in terms of geologic history, magma chemistry and geophysical data, will give another "type" arc system for understanding the role of arc systems in crustal evolution. A good case can be made for continued work in the Marianas but it is important to understand other arcs so that our thinking about geologic processes is not biased by data from only one component in a multi-component system.

The sites proposed are on the Tonga Ridge, the Lau Basin and the Lau Ridge.

### A. Lau Basin Crustal Evolution - Proposed Drill Sites

The Lau Basin (Fig. 6) is an excellent site for testing models for the origin and evolution of backarc basins. As part of a broader study in the Lau-Tonga arc system that will study crustal evolution at a convergent plate margin, five sites in the backarc basin are proposed. At least one of these sites should be considered as a potential "natural lab" location for long-term studies, with deep drilling to layer 3 as a goal, and a plan for down hole physical and chemical studies.

The five sites proposed for the Lau Basin are designed to investigate the following problems:

1. The early rifting history of the basin; the record of volcanism on the remnant arc (Lau Ridge) as preserved in the sedimentary infilling of the basin; the composition of the basaltic crust on the western (older) edge of the Lau Basin; the sedimentologic-paleo-oceanographic history of the basin filling; the role of hydrothermal circulation in modifying the crust under sediment filling. Two holes (L-7 and L-8) are proposed here, another hole (Lau-2) with similar objectives is proposed by Stevenson et al in this report. The latter is located near DSDP site 203 on the western edge of the Lau Basin near lat. 22°S. Site 203 penetrated 409 m of calcareous fossil ooze with high concentrations of ash and volcanic sands. The acoustic basement was not reached but a late Miocene age was postulated on the basis of extrapolating the estimated accumulation rate. Up to 1.5 seconds (two-way travel time) of sediment was found in the sediment ponds near site 203 and comparable thicknesses (0.5 to 1+ seconds) are present all along the western edge of the Lau Basin.

Site L-7, proposed here, was chosen to provide data listed above from a basin margin site near a probable "flow line" that can be tied in with a site in the central part of the basin.

In addition to exploring the geochemistry of magmatism and depth of basin during initial backarc basin formation, site L7 will add important constraints to study of the plumbing system and source composition of arc volcanism. If L7 is floored by basaltic backarc basin crust, then this crust probably is 3 to 5 Ma old (magnetic anomalies 2' to 3: Weissel; Malahoff). During this time, the remnant arc was the site of shoshonitic to tholeiitic volcanism whose trace element and isotopic traits unambiguously are characteristic of island arc volcanism (Gill, 1984). This volcanism includes the 4.0 +/- 0.5 Ma medium-K tholeiitic basalt (K51=1.2-1.5) of Moce island immediately west of the proposed drill site (Cole et al, 1985). At the time of Moce volcanism, the incipient Lau Basin may have been as much as 100 km wide--i.e., the distance from the base of the Lau Ridge to anomaly 2'. Hence, if the site returns Pliocene backarc basalt, then arc volcanism clearly continues on the eventual remnant arc for up to 2 m.y. after opening of the basin, even while chemically different basalt erupts in the basin itself. Effectively this means eruption of backarc basalt in the forearc! Alternatively, if backarc formation begins at 3 Ma, which is the age of the oldest well-defined magnetic anomaly and the time of transition to intra-oceanic basalt-type volcanism on the remnant arc (Gill et al, 1984) then site L7 should penetrate subsided remnant arc crust, and the overall Tonga-Lau arc edifice is very wide (~400 km), presumably due to dilation and attenuation.

Expedition track lines and a single channel airgun seismic reflection profile near site L-7 are in Figures 9 and 10. The seafloor near site L-7 is formed of extensively faulted and titled blocks of bedded rocks with about 0.3 seconds (two-way travel) of sedimentary rock above acoustic basement. The acoustic basement may be the basaltic crust of the backarc basin or some other type of lithified arc-derived rock. A dredged sample (ANTP -244) from exposures of the bedded rocks is siltstone and fine-grained sandstone - derived from a volcanic terrane. The crystalline basement beneath these sediments is assumed to be the earliest extrusions of backarc basin basalt but this is not known and is one of the objectives of this site. A hole through the bedded sediments and into igneous crust is proposed. The area around site L-7 will be surveyed more extensively on the SIO expedition to the Lau Basin in December 1985, J. Hawkins, Chief Scientist. This survey will include SEABEAM bathymetry, magnetic profiling, rock dredging and sediment coring with gravity cores.

…ed Site:
…-7

…al Area: Lau Basin Western side
…on: 19 14' S 177 37' W
…nate Site: site Lau -1 or 19 20' S 177 35'W

General Objective: Determine nature of crust on west side of Lau Basin, arc record of Lau Ridge, hydrothermal circulation history, paleo-oceanogr… record in sediments, early rifting history of ba…

Thematic Panel interest: LITHP
Regional Panel interest: WPP

…ific Objectives: To determine the early rifting history of the Lau Basin by coring through sedi… cover into basement. Collect samples for radiometric and paleontologic age determinations, lo… for the volcanic record of remnant arc (Lau Ridge), determine role and effect of hydrothermal circulation under arc derived sediment cover, look for metallogenetic processes, determine th… composition of the crystallline basement (arc ? backarc? transitional?) This will give baseme… rock samples for the earliest stages of the backarc opening

…ground Information:
…gional Data: Good record of Lau Ridge history from island studies, Lau Basin studies of evolution,
…ronic profiles: magnetics available. rock chemistry of basin is known
Seismic profiles : Single channel airgun from SIO expeditions
…ther data: Bathymetry, magnetics, dredged samples
Area will be charted with SEABEAM, andmagnetics collected and samples dredged in Dec 1985
…e Survey Data – Conducted by:
…ate:
…ain results:

…rational Considerations

…er Depth: (m) 2200-2300 Sed. Thickness: (m) 0.4 secs Total penetration: (m) 400 - 500 m sediments p… 100 - 200 m

… x Double HPC ______ Rotary Drill x Single Bit x Reentry ______

…ure of sediments/rock anticipated: indurated siltstone and volcanic sandstone, basement probabl… is basalt Age Oligocene ? to present

…ather conditions/window: none

…ritorial jurisdiction: Tonga - Fiji

…her:

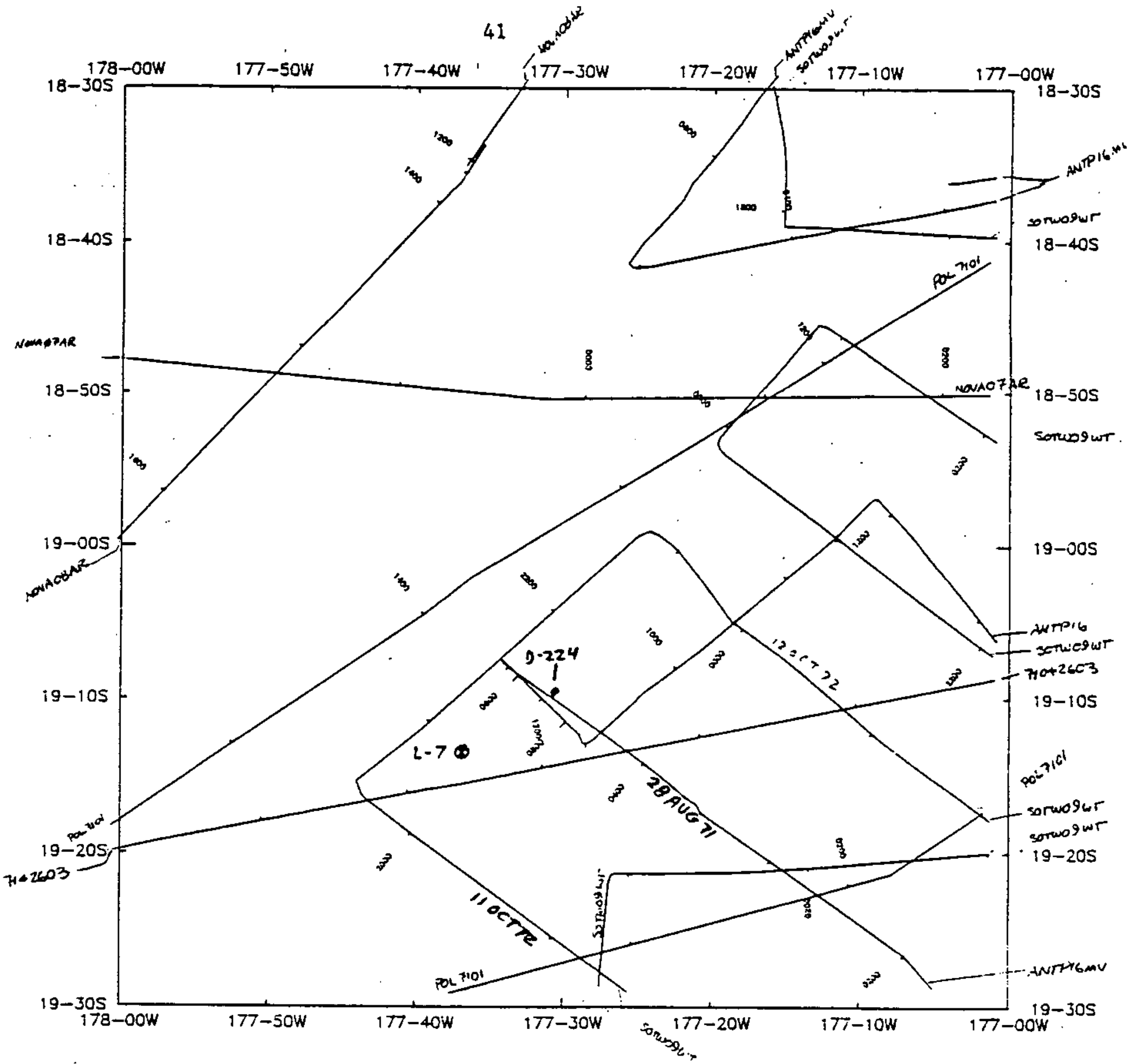
…cial requirements (Staffing, instrumentation, etc.)

none

…oponent: James Hawkins Scripps Inst. Oceanography La Jolla , Calif 92093

Date submitted to JOIDES Office:

Rev. 0.




AREA 2 CRUISES: NOVA07,08AR – ANTP16MV – SOTW09WT – P – 71042603

TRACKS from uwmrg files – Mercator at 8.0 in/deg long

Fig 9

Figure 9: Ship tracks for expeditions near Site L-7, western Lau Basin. From SIO Geological Data Center.

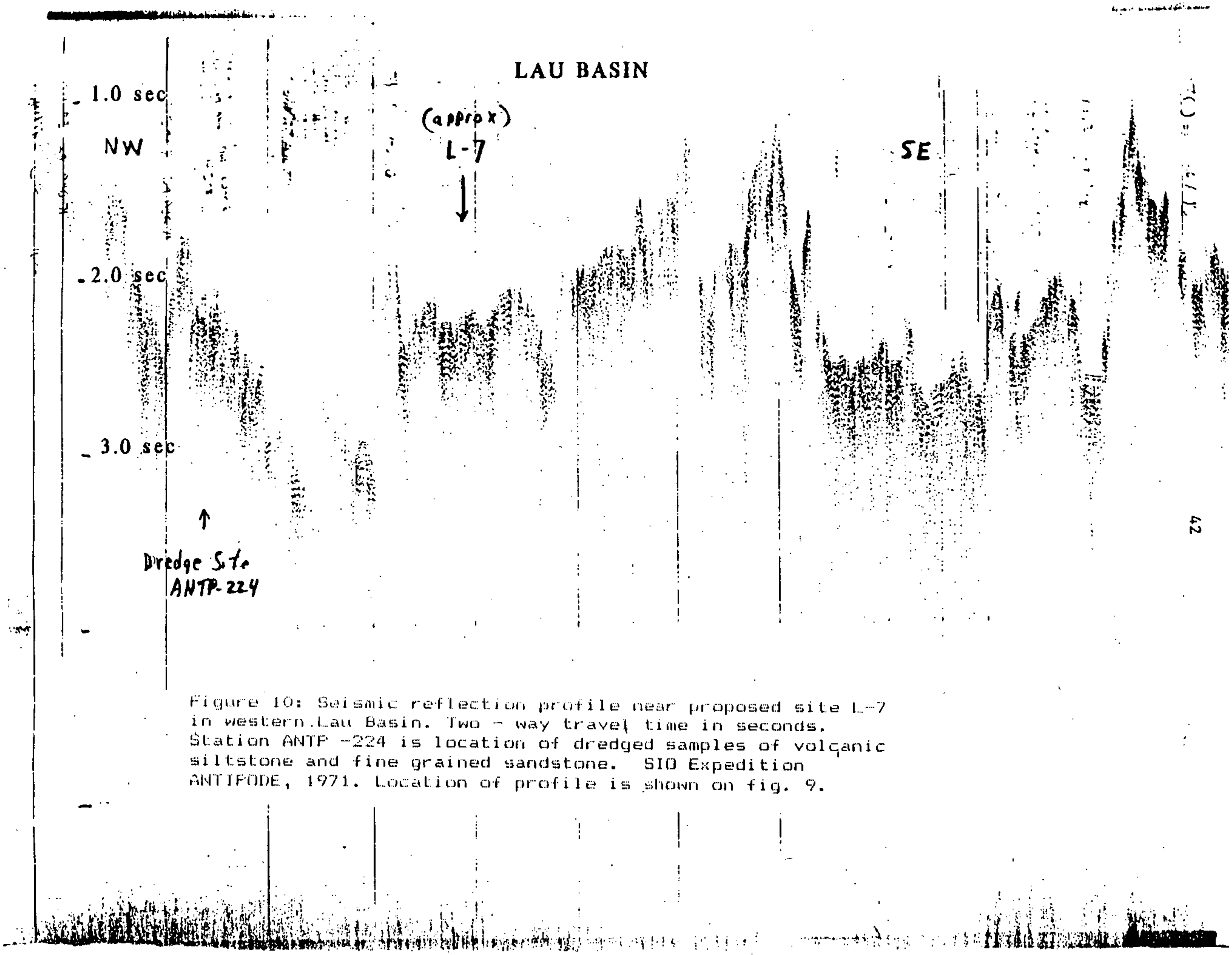



Figure 10: Seismic reflection profile near proposed site L-7 in western Lau Basin. Two - way travel time in seconds. Station ANTP -224 is location of dredged samples of volcanic siltstone and fine grained sandstone. SIO Expedition ANTIPODE, 1971. Location of profile is shown on fig. 9.

**A second site proposed for the western edge of the basin (L-8) will serve slightly different purposes as it is intended to focus mainly on the geochemical evolution of the Lau Ridge volcanic arc and the transition to the Lau Basin crust.**

The most recently-rifted margin of remnant arcs are valuable drilling objectives for understanding the evolution of oceanic island arcs. They record the vertical motion of an island arc during a rifting episode; they record the apparently distinctive magmatic phenomena associated with arc rifting; and they may provide access to early arc basement at a site far removed from the frontal arc. All three objectives can, in principle, be met by studying the complementary margin of the active arc, but the record there is covered and complicated by subsequent volcanism and the rifting-related volcanism is best developed on the remnant arc.

Within this context, the Lau Ridge is the sensible initial drilling objective for several reasons: it has the most subaerial exposure and the islands have been well-studied; it is the best surveyed geophysically, although the existing coverage is scant; and it is a natural component of an integrated drilling program in the Tonga-Lau region.

The Lau Ridge site has three specific objectives: (1) to determine the vertical motion of the Lau Ridge during opening of the Lau Basin; (2) to confirm and explore the lateral extent of the 7 M.a. boninitic and low-K rhyolitic magmatism which presaged this opening; and (3) to reach the Oligocene-Eocene basement of the Lau-Tonga arc. Each objective is discussed separately below after a brief description of the proposed site.

Site Description.
The eastern edge of the Lau Ridge is the youngest rifted margin of a remnant arc available for drilling. Backarc basin crust 3 to 5 M.a. and younger separates it from the Tonga frontal arc to the east. Fortuitously, thesubaerial portions of this remnant arc, i.e. the Lau islands of Fiji, are relatively extensive and well-studied geologically, chronologically, and petrologically (Woodhall, 1985; Whelan et al., 1985; Cole et al, 1985; Gill, 1976). South of the proposed site, the exposed basement consists of volcanic rocks 14 to 5 M.a. old: the Lau Volcanic Group. On the easternmost Lau islands (Cikobia-i-Lau, Katafaga, Oneata), this formation contains subaerially-erupted island arc tholeiitic basalts to acid andesites indicative of eruption at a volcanic front ($K60=1.0$; $FeO^*/MgO=3.0$; flat REE). Locally this formation is overlain by reefal limestone, epiclastic sediment, and chemically different volcanics. Elsewhere on the Lau and Tongan Ridges (i.e. Viti Levu and Eua islands, respectively) correlative formations are underlain by Eocene to Oligocene "arc basement". This overall context has been summarized recently by Gill et al. (1984), Whelan et al. (1985), and Kroencke and Rodda (1985).

The specific site proposed here (Fig. 11) is preferred for three reasons. (1) Nearby Cikobia island (Fig. 12), 40 km away, exposes basal 7.4 M.a. old boninitic pillow lavas and hyaloclastite sediments overlain first by calcareous sandstone and later by dense limestone. The site also lies 55 km along strike of the Udu Peninsula of Vanua Levu island where the basement is voluminous 7.0+/-0.5 M.a. old low-K rhyolitic domes and pyroclastic rocks (Stork and Gill, 1985) which host commercial Kuroko-type ores (Colley and Rice, 1975). These magma types require high thermal gradients in the upper mantle (boninite) and crust (rhyolite), and apparently presage opening of the Lau Basin. These boninitic rocks are the youngest in the western Pacific, and the low-K rhyolites are the most voluminous and best studied example of this widespread yet distinctive rock type of ocean arcs and backarcs. The rest of the easternmost remnant arc, for 30 km south to the Nanuku Basin exposes only Quaternary reef. (2) There is a 2400 meter-high scarp along the rifted arc at this point, and a 2000 meter-deep canyon is cut transverse to the strike of the arc. These scarps should provide access to the pre-Miocene basement. The steepness results from proximity to transform faults and from lying at the point of maximum flexure during rotation (Malahoff et al., 1983). This may be disadvantageous, resulting in extensive cataclasis. However, subaerially exposed rocks are undeformed. (3) There is at least some geophysical coverage. Mobil has made public several single channel lines >100 km to the south (Fig. 13) which are interpreted as showing "Miocene/Pliocene volcanic rocks and sediments" at the surface of the easternmost edge of the Ridge, with younger sediment ponded in westerly basins. Also, a shallow scientific hole was drilled in Wailanga Reef, 110 km to the south, in the 1940s; information is being sought.

Objectives.

(1) Vertical Motion. The regional subaerial geology indicates subsidence 7 to 4 M.a. ago (Woodhall, 1985). Nearby Cikobia island was the site of submarine volcanism 7 M.a. ago, and the volcanics are overlain by foraminiferal, calcareous sandstones. Facies and flora/fauna of the sediment may record the vertical history of the arc during its most recent rifting episode, but insufficient section is available for study on the islands.

(2) Volcanism Accompanying Rifting. Rifting in the northern Marianas and Bonins (Stern, 1984; Taylor et al., 1985) and elsewhere in Fiji (Gill et al., 1984) is accompanied by geochemically distinctive low-K rhyolite and high-K shoshonite, together with more conventional magma. It has been speculated that boninite also may occur in this context (Becceluva, 1982). Voluminous rhyolite and one small body of boninitic pillows form local basement near the proposed drill site. Drilling would explore the aerial extent and stratigraphic context of this rifting-related magmatism.

(3) Arc basement. The oldest rocks of Fiji and Tonga, like those of other western Pacific arcs, are Eocene sediments associated with 40-44 M.a. and 30-33 M.a. old arc tholeiitic and boninitic lavas (Ewart and Bryan, 1972; Whelan et al., 1985).The spatial distribution and variation in age and composition of this distinctive basement is important to establish because it is unknown whether the volcanism occurred over a wide area, covering

pre-existing oceanic crust, or occurred in an ordinary volcanic arc, displacing oceanic crust trenchward and eventually creating wide, young crust. In the Marianas, this distinctive basement apparently extends at least from the trench to Guam. Less is known in the southwest Pacific, but small exposures occur in the northernmost Tonga trench (Russian dredging, 1985), on the forearc high (Eua) and in the remnant arc (Viti Levu). Quite possibly none of this is in place. The proposed site offers the deepest exposure of the remnant arc, possibly exposing this basement. Together with work in the Tongan forearc, this would provide a wide sampling of arc basement for comparative study.

Site Status. Clearly this is a tentative proposal. Substantial site survey is needed, including multichannel seismic, dredging of canyon walls, and swath mapping.

..ed Site: L-8

General Objective: Rifting history and basement of oceanic island arc

..al Area: Lau Ridge, FIJI
..on: 179 34' W, 15 55' S
..ate Site: farther south, eaternmost Lau Ridge

Thematic Panel interest: LITHP
Regional Panel interest: WPP

..ific Objectives:
1. Vertical motion of an island arc during a rifting episode, (sedimentary paleo-environment
2. Volcanism accompanying rifting (age, petrology)
3. Arc basement (age, petrology, paleo-environment)

..ground Information:
..gional Data: industry single channel seismic profile
..eismic profiles: Nearby island geology, nearby shallow drill holes

..ther data:

..e Survey Data - Conducted by:
..ate:
..ain results:

..rational Considerations

..er Depth: (m) 2000 Sed. Thickness: (m) ? Total penetration: (m) ?

..C _____ Double HPC _____ Rotary Drill __x__ Single Bit __x__ Reentry _____

..ure of sediments/rock anticipated: volcaniclastic sediments and lava

..ather conditions/window: none

..ritorial jurisdiction: Fiji

..er:

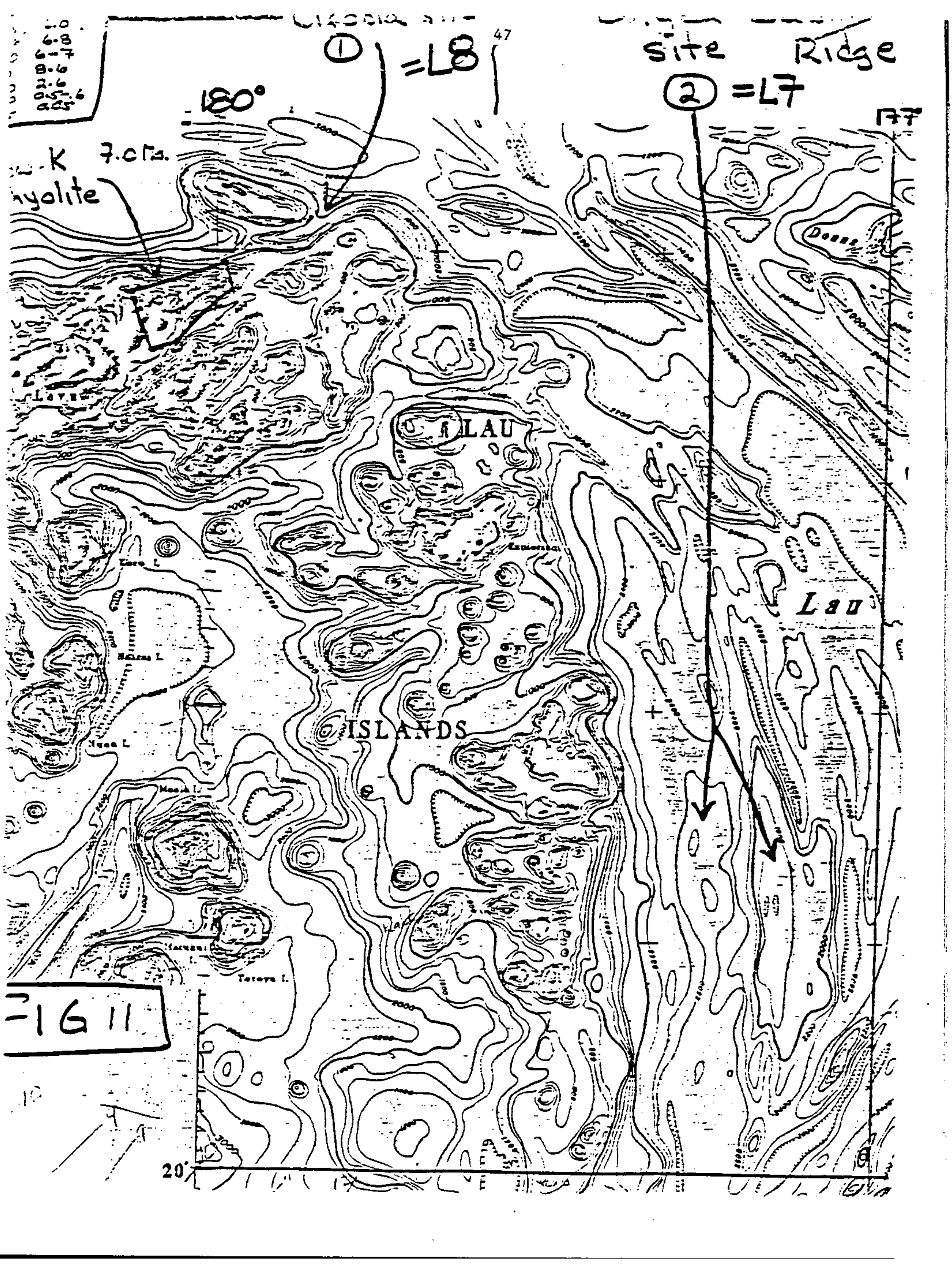
..cial requirements (Staffing, instrumentation, etc.)

..oponent:

James Gill, Earth Sciences Board, Univ Calif Santa Cruz

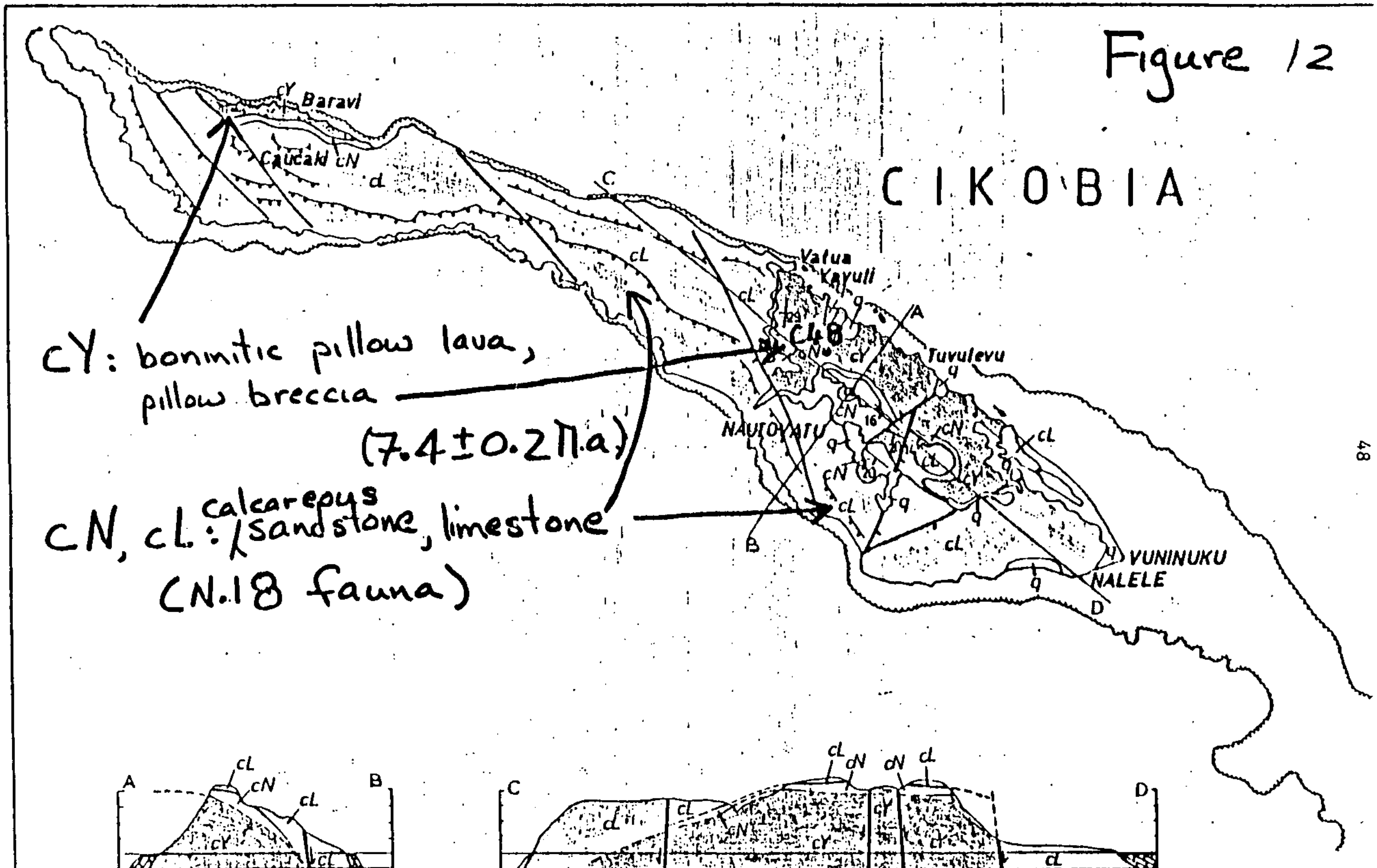
Date submitted to JOIDES Office:

Rev.



① =L8
Site Ridge
② =L7
180°
7.crs.
hyolite
LAU
ISLANDS
Lau
20°
FIG 11

Figure 12


CIKOBIA
Baravi
Caucalo
Valua
Kavuli
Tuvulevu
NAUTOVATU
VUNINUKU
NALELE
cY: bonnitic pillow lava, pillow breccia
(7.4±0.2 Ma)
cN, cL: calcareous sandstone, limestone
(N.18 fauna)
A
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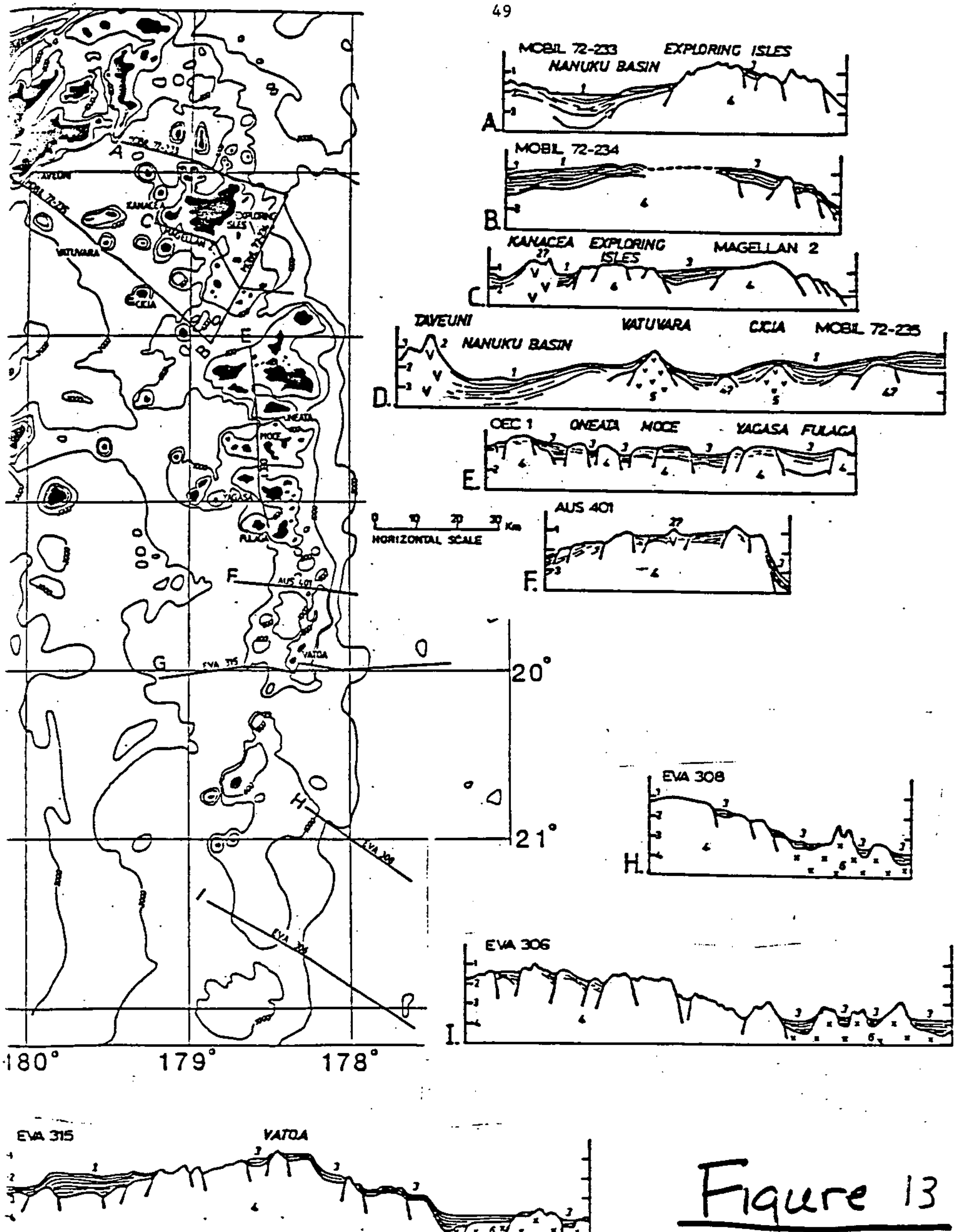
MOBIL 72-233
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VATUVARA
CICIA
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FULAGA
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HORIZONTAL SCALE
AUS 401
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EVA 308
H
EVA 306
I
20°
21°
180°
179°
178°
EVA 315
VATOA

Figure 13

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Whelan, P., Gill, J., Kollman, E., Duncan, R., and Drake, R. (1985) Radiometric dating of magmatic stages in Fiji. (In: Geology and Offshore Resources of Pacific Island Arcs - Tonga Region (Ed. D. W. Scholl and T. L. Vallier). Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, vol. 2. (in press).)

Woodhall, D. (1985) The geology of the Lau Ridge. Ibid.

2. The magmatic history of the Lau Basin spreading zone; hydrothermal circulation processes; possible effects of metallogenetic fluids; and the initial drilling of a "typical" backarc basin natural lab hole for comparative studies with the "lab" planned for the mid-Atlantic Ridge and East Pacific Rise. This site (L-11) is proposed as a bare rock drilling site near the axis of spreading in the Lau Basin. The chemistry of rocks dredged from the site indicates that they are "primitive" N-MORB (Hawkins, 1977; Hawkins and Melchior, 1985). One of the main objectives of drilling here will be to look for downhole variability in magma chemistry. The estimated spreading rate here is about 6 cm $yr^{-1}$ full rate and there is a probablity that shallow depth fractionation of magmas in near surface magma chambers has promoted temporal variability in magma chemistry. Hydrothermal circulation should have been extensive and deposition of surficial and intra-flow metalliferous deposits is likely - but not yet proved.

Site L-11 will most likely be a bare rock drilling site although it may be possible to find a small sediment pond near the axial region. May of these are known to be filled with the drift pumice that is so widespread in the basin. Expedition track lines and a representative single channel air gun seismic reflection profile are in Figures 14 and 15. Data from dredging and from SRP studies show that nearly all of the area near the presumed spreading axis is underlain by pillow basalts or by complex interfingering of both pillows and sheet flows. The topography is irregular and dominated by tilted blocks and half-grabens. It is typical of slowly-spreading ridge systems. More detailed discussions of the topography, structure and petrology are in Sclater et al., 1972; Hawkins, 1974, 1976; Hawkins and Melchior, 1985; and Lawver and Hawkins, 1978. The objective here is to begin a hole, near to the axial region, to collect samples to study temporal variability in magma chemistry; to make downhole measurements of physical properties; and to begin a backarc basin "natural lab". The initial hole depth objective would be 500 meters; the long term plan would be to deepen the hole and make long term physical and chemical properties measurements. The specific site selection should wait until a SEABEAM chart of the area is made and more magnetic profiling is done. This work, as well as extensive sampling of the axial region, will be done on the SIO expedition to the Lau Basin planned for December, 1985, J. Hawkins, Chief Scientist. By January, 1986, the data for making a specific site selection will be available.

3. The role of silicic magmas in backarc crust generation will be addressed at two sites. Site L-9, at the Valu Fa ridge "magma chamber" site will look for effects of magma mixing between silicic and basaltic liquids. Because there is good geophysical evidence for a volatile-rich magma chamber under Valu Fa ridge, the site will be important for making physical properties studies in an area with steep thermal gradients. The effects of hydrothermal circulation, low (?) grade metamorphism and deposition of sulfide minerals by circulation of metal enriched fluids will also be possible. The Valu Fa site may be a unique opportunity to sample and monitor new formed silicic crust in a backarc setting. The hole may require bare rock drilling but an alternate site is available on a small sediment pond. Ultimately this site may be used as a deep sampling site and re-entered periodically for long term chemical and physical measurements.

..ed Site: L-11

General Objective: Magmatic history of axial region of Lau Basin, temporal variability in magma composition, role of hydrothermal circulation, metallogenesis, initial drilling for a natural lab site in a backarc basin

..al Area: central Lau Basin
..on: approx 18 S 176 W (specific site
..nate Site: to be determined in Jan 86)

Thematic Panel interest: LITHP
Regional Panel interest: WPP

..ific Objectives: Drilling close to axis of spreading in backarc basin to look for magma variabili with time, consider possible effects of magma mixing between arc and backarc sources or differe mantle sources under the basin. Look for role of hydrothermal circulation in modifying crust ar possible formation of metalliferous deposits. Look for interbedded arc-derived clastic rocks ar their effect on magma compositon. Down-hole measurements and long - term plan to make this a natural lab site for eventual extension to greater depths and bore hole instrumentation.

..ground Information:
..gional Data: Published reports on geology of Lau Basin, SEABEAM coverage , shipboard and
..eismic profiles: aeromagnetc surveys, single channel seismic lines, rocks and sediment samples
Seismic Profiles: SIO expeditions, others ?

..ther data:

..e-Survey Data - Conducted by: SEABEAM charting , magnetic profiling and sampleing planned on SIO cruise inec 85
..ate:
..ain results:

..rational Considerations

..ter Depth: (m) 2200 m  Sed. Thickness: (m) bare rock  Total penetration: (m) 500 m

..C ____ Double HPC ____ Rotary Drill ____ Single Bit ____ Reentry x

..ure of sediments/rock anticipated: little or no sediment cover bare rock site on fresh basalt pillows and sheet flows

..ather conditions/window: none

..rritorial jurisdiction: Tonga - Fiji

..her:

..ecial requirements (Staffing, instrumentation, etc.)

bare rock drilling bottom assembly

..oponent:

Date submitted to JOIDES Office:

James Hawkins, Geological Research Div, Scripps Inst. Oceanography, La Jolla, Calif 92093

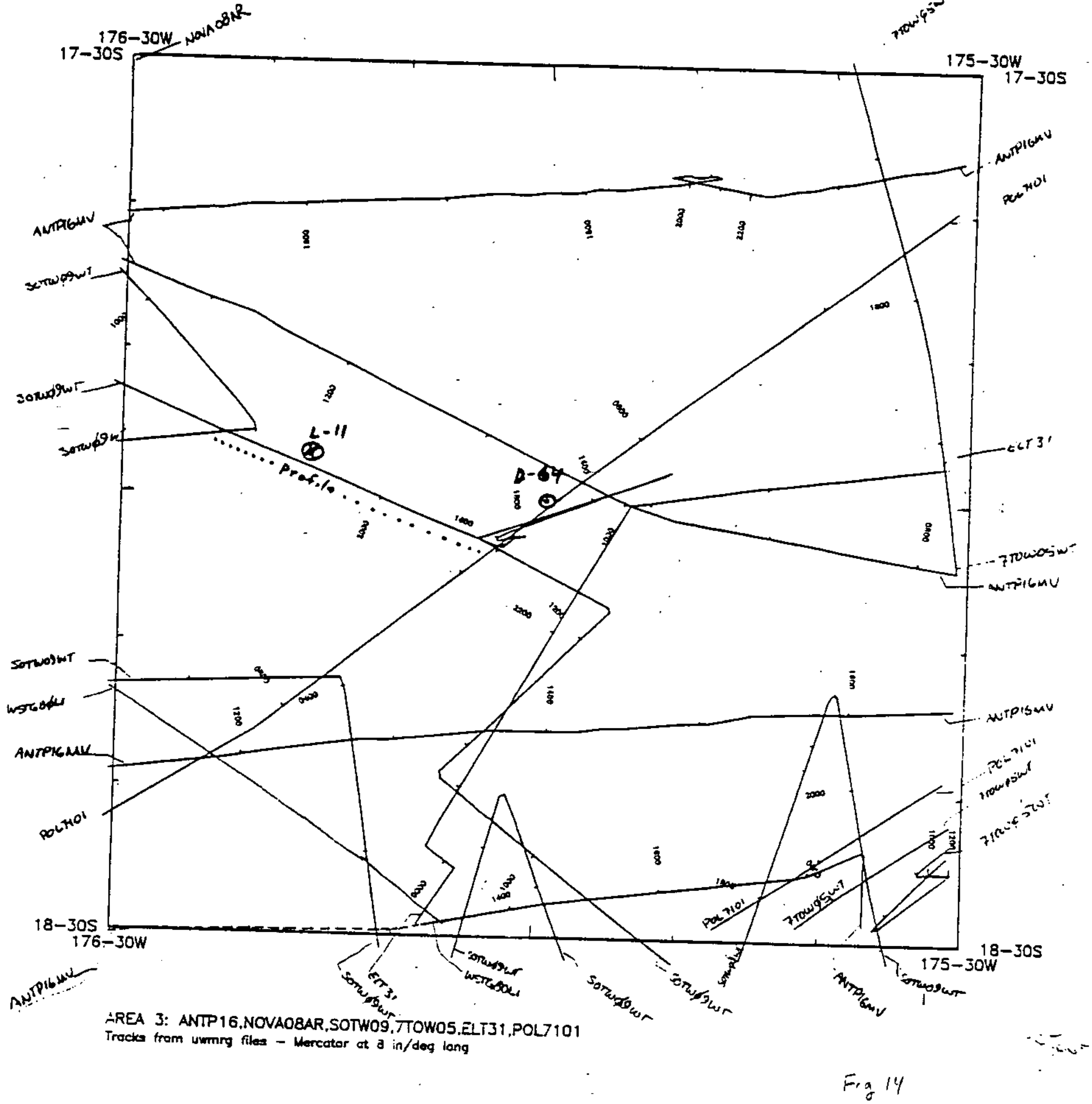


Figure 14: Ship tracks for expeditions near Site L-11, Lau Basin axial spreading region.From SIO Geological Data Center.

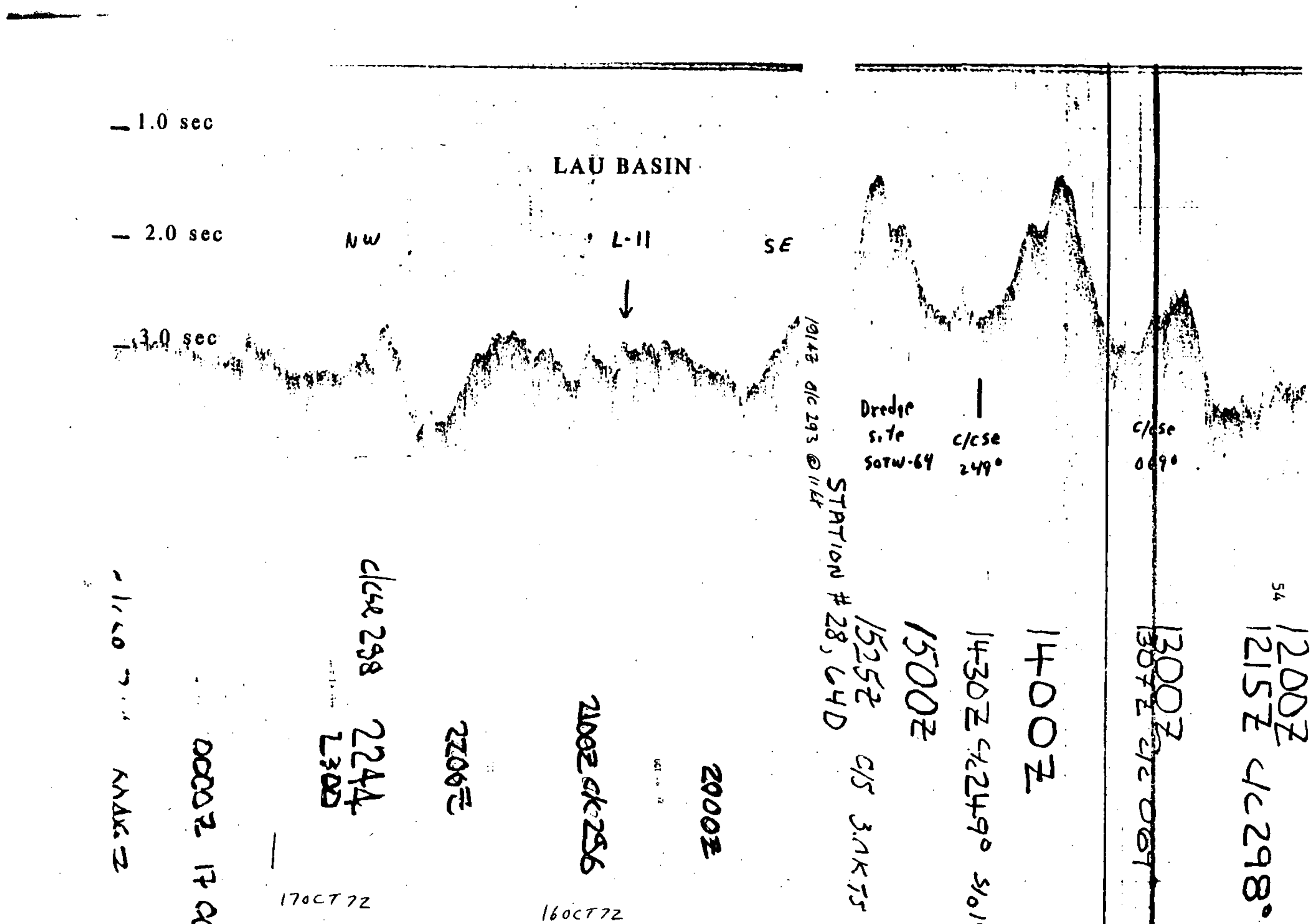


Figure 15: Seismic reflection profile near proposed bare-rock drilling site L-11 in central Lau Basin. Two -way travel time in seconds. Station SOTW -64 is location of samples of "primitive" N-MORB basalt. SIO expedition

# VALU FA RIDGE, LAU BASIN L-9

## A PRELIMINARY DRILLING PROPOSAL AT A BACK-ARC SPREADING CENTER

J. L. Morton, T. L. Vallier
U. S. Geological Survey, Menlo Park, CA 94025

and J. Hawkins
Scripps Institution of Oceanography, La Jolla, CA 92093

### BACKGROUND

The Lau Basin is an actively spreading back-arc basin located west of the Tonga arc-trench system. The spreading center in the southern part of the basin is the Valu Fa Ridge, a north-north-east trending ridge situated along the eastern side of the basin approximately 40 km west of the Tofua volcanic arc (Figure 16). Magnetic anomalies indicate that the crust between Valu Fa Ridge and the Tofua arc was created by back-arc spreading at Valu Fa Ridge (Morton and Sleep, 1985) (Figure 17). Valu Fa Ridge has been spreading for at least the past 700,000 yrs at a full rate of about 7 cm/yr, similar to the spreading rate determined for the northern part of Lau Basin by Weissel (1977). The ridge has a narrow, non-rifted crest and extends for about 90 km from at least lat 21° 51'S, long 176° 30'W to lat 22° 42'S, long 176° 46' W. A small offset of the ridge at lat 22° 10'S appears to be formed by an overlapping spreading center pair.

Multichannel seismic reflection profiles over Valu Fa Ridge show a strong reflection 3.5 km beneath the seafloor. The polarity of the reflection, determined by pre-stack deconvolution, indicates that the reflecting horizon represents a low velocity zone (Morton and Sleep, 1985). The reflector is interpreted as the top of an axial magma chamber. The top of the chamber is flat-lying and 2 to 3 km wide (Figure 18). The magma chamber appears to be continuous along strike, as it was observed on each of seven cross-strike profiles (from 1982 and 1984 cruises of the S. P. Lee ) spaced over 84 km of ridge crest (Morton et al., 1984). One profile which crosses the ridge at the overlapping spreading centers shows only one magma chamber, centered beneath the overlap basin.

The reflection coefficient for the top of the chamber, determined by comparing the amplitude of the magma chamber reflection to the seafloor reflection, indicates a low acoustic impedance (product of density and seismic velocity) for the material at the top of the chamber. If a density of 2.4 to 2.7 $gm/cm^3$ is assumed for the melt, then the velocity is approximately 1.8 to 2.0 km/sec. This velocity is considerably lower than experimentally determined velocities of basaltic and andesitic melts (about 2.5 km/sec) (Murase and McBirney, 1973; Rai et al., 1981). One possible explanation for the low seismic velocity is the presence of a small amount (approximately 1 volume percent) of exsolved gas in the melt at the top of the chamber. Fresh, highly fractionated glassy andesite dredged from the crest of Valu Fa Ridge is highly vesicular with some vesicles more than 6 cm in length.

Rocks from two dredge hauls that were recovered on the 1984 S. P. Lee cruise show very little isotopic heterogeneity ($^{87}Sr/^{86}Sr=0.70330\pm2$; $^{143}Nd/^{144}Nd=0.51303\pm2$; $^{206}Pb/^{204}Pb=18.65\pm2$; $^{207}Pb/^{204}Pb=15.55\pm1$; $^{208}Pb/^{204}Pb=38.34\pm4$) but have small but consistent differences between dredge hauls in terms of their major and trace element compositions (Jenner et al., 1985; Vallier et al., in prep.). These differences cannot be easily explained by simple fractional crystallization of a common parental magma because of an inverse relationship between degree of fractionation and some incompatible element abundances and changes in ratios of the highly incompatible elements. On Sr-Nd, Sr-Pb, and Pb-Pb plots the Valu Fa samples lie just within or on the limits of the MORB fields, overlapping with island arc volcanics from the Marianas, Tonga, and the Aleutians. These isotopic characteristics and some other geochemical data (e.g. enrichment of Cs relative to Rb, plus enrichment of K, U, Rb, Cs, and Ba over MORB values of 3 to 20x) indicate a minor but significant subduction zone effect on the source area.

Elevated concentrations of particulate and total dissolvable manganese in the water column above the ridge and ferromanganese crusts up to 10-mm thick of hydrothermal origin dredged from the ridge crest suggest that hydrothermal circulation is occurring at the ridge.

## DATABASE CONSIDERATIONS

Surveys of Valu Fa Ridge aboard the S. P. Lee in 1982 and 1984 and the Sonne in 1985 have yielded a considerable amount of geophysical and geologic information. 450 km of 24-channel seismic reflection profiles and accompanying gravity and magnetics data and 3.5 kHz and 12 kHz profiles include 7 crossings of the ridge axis (Figure 6). More than 2000 km of Seabeam profiling, accompanied by magnetics and 3.5 kHz profiling, yielded detailed bathymetry of the ridge from about lat 22° 8'S to 22° 40'S. Geochemical studies are in progress on samples obtained from 21 dredge hauls along the ridge and on sediment samples obtained by gravity and piston coring in basins east and west of the ridge. Six deep-towed photographic stations and one hydrocast station have also been conducted along the ridge axis. Upcoming cruises to Valu Fa Ridge aboard French and U.S. vessels in 1985 and 1986 will provide additional rock and water samples and geophysical data.

## OBJECTIVES

Valu Fa Ridge presents a unique opportunity to study hydrothermal circulation at a spreading ridge where the depth to the heat source is known. We propose drilling one hole to penetrate into the upper plutonic section along Valu Fa Ridge crest at lat 22° 15'S, long 176° 37'W (requires bare-rock capability). An alternate drill site is in one of the small sediment basins on the eastern flank of the ridge (22° 37'S, 176° 43'W and 22° 38'S, 176° 38'W) where bare rock drilling capabilities may not be necessary. Specific objectives to be addressed by drilling at Valu Fa Ridge include:

### VALU FA RIDGE CREST

1. What is the nature of hydrothermal circulation at the ridge axis and its relationship to the axial magma chamber?

   Is the upper crust over the magma chamber completely cooled by cool seawater, or is there a thermal gradient in the shallow crust? What is the permeability and pore pressure in the crust and how does it relate to convection? Are high temperature minerals being crystallized at depth? What is the chemistry of the circulating fluids?

2. What factors affect the chemistry of rocks erupted at back-arc spreading centers? Does chemistry change with depth?

Rocks dredged from Valu Fa Ridge are andesites with MORB affinities, but also showing subduction zone effects. They have a high volatile content. What is the affect of magma mixing on back-arc lava chemistry? How much effect does the down-going slab have on the chemistry?

3. What are the physical properties of the crust near the spreading center?

Seismic reflection and refraction results indicate that the shallow crust at the ridge has a low velocity. Sonobuoy refraction records suggest that this low velocity region is about 500 to 1000m thick. Highly vesicular samples dredged from the ridge suggest that the low velocity may result from a high porosity. Does the low velocity reflect high porosity only? or a high degree of fracturing? How thick is the low velocity layer? Down hole experiments (seismic, televiewer, etc) would address these questions.

VALU FA FLANKS

Sedimentation rate is high in the region, especially east of the ridge near the arc. Small sediment-filled basins lie within 4 km of the ridge axis and basins with thicker sediment fill within 7 to 8 km (Figure 19). A gravity core that was "warm to the touch" was recovered from one of the basins adjacent to the ridge. Drilling at Valu Fa would require hard rock capabilities, but this might not be required in these basins. Drilling in these basins might also help answer questions such as: When does the sediment cover become thick enough to provide an impermeable cap to a hydrothermal convection system? What is the timing of recent arc eruptions (tephrochronology)?

## COMPARISON WITH SPREADING CENTER IN NORTHERN LAU BASIN

Valu Fa Ridge lies in the southern part of the basin, near the eastern side. Further north in the basin, the spreading center lies nearer the center of the basin and is characterized by MORB-like volcanism. Does Valu Fa represent an early stage of opening and the northern spreading center a more mature spreading center?

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Vallier, T., J. Hawkins, G. Jenner, J. Gill, F. Frey, P. Cawood, J. Morton, D. Scholl, R. Herzer, W. White, M. Rautenschlein, A. Volpe, L. White, R. Williams, and A. Stevenson, Petrogenesis of andesite from Valu Fa Ridge, Lau Basin: subduction zone effects in rocks from a back-arc spreading ridge, in prep.

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## FIGURE CAPTIONS

Fig. 16 Bathymetric map of the eastern Lau Basin and the southern Tonga Platform showing the location of Valu Fa Ridge and multichannel seismic reflection lines from the 1982 and 1984 S. P. Lee cruises. Triangle marks the location of 2 dredge stations, 3 photographic stations, and 1 hydrocast station from the 1984 S. P. Lee cruise. Additional dredge, photographic, and coring stations from the 1985 Sonne cruise located along Valu Fa Ridge between lat 22° 8'S and 22° 32'S are not shown. Bathymetric mapping by T. E. Chase, B. A. Seekins, S. C. Vath, and M. A. Cloud. Contour interval is 400 m.

Fig. 17 A) Observed total field magnetic anomaly along line 10. B/M marks the Brunhes/Matuyama boundary. J? marks the Jaramillo event. B) Observed magnetic anomaly along line 11. C) Synthetic profile for a ridge spreading at 7 cm/yr. D) The input model for the synthetic profile. Dark areas represent normal periods; light areas represent reversed periods.

Fig. 18 Migrated depth section for multichannel line 10 over Valu Fa Ridge. Note that the magma-chamber reflection (arrow A) is flat-lying after depth migration.

Fig. 19 Time section of multichannel line 11 over Valu Fa Ridge showing magma chamber reflection (arrows A) and small sediment basins to the east of the ridge.

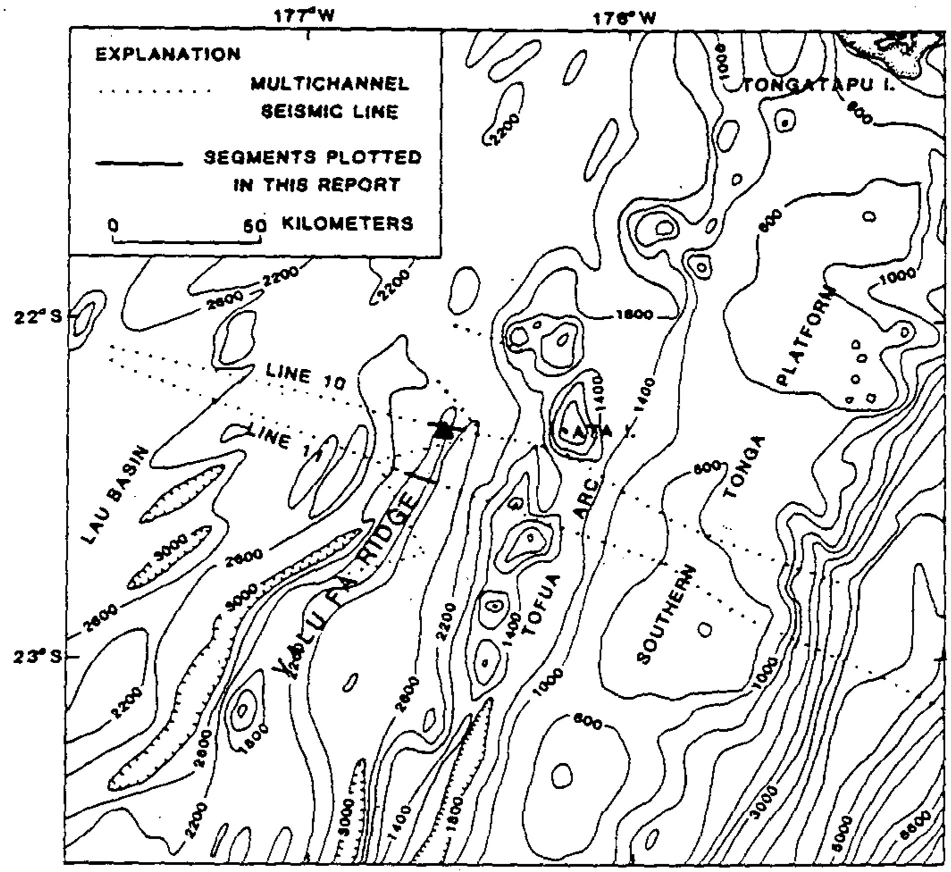
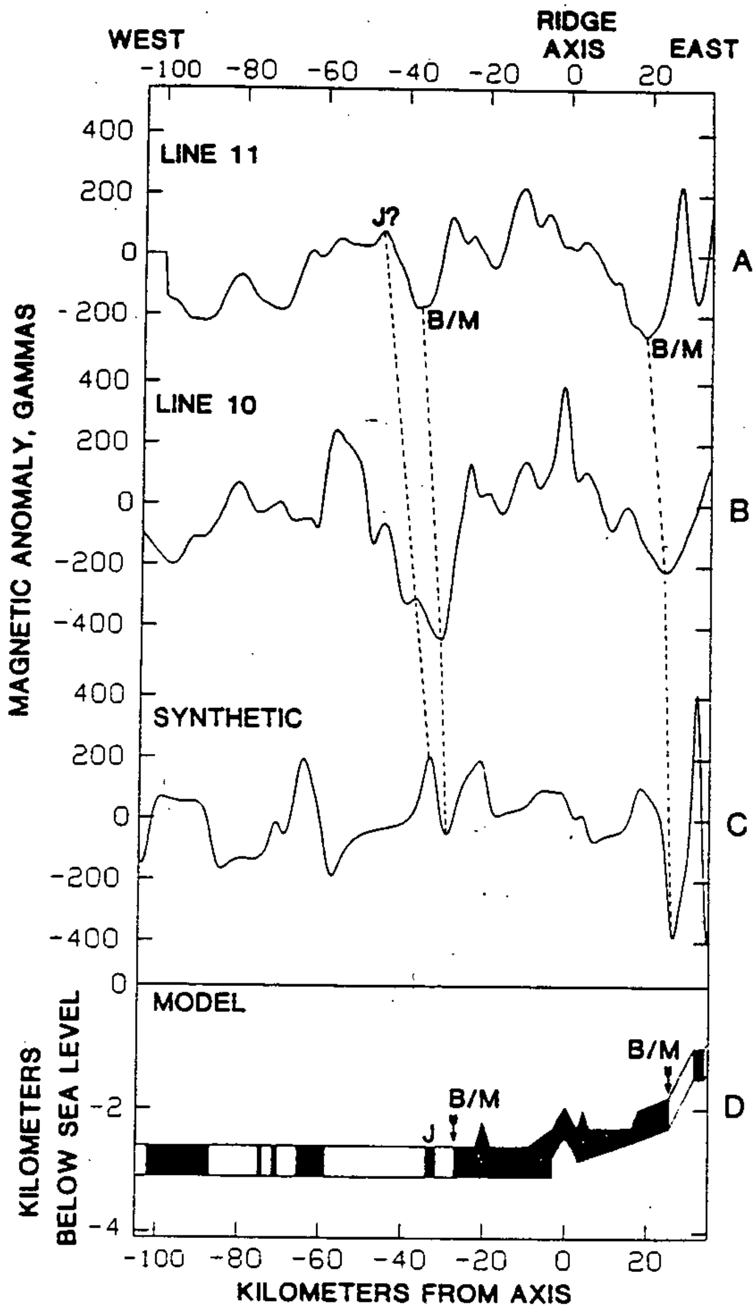

177°W
176°W
22°S
23°S
EXPLANATION
MULTICHANNEL SEISMIC LINE
SEGMENTS PLOTTED IN THIS REPORT
0 50 KILOMETERS
TONGATAPU I.
LINE 10
LINE 11
LAU BASIN
TOFUA ARC
SOUTHERN TONGA PLATFORM
ATA
2200
2600
3000
1800
1400
1000
600
5000
5600

Fig. 16



WEST
RIDGE AXIS
EAST
-100 -80 -60 -40 -20 0 20
400
200
0
-200
400
200
0
-200
-400
400
200
0
-200
-400
0
-2
-4
LINE 11
J?
B/M
B/M
A
LINE 10
B
SYNTHETIC
C
MODEL
B/M
B/M
J
D
MAGNETIC ANOMALY, GAMMAS
KILOMETERS BELOW SEA LEVEL
-100 -80 -60 -40 -20 0 20
KILOMETERS FROM AXIS


Fig. 17

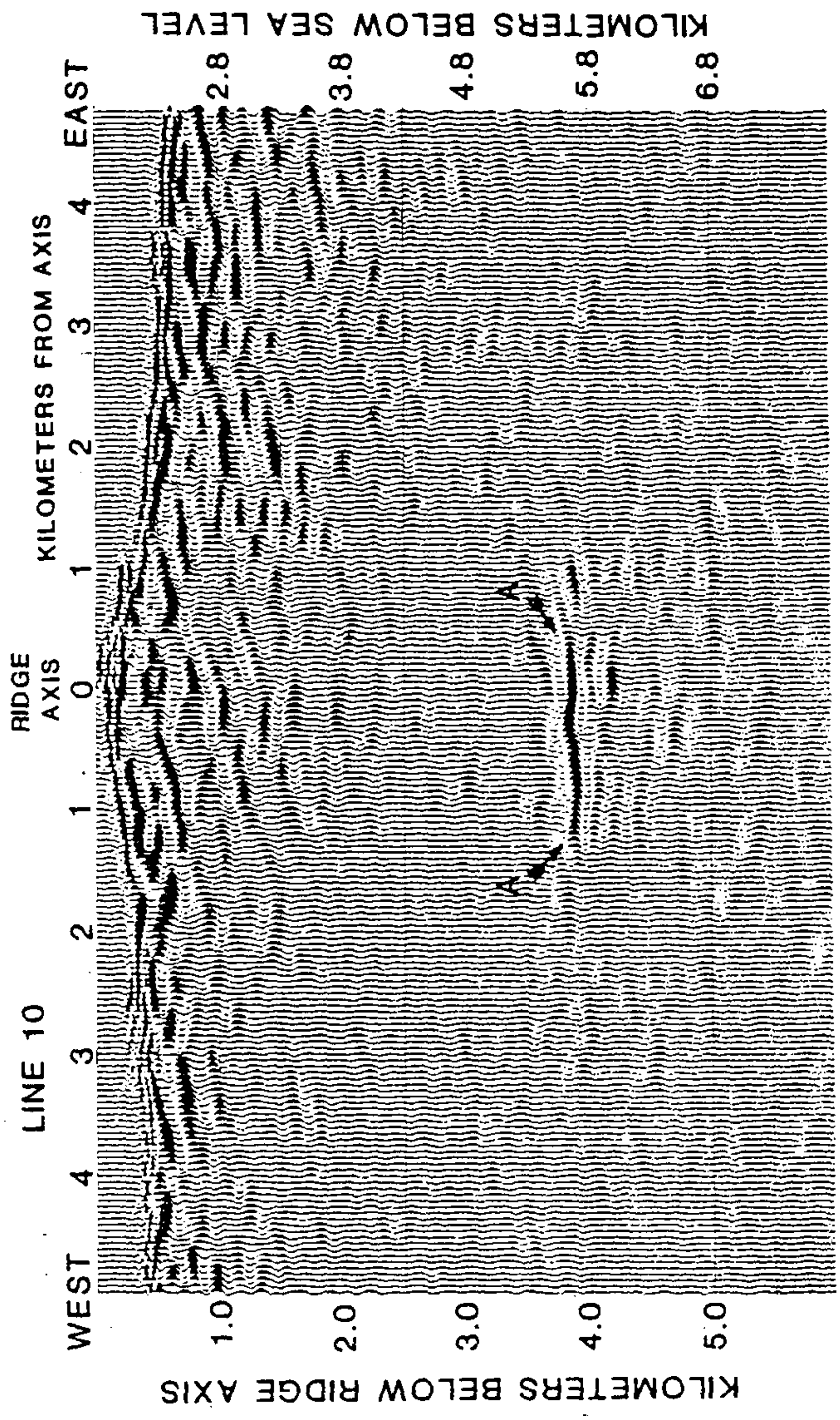

KILOMETERS BELOW SEA LEVEL
2.8
3.8
4.8
5.8
6.8
EAST
KILOMETERS FROM AXIS
4
3
2
1
RIDGE AXIS
0
1
2
3
4
LINE 10
WEST
A
A
1.0
2.0
3.0
4.0
5.0
KILOMETERS BELOW RIDGE AXIS

Fig. 18

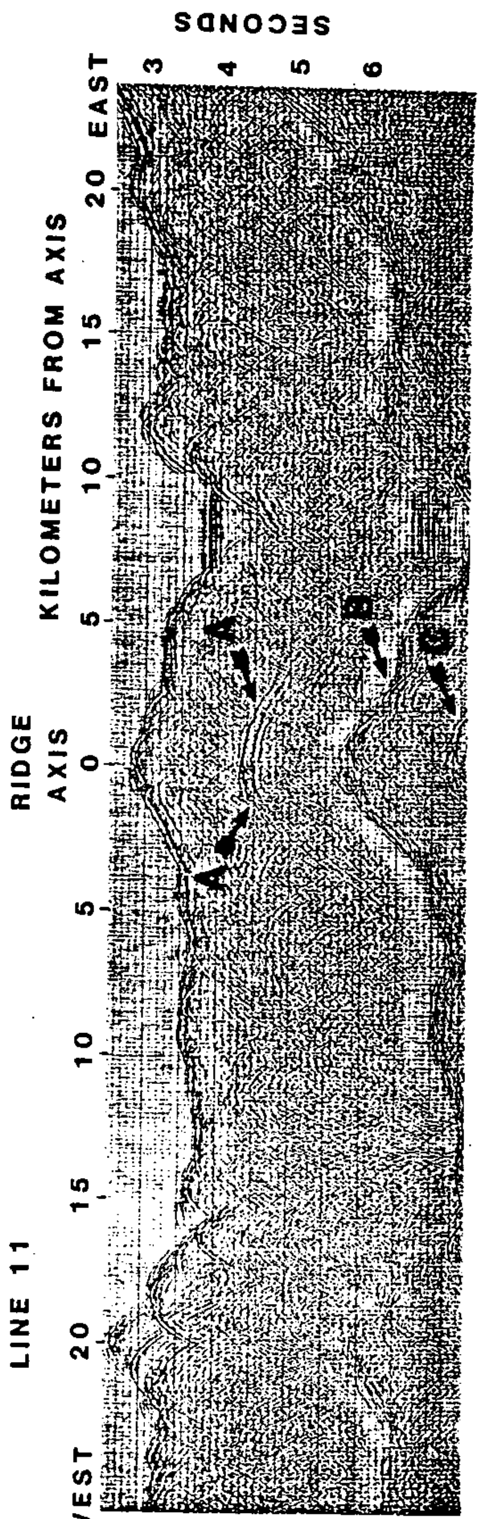

LINE 11
WEST
EAST
KILOMETERS FROM AXIS
RIDGE
AXIS
SECONDS
A
A
B
C

Fig. 19

Proposed Site: Crest of Valu Fa Ridge back-arc spreading center

L-9

General Area: Lau Basin
Position: 22°15'S, 176°37'W
Alternate Site: eastern flank of Valu Fa Ridge

General Objective: Magmatic and hydrothermal processes at a young back-arc spreading center.

Thematic Panel interest: Lithosphere
Regional Panel interest: western Pacific

Specific Objectives:

1. Relationship of hydrothemal processes to underlying magma chamber.
2. Petrologic processes and the role of magma mixing.
3. Physical properties of the crust.

Background Information:

Regional Data:

Seismic profiles: 24 channel seismic profiles (U.S.G.S.), single channel, 3.5 kHz and 12 kHz profiles

Other data: SeaBeam (B.G.R.), sonobuoy, magnetics, gravity, seafloor photography, dredging, geochemistry of dredge hauls, water column chemistry, gravity cores from nearby basins.

Site Survey Data - Conducted by:

Date:

Main results:

Operational Considerations

Water Depth: (m) 1700 m   Sed. Thickness: (m) 0m   Total penetration: (m) 1500 m

HPC ____   Double HPC ____   Rotary Drill ____   Single Bit ____   Reentry X

Nature of sediments/rock anticipated: Volcanic ash, brown clay, volcanic sediments, fresh andesitic sheet flows and aa flows.

Weather conditions/window:

Territorial jurisdiction: Tonga

Other:

Special requirements (Staffing, instrumentation, etc.)

Bare rock spud-in (not required at off-axis alternate site) special logging tools: bore hole televiewer and high temperature probe rock and water chemistry laboratories.

Proponent: Janet Morton
U.S. Geological Survey
345 Middlefield Rd., MS 999
Menlo Park, CA 94025

Date submitted to JOIDES Office:

**The Zephyr Shoal site (L-10) is selected to drill into the flanks of a known extrusion of dacite vitrophyre. The purpose will be to sample the contact zone; to look for effects of magma mixing; assimilation of silicic rock in mafic melts, or reaction relations between older mafic and younger silicic bodies; stockwork brecciar; metalliferous deposits; and, if deeper drilling is possible, the transition to hypabyssal or plutonic tonalite. This site will be an important place to investigate the possible relationship between tonalite-plageogranite masses of ophiolites and backarc crustal rocks.**

Zephyr Shoal has been sampled and charted on previous expeditions (Sclater et al, 1972; Hawkins,1974;1976). Surface exposures are dacite vitrophyre with phenocrysts of hypersthene and bytownite in a high silica groundmass. It must be underlain by a hypabyssal pluton of tonalite and must have a margin of mixed rock formed of silicic and mafic magmas. Expedition track lines near Zephyr Shoal, and a representative single channel air gun seismic reflection profile are in Figures 20 and 21. The top of Zephyr Shoal appears to be bare rock or has a very thin sediment cover. However, there is a sediment filled moat around the base that has up to 0.2 seconds of silt and fine grained foram - bearing sands. A heat flow measurement made in this moat gave a values of 2.62 HFU ( cal cm sec ). The sediment filled moat appears to offer a site suitable for spudding in. Additional surveying, including SEABEAM charting, magnetic profiling and dredge/gravity core sampling will be done on the SIO expedition to the Lau Basin in Dec, 1985, J. Hawkins, Chief Scientist.

sed Site: Zephyr Shoal, Lau Basin

L-10

neral Area: central Lau Basin
sition: 15 53' S, 176 42' W
ernate Site:

General Objective: Petrologic study of backarc cr at site of known silicic extrusion to study the possible relationships to silicic bodies in ophioli Hydrothermal circulation studies, look for effects metallogenesis

Thematic Panel interest: LITHP
Regional Panel interest: WPP

ecific Objectives: Zephyr Shoal is known to be a dacite vitrophyre extrusion, presumably very young as there is very high heat flow in nearby sediment ponds. At depths there must be a small plutonof tonalite. The purpose will be to sample it to look for the mixing relations with the basaltic crust and to consider it as as analog for the silicic bodies common in ophiolites but rare to non-existent on the deep ocean floor. High probability that the hydrother cooling of the silicic body is favorable to metal transport and stockwork or disseminated sulfides are likely.

ckground Information:
egional Data: Geology of Lau Basin is known, area has been mapped and samples studied.
Seismic profiles: SIO expeditions and others?

Other data: Area will be charted with SEABEAM, magnetic profiles taken and sampled on SIO expedition in Dec 1985

ite Survey Data – Conducted by:
Date:
Main results:

perational Considerations

ater Depth: (m) 2200   Sed. Thickness: (m) 0.4 secs   Total penetration: (m) 400 -500 m sediment plus 500 m basemen

HPC ____   Double HPC ____   Rotary Drill x   Single Bit ____   Reentry x

Nature of sediments/rock anticipated: silts and volcanic sands, igneous basement probably basalt and dacite

Weather conditions/window: none

Territorial jurisdiction: Tonga - Fiji

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent:   Date submitted to JOIDES Office:

James Hawkins, Geological Research Division, Scripps Inst. Oceanography, La Jolla, Calif 92093
Debra Stakes, Geology Dept. Univ South Carolina, Columbia, SC

Rev. 0284

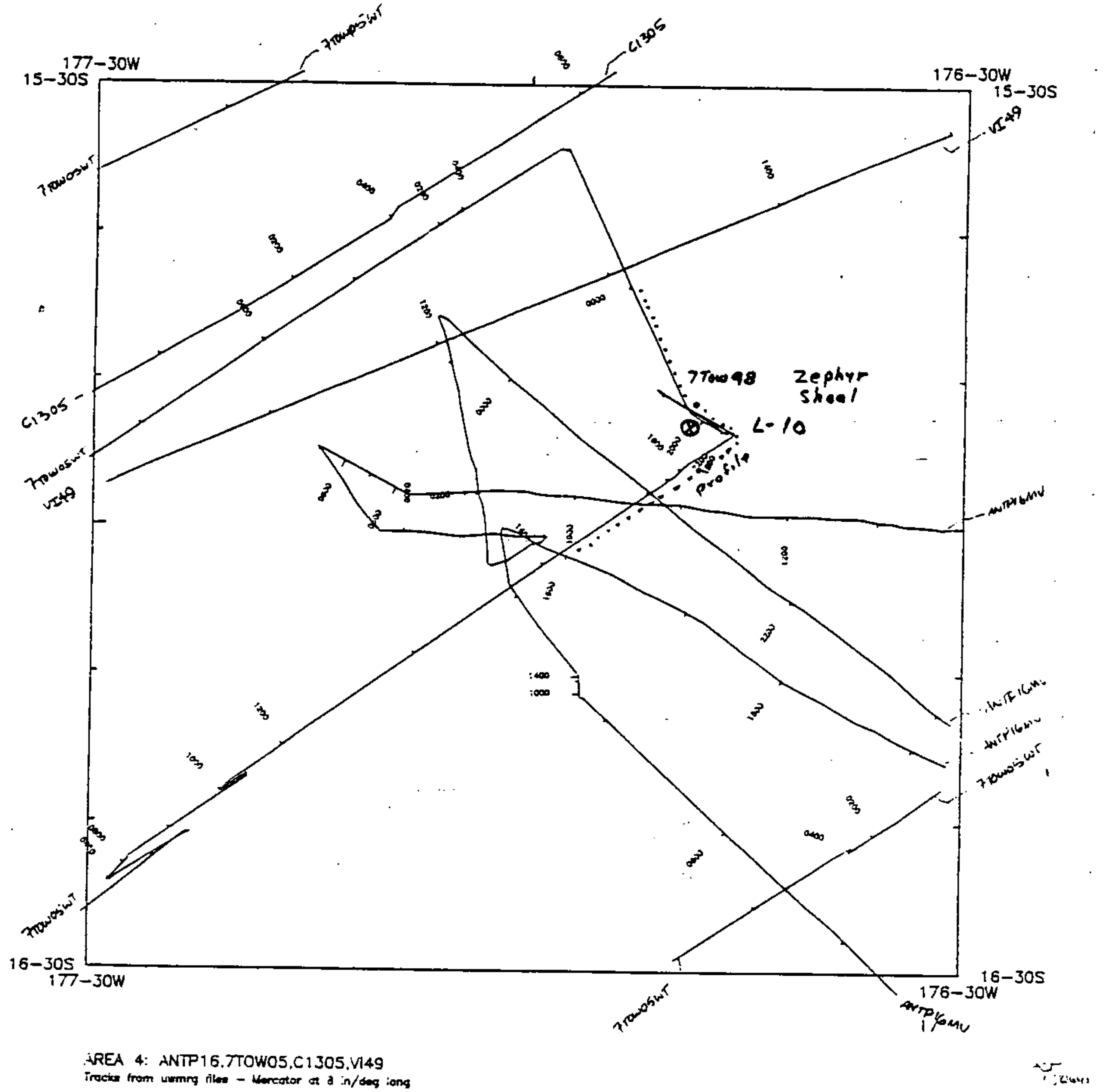



Figure 20: Ship tracks for expeditions near Site L-10, Zephyr Shoal. From SIO Geological Data Center.

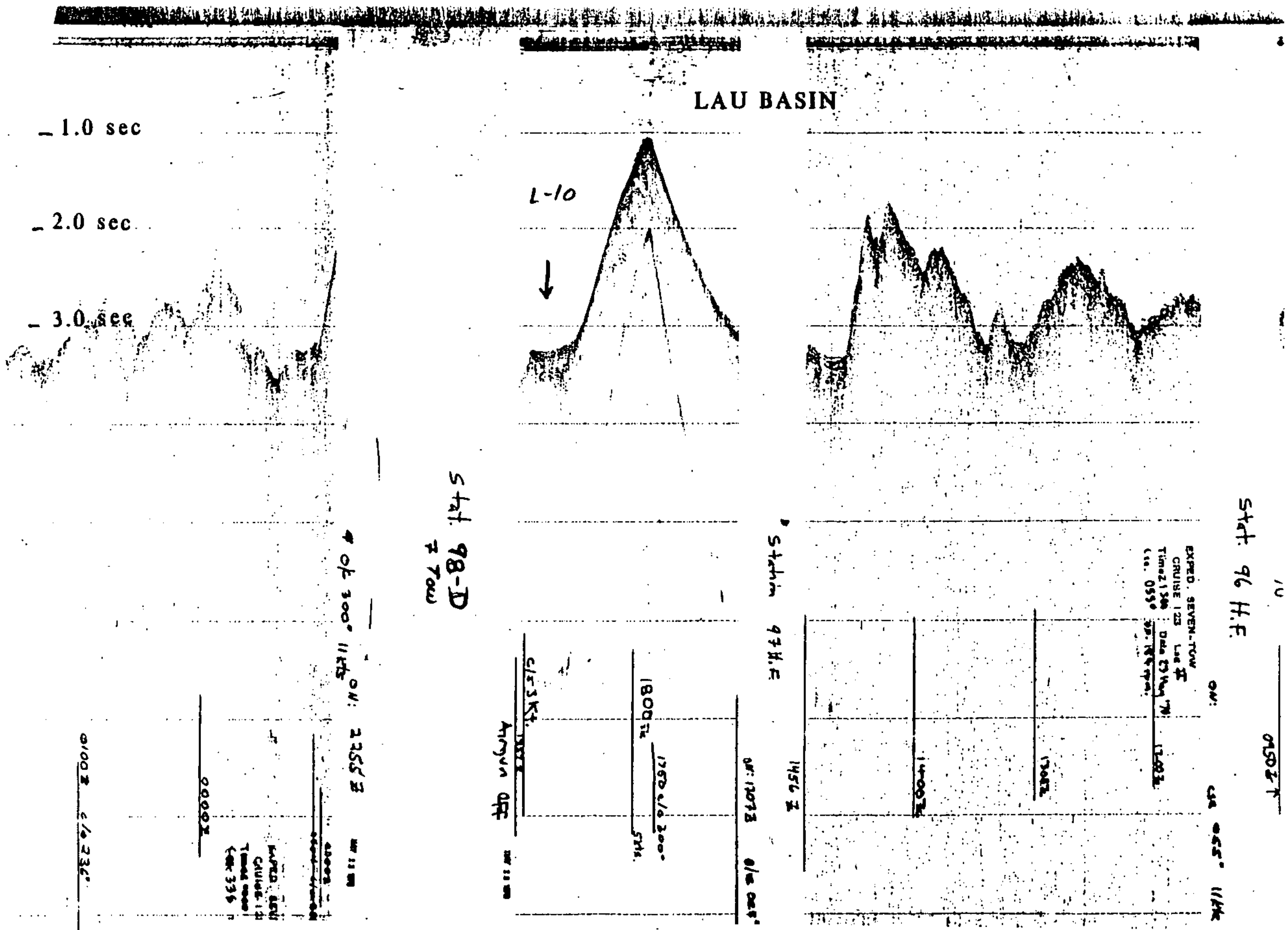



Figure 21: Seismic reflection profile near proposed drill site at Zephyr Shoal. Two - way travel time in seconds. Station 98 is location of dacite vitrophyre samples. SIO Expedition 7-TOW, 1970. Location of profile is shown on Fig.

ODP DRILLING PROPOSAL, TONGA - LAU REGION

A. Stevenson, D. Scholl, T. Vallier, R. Herzer, P. Ballance, G. Chaproniere

## INTRODUCTION

The Tonga Ridge - Lau Basin - Lau Ridge system represents an arc-backarc basin-remnant arc triplet lying along the north-eastern margin of the Indo-Australian plate. The Tonga Trench, an active subduction zone, lies immediately East of the Tonga Ridge and constitutes the modern Pacific - Indo-Australian plate boundary. Subduction of Pacific lithosphere westward under the triplet is occurring presently at a rate of 90 mm./yr (Minster and Jordan,1978), and has maintained this general geometery since the demise of South Fiji Basin spreading at 26 Ma (Malahoff et al, 1982). Prior to the onset of South Fiji Basin spreading at 36 Ma basement rocks currently incorporated into the Tonga Ridge ('Eua outcrops) were located along the New Caledonia-Norfolk arc trend (Falvey and Cassie, 1979). These rocks are separated from overlying Miocene volcaniclastic deposits of presumed Lau arc origin by a hiatus that represents most (or all) of the Oligocene South Fiji Basin spreading interval.(Chaproniere, pers. comm., 1985). The remnant Lau arc was split from the Tonga Ridge by the inception of spreading in Lau Basin sometime in Pliocene time. Ages postulated for this event range from 5 Ma (Cherkis,1980) to 2.5 Ma (Malahoff et al,1982). Modern arc volcanism in the triplet is confined to the western Tonga Ridge along the Tofua Arc, which began about 3.4 Ma (Woodhall,in press,1985).

The history of the triplet can be divided broadly into three major phases. Phase 1 is represented by the 'Eua Eocene arc volcanic sequence and is separated from phase two by the Oligocene South Fiji Basin spreading hiatus. Phase two is represented by the Miocene-lower Pliocene Lau-Tonga arc, and is separated from phase 3 by the opening of Lau Basin. Phase 3 is represented by continued spreading in the Lau Basin and volcanism along the Tofua arc.

This relatively simple tectonic history compared to other arcs in the western Pacific provides several opportunities to answer questions about the mechanisms by which arcs evolve, the processes of back arc spreading, and the formation of new arcs. These opportunities will be described in detail in the following sections.

In addition to these questions the interaction of the descending Pacific lithosphere with the overlying Tonga Ridge provide opportunities to examine several subduction related processes. The oblique subduction of the Louisville Ridge beneath the Tonga Ridge over the last 3-4 m.y. (Dupont and Herzer, in press,1985) has swept from the north end of the trench to it's current intersection south of Tongatapu. This has resulted in the subduction of a large number of massive seamounts in a sediment starved (unlubricated) system. Subduction of these seamounts is believed to have had a profound effect on the forearc (Dupont and Herzer, in press, 1985). The proximity of this event in time to the inception of spreading in Lau Basin allows for the possibility of a genetic relations between the two (see following).

## CESSATION OF ARC ACTIVITY AND IT'S RELATION TO BACK-ARC SPREADING

The Tonga Ridge-Lau Basin-Lau ridge triplet contains within it the record of two episodes of arc dismemberment and rafting of an arc fragment away from it's sister by back-arc spreading. The first episode of arc sundering is represented by the Eocene section on 'Eua island and western Viti Levu. This section was formed above the early Tertiary Norfolk Ridge-New Caledonia subduction zone, then transported eastward by the opening of the South Fiji and Loyalty Basins (Falvey and Cassie, 1979). Cessation of volcanism along this arc trend could be compared to the known period of South Fiji Basin spreading to determine whether or not these two events are synchronous in time, or whether arc volcanism persists after back-arc spreading begins. Proposed sites Lau-1 and Tonga Terrace 1 and 2 are sited to bottom in the uppermost preserved section of this Eocene arc terrane

The 'Eua outcrops and rocks dredged from the Tonga Ridge indicate the existence of a hiatus in the depositional history of the ridge that appears to correlate with the period of South Fiji Basin spreading. The proposed sites mentioned should provide a refined age range for this hiatus and indicate when, in relation to the end of spreading, the arc again became volcanically active. Scott et al (1980) has proposed a similar relationship for the Mariana arc system (back-arc spreading = no volcanism on frontal arc), but this has been disputed (Hussong and Uyeda, 1981). This area provides another opportunity to test the theory. Current data from the triplet supports the view of Scott, although in the more modern Lau Basin spreading episode, back-arc spreading and volcanism on the Tofua Arc are proceeding together.

The size of the displaced terrane underlying the Tonga and Lau Ridges is unknown. Outcrops of this terrane are known from 'Eua island in the Tonga group and from western Viti Levu in the Fiji islands (Colley,1976; Stearns,1971). Rocks dredged from the Tonga forearc and the western flank of Lau Ridge (and DSDP site 205) contain reworked clasts and microfauna derived from this terrane. Proposed sites Lau-1,Tonga Terrace-1 and Tonga Terrace-2 will help to define the areal extent of this terrane and may provide samples suitable for age dating and paleomagnetic investigation to reconstruct the original position of this old arc. Similar rocks from Fiji and Tonga have so far proved unsuitable for this investigation (Rodda, 1982).

The second episode of arc splitting and back-arc spreading involving the triplet can be investigated with a great deal more precision than it's earlier counterpart. proposed site Lau-1 is sited to obtain a complete record of Lau Ridge volcanism proximal to the arc axis, and site Lau-2 is positioned to obtain samples of the oldest sediment in Lau Basin that are presumed to overly the oldest crust in the basin. The two Tonga Terrace holes will provide a history of the vertical tectonics of the arc prior to sundering as will site Lau-1. Combined with the known magnetic anomaly ages from the basin (Weissel,1977 Malahoff et al,1982, Dupont and Herzer,in press,1985) these drilling data should provide a high resolution view of the relation of arc volcanism to back-arc spreading in time and space. In addition to the foregoing, the cores recovered from these holes can be used to track the evolution of the petrology of volcanism in the triplet through a sundering and spreading event. It should be noted that this second sundering has again divided the Eocene arc fragment that underlay the Lau-Tonga arc and is once again distributing these fragments, encapsulated in a later arc structure, around the rim of the Indo-Australian plate.

## RELATION OF FOREARC VERTICAL TECTONICS TO BACK-ARC SPREADING AND OBLIQUE SUBDUCTION OF A SEAMOUNT CHAIN

In the vicinity of 'Eua Island Upper? Cretaceous Pacific crust is underthrusting a very large Tonga Ridge (10.5 km. high and 180 km. wide from trench to the western edge of the platform). This old thick oceanic crust is in direct contact with the ridge basement owing to the absence of any significant terrigenous sediment input to the trench and the relatively thin sedimentary cover on the descending plate(100m at nearby DSDP site 204). South of Tongatapu the trench makes a sharp step eastward immediately south of it's intersection with the Louisville Ridge. This morphology, coupled with the unlubricated nature of the subduction zone, suggests the possibility of subduction erosion of the forearc in response to the subduction of the Louisville chain. This possibility is strengthened by the interpretation of seismic profiles across the forearc that show downdropped platform sedimentary sections underlying the forearc terrace and by the recovery of rocks indicative of arc basement in dredge hauls from the lower trench slope.

The timing of the arrival of the seamounts at the trench has been worked out by Dupont and Herzer (in press, 1985) and can be compared to the paleodepth and sedimentary history obtained from proposed sites Tonga Terrace 1 and 2 and Tonga Slope 1 and 2 to document the effects of seamount subduction in time and space (effects on trench slope vs. forearc terrace, subduction complete in the north vs. just beginning in the south).

A well controlled paleodepth history for the Tonga Ridge forearc will help to explore the possibility of a genetic relationship between subduction of the Louisville Ridge and opening of Lau Basin. The sundering of the arc prior to the initiation of spreading may have been preceeded by substantial heating and "inflation" of the arc.(Scholl and Vallier,in press,1985) If the effect of the heating event is recorded prior to ridge collison then basin opening is unrelated to the subduction of the Louisville Ridge. However, if collision and thermal uplift of the arc are coeval, then a genetic link may exist between ridge subduction and back arc spreading.

## AREA CONSIDERATIONS

In addition to the tectonic processes addressed by these holes this proposed program will provide new data to assist and constrain reconstructions of the tectonic history of the southwest Pacific, an area woefully lacking in unambiguous controls. Kowledge about the origin and history of the Eocene arc fragments of Tonga and Fiji is essential for the reconstruction of the western Indo-Australian plate region, and has important implications for the history of it's surrounding area. As part of a broader investigation involving the Solomons and Vanuatu (see separate proposals) Tonga - Lau drilling offers the opportunity to develop a unified Cenozoic plate tectonic evolution for the Southwest Pacific, and a greater understanding of the evolution of oceanic island arcs in general.

## SPECIFIC SITE OBJECTIVES

SITE LAU-1 see figures 2,3,4

The geologic section at this Lau Ridge site is expected to be as follows:

1) Thin Upper Pliocene to Holocene hemipelagic section
2) Thick Lower Miocene? to Upper Pliocene? volcaniclastic deposits derived from the Lau Arc
3) Thick Upper Eocene to Upper Oligocene sedimentary sequence possibly containing limestone and coarse detritus from older Eocene arc basement
4) Eocene arc basement, flows, dikes, intrusions, and epiclastic arc debris

Interval 2 is of interest as it will provide an age range for Lau Ridge volcanism and a profile of volcanic petrology of the arc via tephrocronology after the opening of South Fiji Basin and prior to Lau Basin opening. Interval 3 records the period of arc breakup and transport by South Fiji Basin spreading. The time of arc fragmentation is of special interest here including identifying a breakup unconformity. Interval 4 is important to determine the location and death age of the ancient Melanesian Eocene arc.

LAU-2 see figures 2,5,6,7

The geologic section at this Lau Basin hole is believed to record the the following information:

1) Upper Pliocene? to Holocene hemipelagic sediment with ash beds from the Tofua Arc
2) Lower Pliocene? to Upper Pliocene hemipelagic deposits with fine volcaniclastic beds from the volcanically waning Lau Arc
3) Early Lau Basin back arc crust of unknown age (Early Pliocene?)

Interval 1 will establish the onset of volcanism on the still active Tofua Arc and could demonstrate the evolution of petrology on the arc. Interval 2 provides an independent age determination of cessation of volcanism on the nearby Lau Arc and the oldest sediments provide control on the minimum date for inception of Lau Basin spreading. Interval 3 could provide a basement age dating the opening of Lau Basin.

TONGA TERRACE 1 AND 2 see figures 5,8,9,11,and 12

A speculative geologic section is summarized below

1)Lower Miocene? to Holocene volcaniclastic/hemipelagic section with possible hiatus in the Lower Pliocene
2)Oligocene hiatus
3)Middle and Upper Eocene limestone or coeval shallow water clastics overlying Eocene? arc basement

Interval 1 should show effect of Late Cenozoic passage of Louisville Ridge (terrace-1) and coeval or older inflation of Lau-Tonga Ridge prior to breakup and spreading in Lau Basin (terrace 1 and 2). A synchronous hiatus (or shallowing) at the two sites would favor regional arc inflation, unrelated to ridge subduction.An asynchronous hiatus (or shallowing) would favor effects of seamount subduction. Interval 2 should record Melanesian Arc breakup and it's relation to initiation of South Fiji Basin spreading. Interval 3 should define age and paleomagnetic position of Eocene arc and information concerning it's petrologic evolution and initial tectonic setting.

TONGA TRENCH SLOPE 1 AND 2 see figures 5,8,10,11,and 13

Section here largely unknown

1)Thin terrigenous and hemipelagic unit (Eocene? and younger)
2)Basement (Eocene arc? or other)

Interval 1 should record the history of the landward wall of the trench including the erosional or accretionary effects of the Late Cenozoic passage of the Louisville Ridge. Interval 2 should record more evidence for possible tectonic erosion of the forearc area by unlubricated subduction. If erosion and it's timing can be documented a comparison between sites 1 and 2 would indicate cause (pre or post Louisville subduction ). If basement is arc rocks of Eocene age, then information bearing on the evolution of the ancient Melanesian arc will be gathered . It is possible that accreted rocks form the landward wall of the trench.

## EXISTING DATABASE AND FUTURE DATA COLLECTION PLANS

The current Tripartate database of reflection profiles (multichannel and single channel) is shown in figure 1. In addition to these lines, single channel data exist from EVA and AUSTRADEC cruises, and some reconnissance multichannel data is available from Shell and Mobil Oil Cos. The Mobil data are currently being reprocessed. Dredge samples have been collected from the Tonga forearc by the USGS, SIO, and others. Many other sources of geophysical data exist, but are not considered directly related to the problems under discussion in this proposal. A continuing work effort is planned in the area by a number of different nations and investigators, among them the French (Seabeam and metallogenisis studies in Lau Basin, Seabeam at Tonga Trench-Louisville Ridge intersection), the Federal Republic of Germany (recently completed Seabeam and dredge studies in Lau Basin). and the Japanese (Natsushima cruise to northern Lau Basin. The Russians remain active in the area (recent Kallisto cruises to the southern Tonga forearc and north Tonga Trench). Tripartite scientists are in the preliminary phases of their analysis of data from the Lau-Tonga area collected in 1984. The results of Tripartite studies, and related reigonal information, undertaken in 1982 are presently in press. Further refinements in this proposal can be expected as new data are fully processed and become available from all sources.

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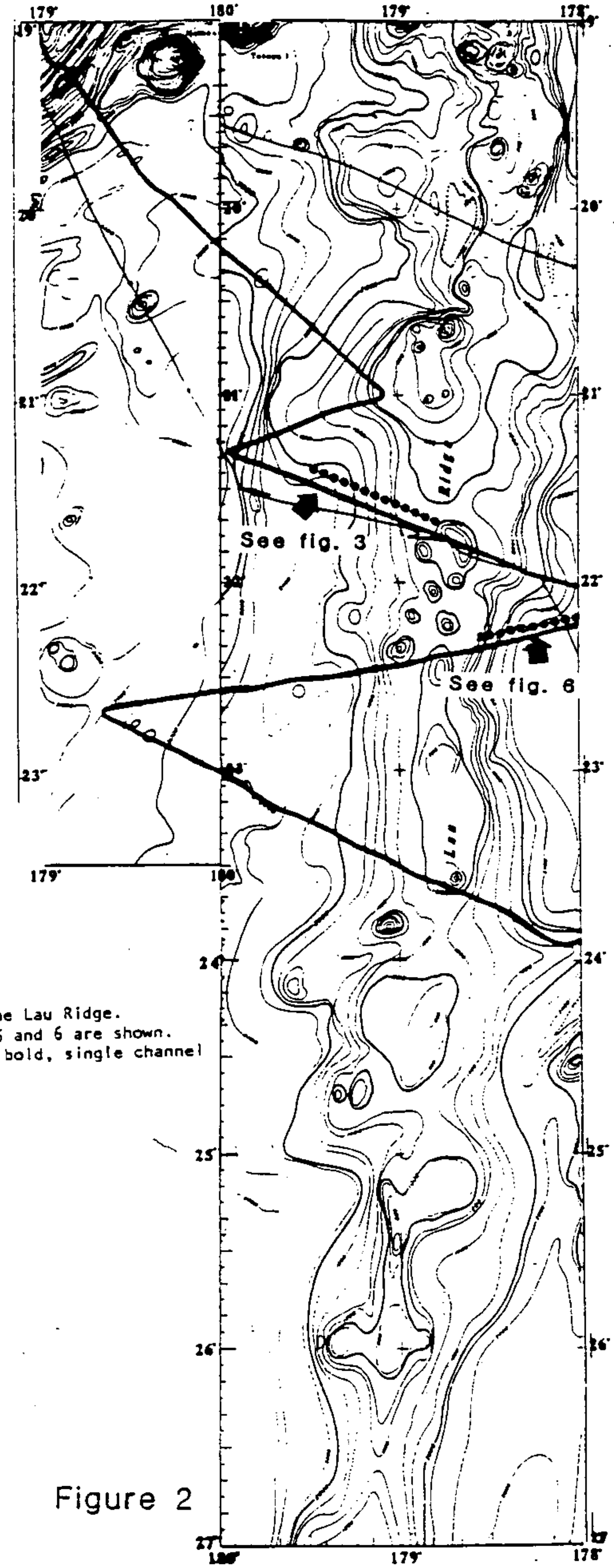



Trackline chart for the Lau Ridge. Location of profiles 5 and 6 are shown. Multichannel lines in bold, single channel lines as thin lines.

Figure 2

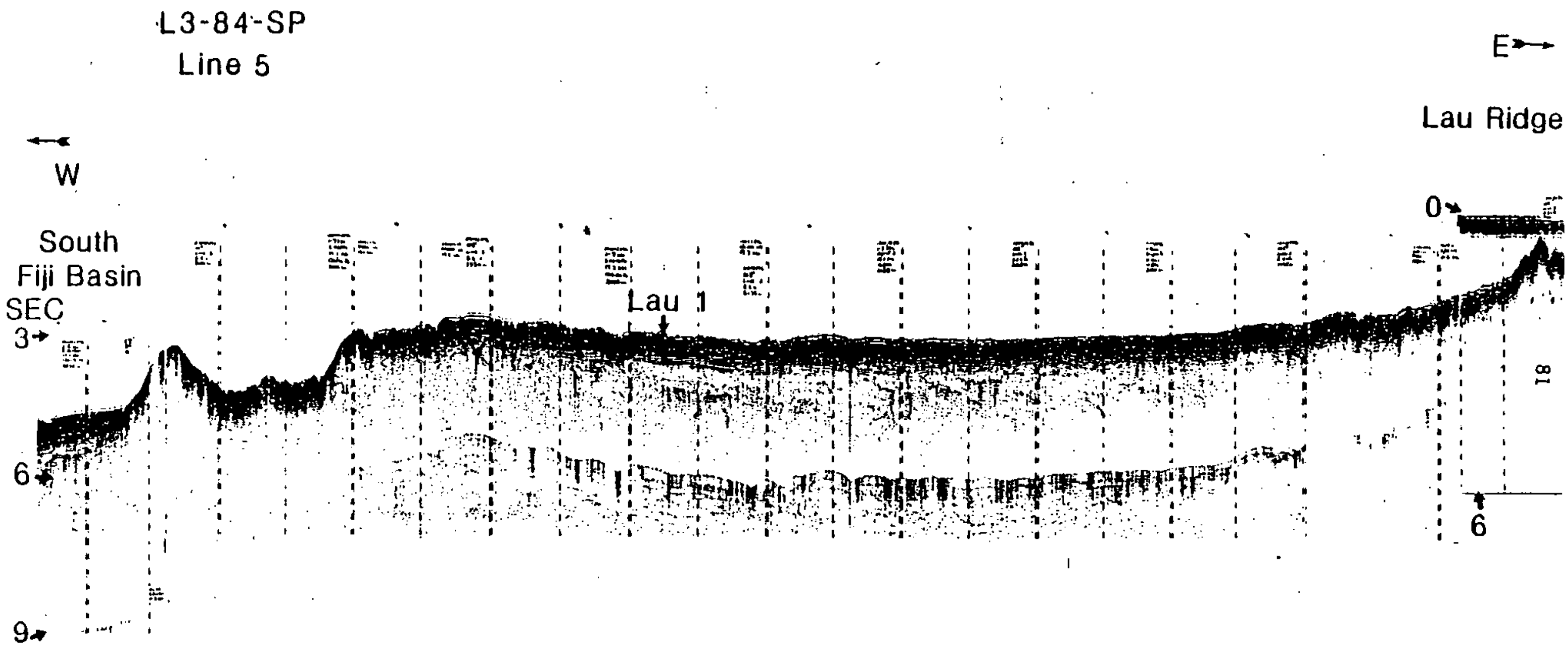
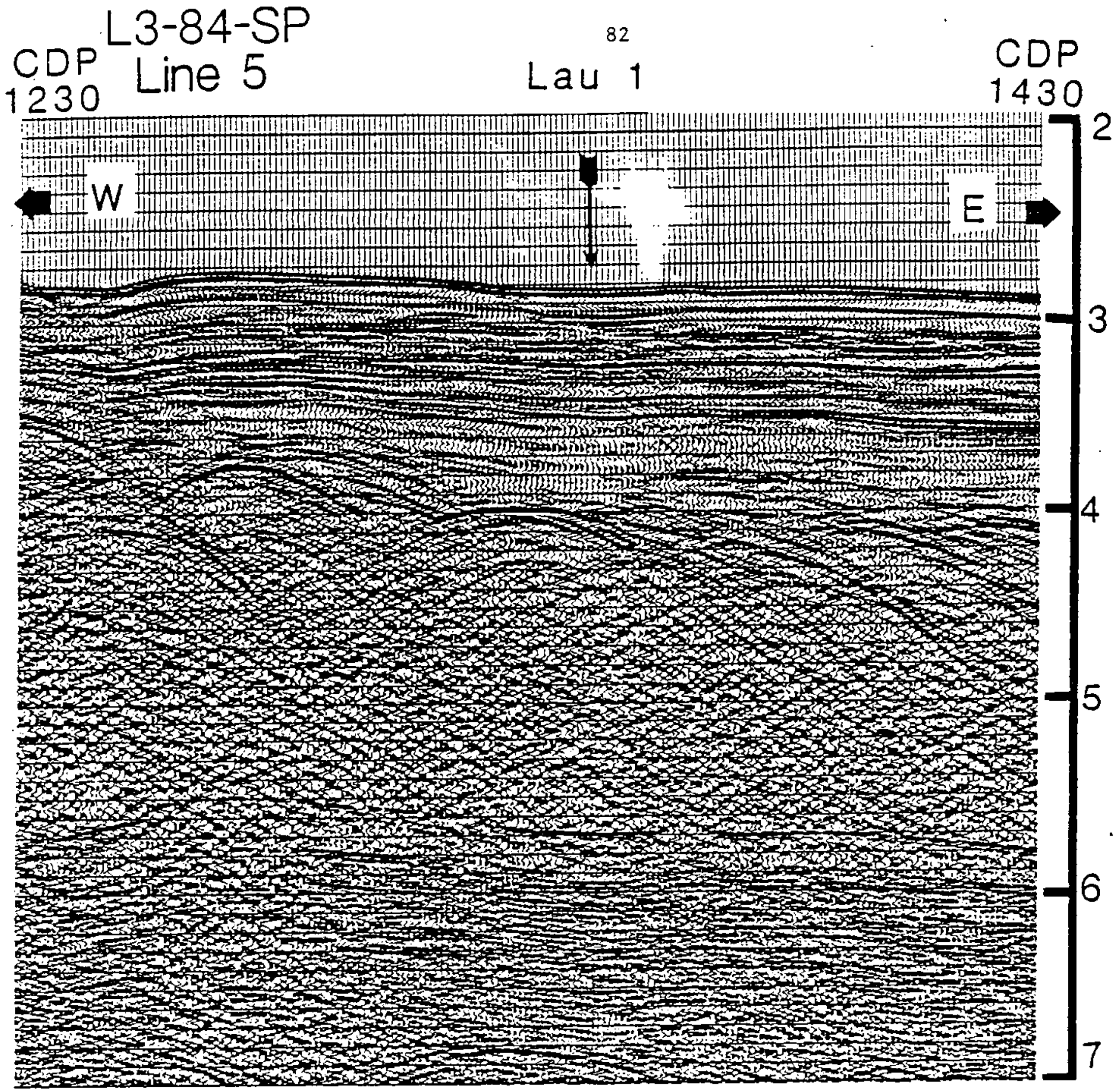


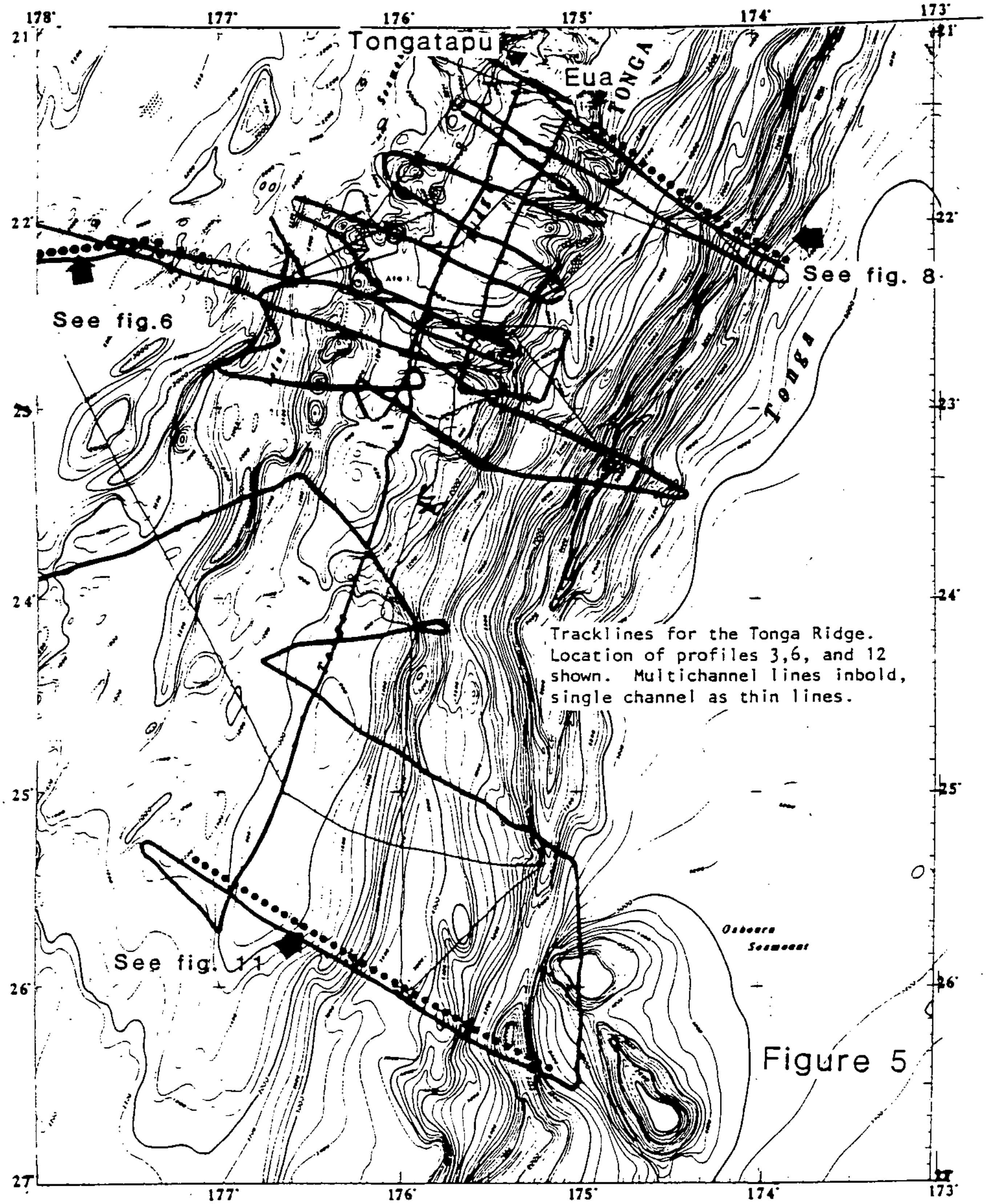

Figure 3

Single channel monitor record of multichannel line 5. High exaggeration, time section. Site Lau 1 is shown. For more detailed site seismic see figure 4.



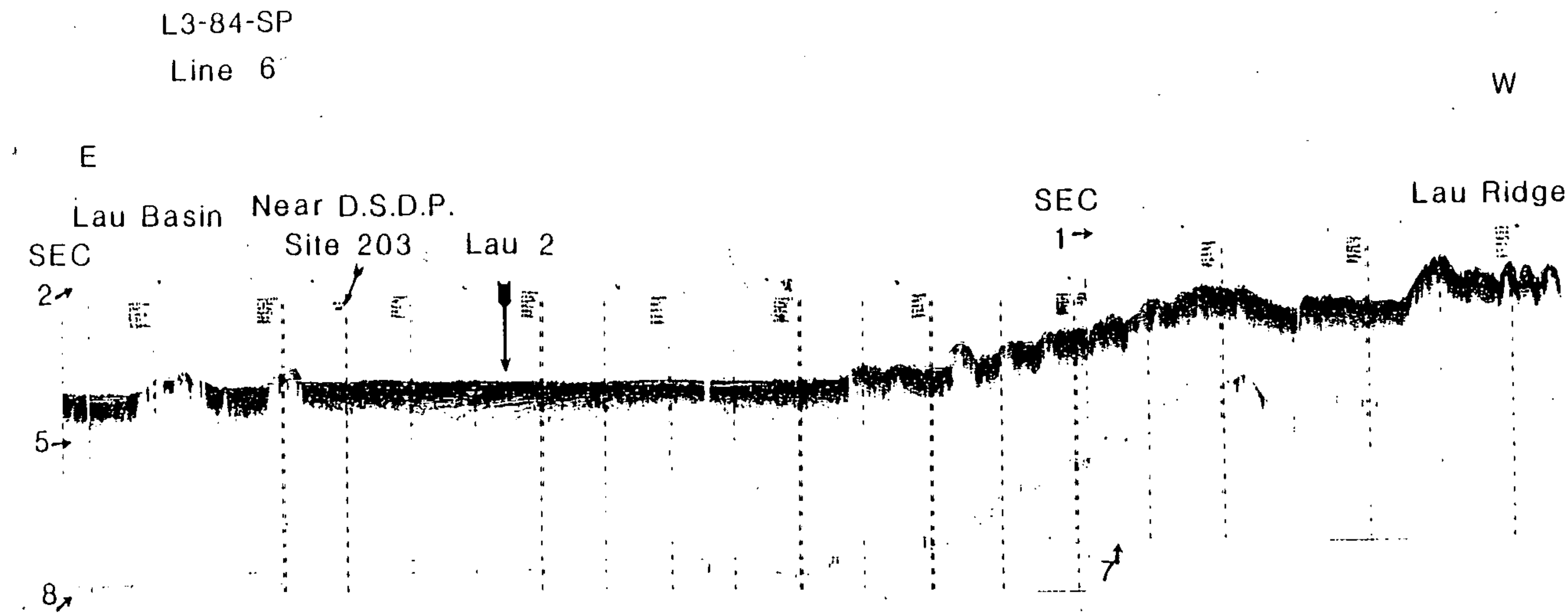

24 Fold Multichannel Profile of Site Lau 1.
Time section, unmigrated, not deconvolved.
Shot interval 50 m.
For location of profile see figures 2 and 3.
Vertical exaggeration 2.3 to 1.

Figure 4



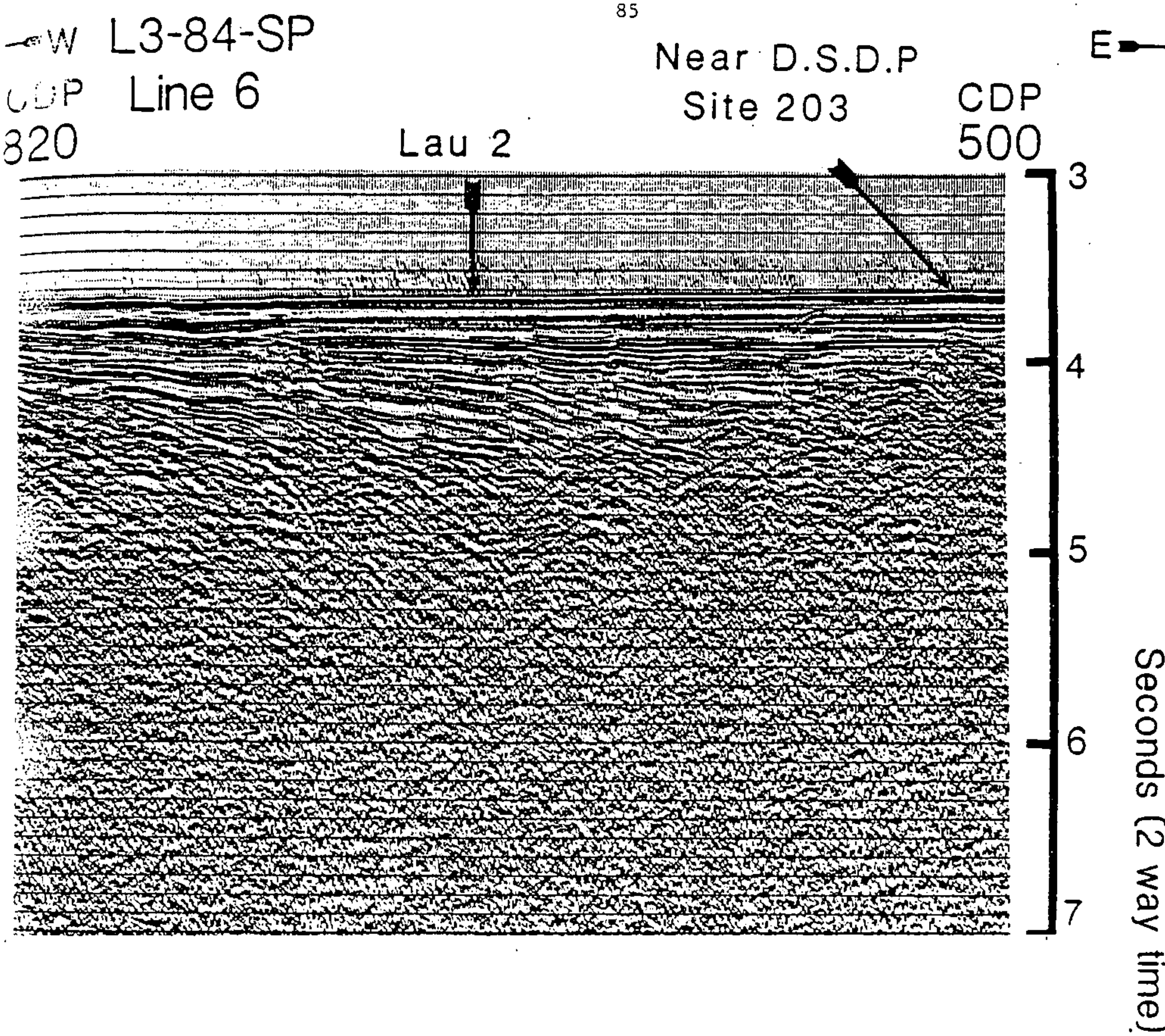
178°
177°
176°
175°
174°
173°
21
22
23
24
25
26
27
Tongatapu
Eua
TONGA
See fig. 8
See fig.6
Tonga
See fig. 11
Osbourn Seamount
Tracklines for the Tonga Ridge. Location of profiles 3,6, and 12 shown. Multichannel lines inbold, single channel as thin lines.


Figure 5



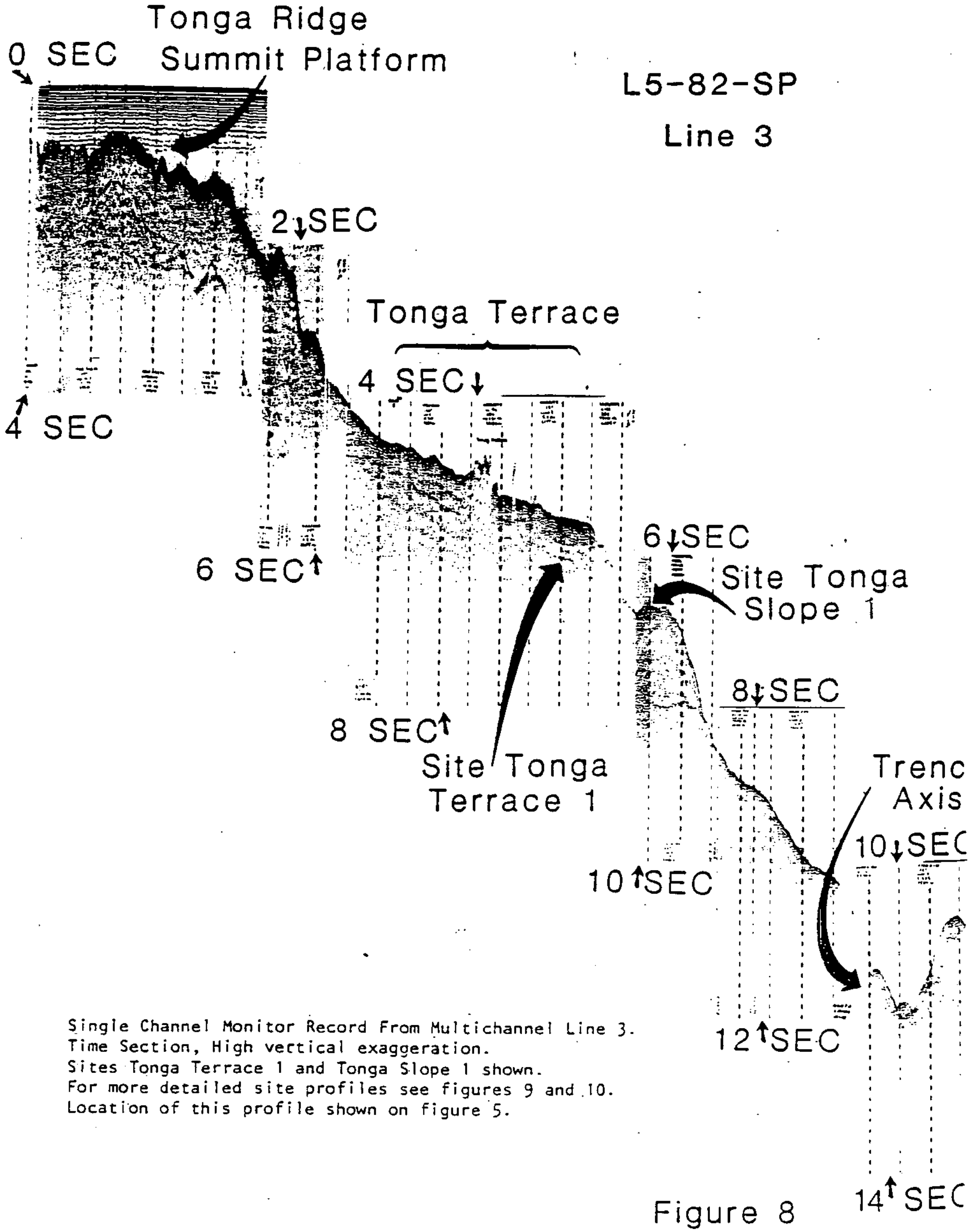
L3-84-SP
Line 6
E
W
Lau Basin
Near D.S.D.P.
Site 203
Lau 2
SEC
1→
Lau Ridge
SEC
2↗
5→
8↗
7↗
84


Figure 6



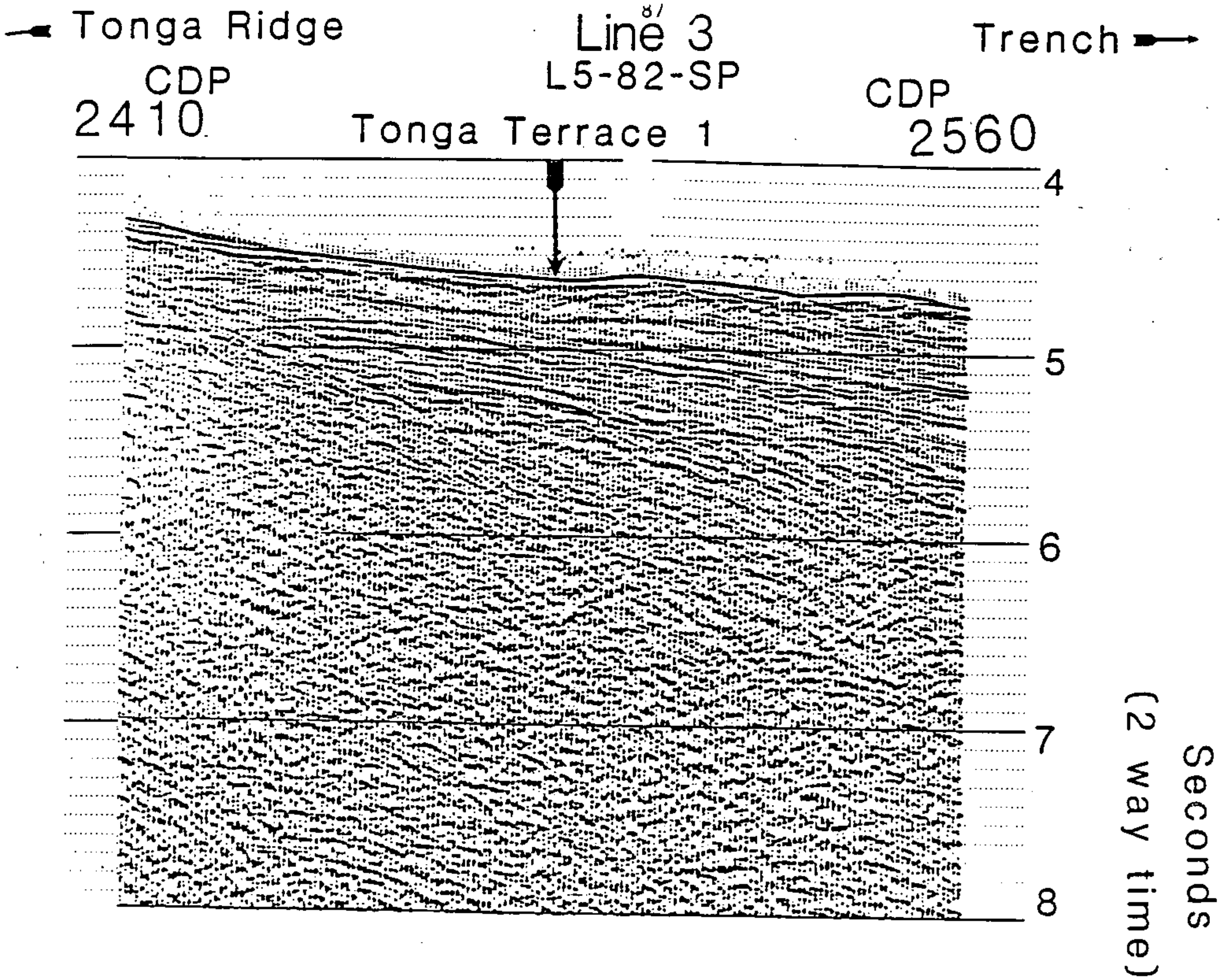

24 Fold Multichannel Profile of Lau 2 Site.
Time section, unmigrated, not deconvolved.
Shot interval 50 m.
Vertical exaggeration 2.3 to 1.
For location of profile, see figs 5 and 6.

Figure 7



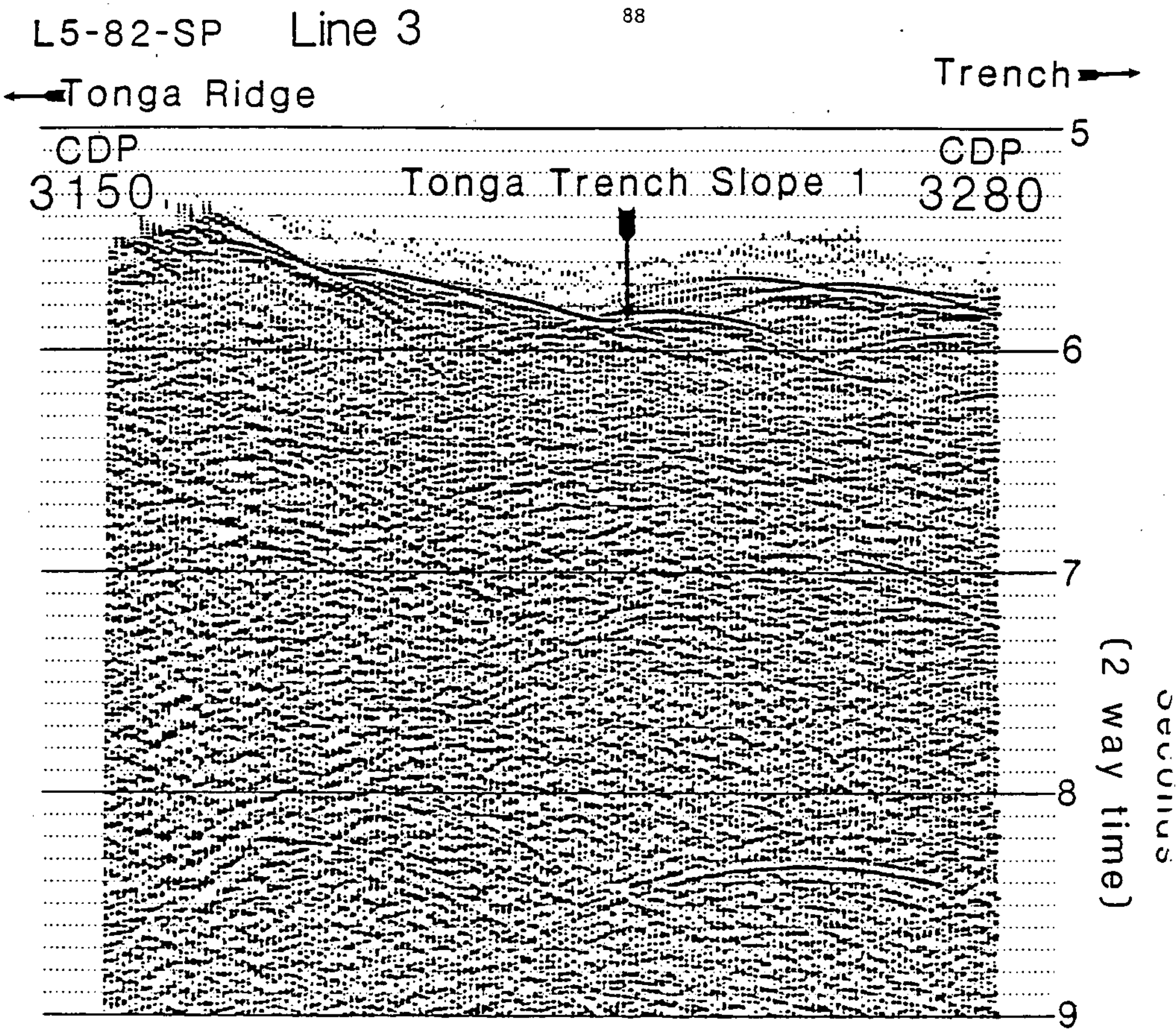

Single Channel Monitor Record From Multichannel Line 3.
Time Section, High vertical exaggeration.
Sites Tonga Terrace 1 and Tonga Slope 1 shown.
For more detailed site profiles see figures 9 and 10.
Location of this profile shown on figure 5.

Figure 8



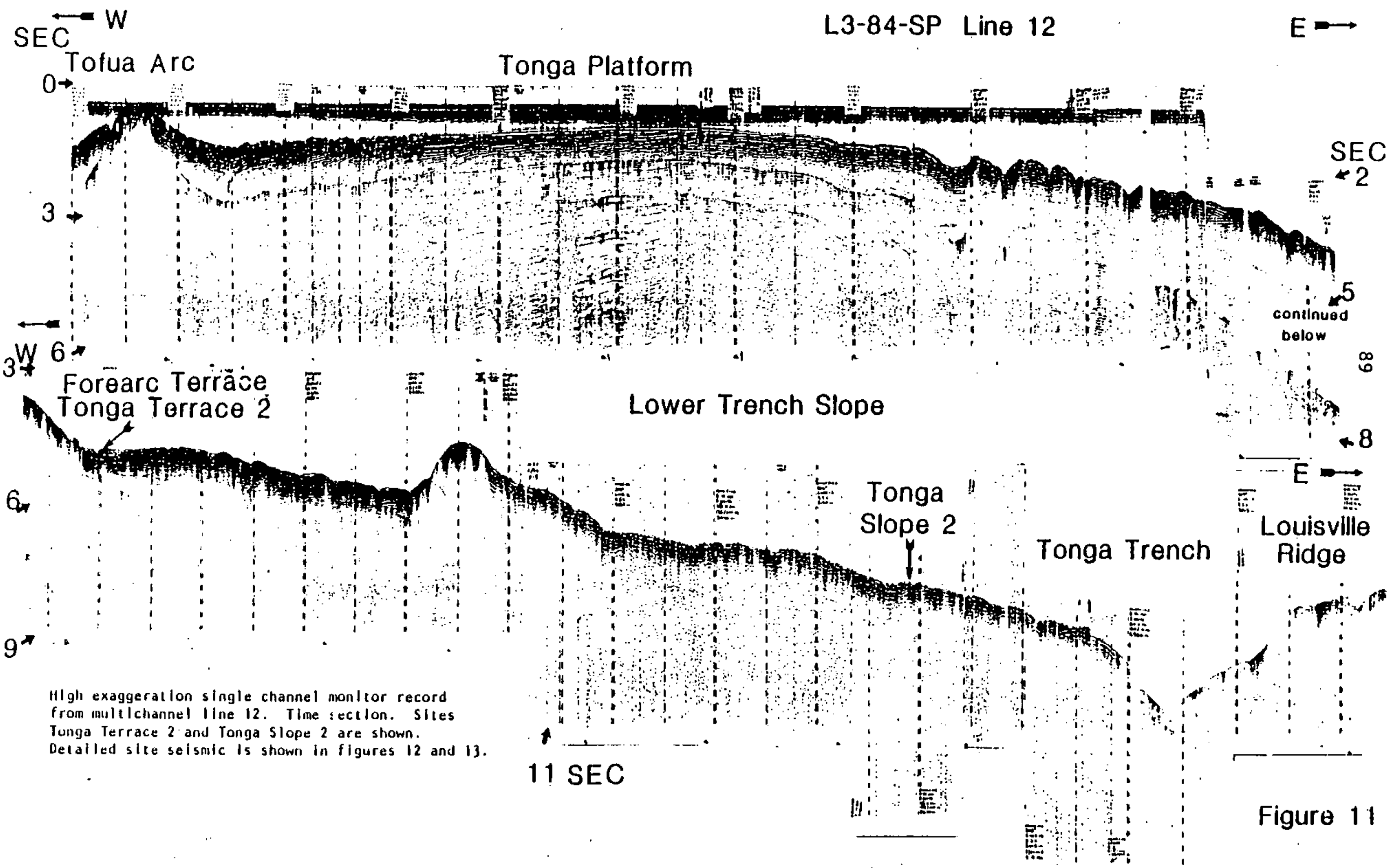

24 Fold Multichannel Profile of Site Tonga Terrace 1.
Unmigrated, not deconvolved (brute stack).
Shot interval 50 m.
Vertical exaggeration 2.5 to 1.
For location of profile see figures 5 and 8.

Figure 9



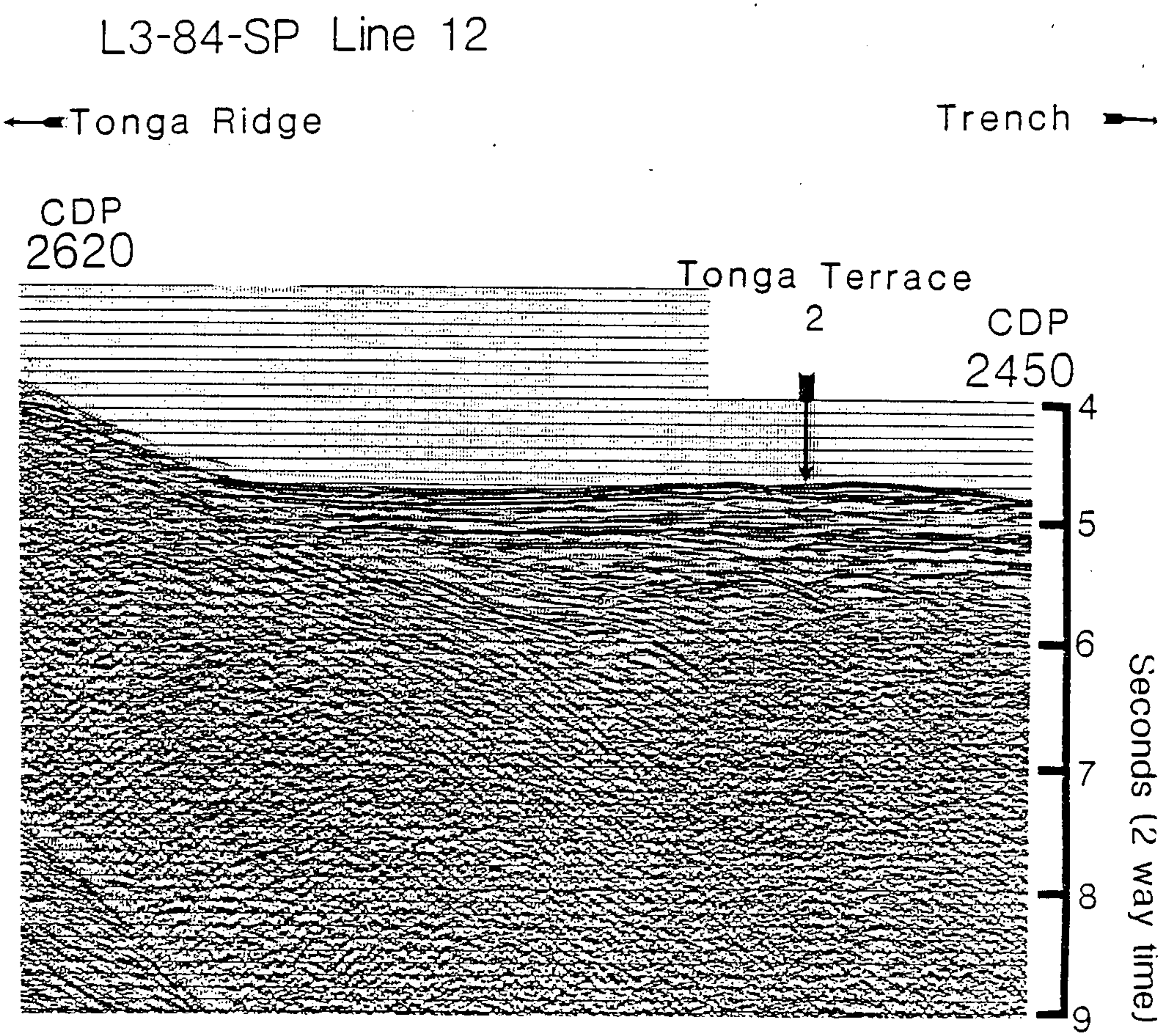

24 Fold Multichannel Profile at Site Tonga Trench Slope 1.
Time section, unmigrated, not deconvolved.
Shot interval 50 m..
For location of profile see figures 5 and 8.
Vertical Exaggeration 2.5 to 1.

Figure 10



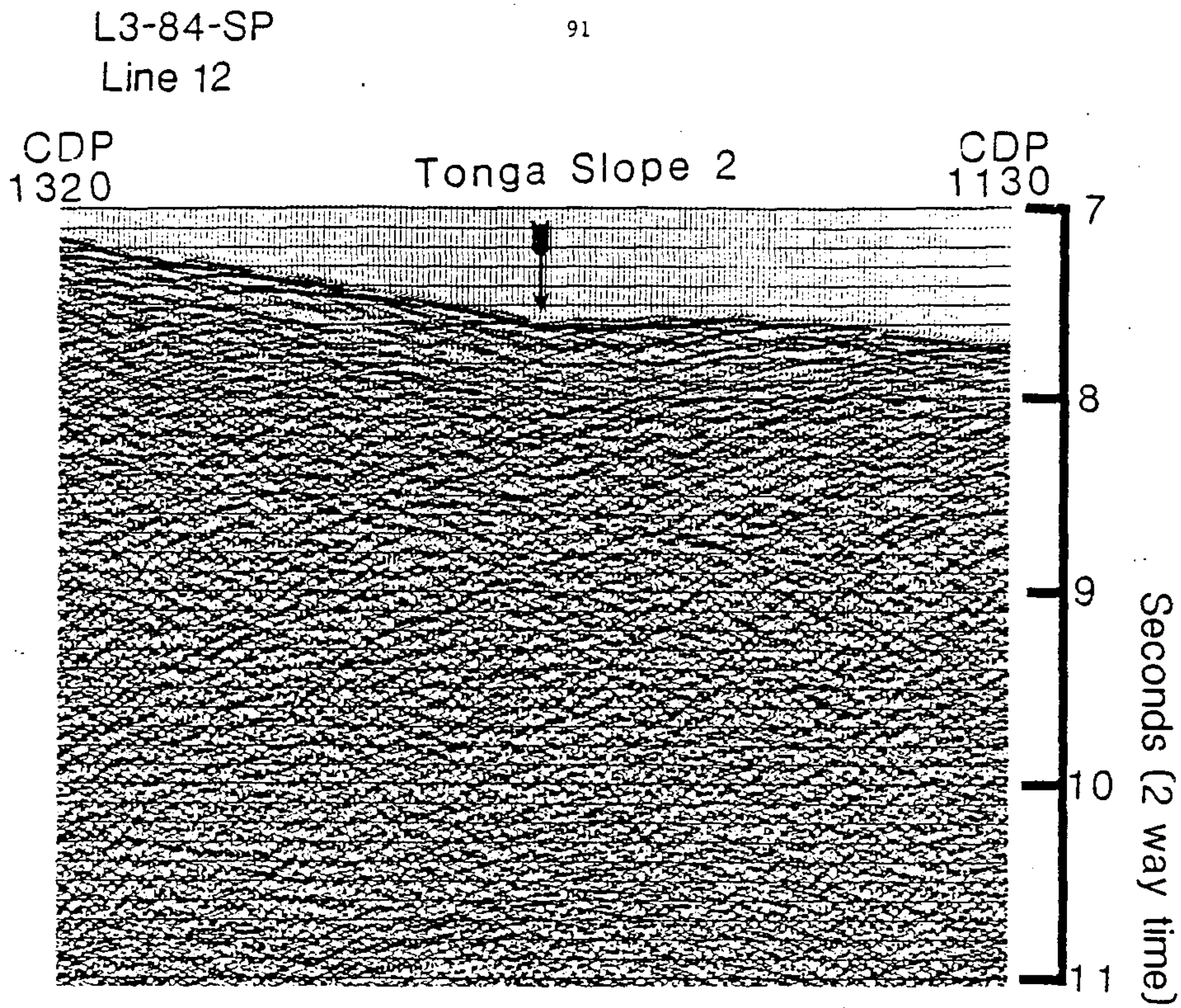

High exaggeration single channel monitor record from multichannel line 12. Time section. Sites Tonga Terrace 2 and Tonga Slope 2 are shown. Detailed site seismic is shown in figures 12 and 13.

Figure 11




24 Fold Multichannel Profile over Tonga Terrace 2.
Unmigrated, not deconvolved.
Shot interval 50 m.
Vertical exaggeration 2.5 to 1.
For location of profile see figures 5 and 11.

Figure 12




24 fold multichannel profile over site Tonga Terrace 2. Unmigrated, not deconvolved. Shot spacing 50 m, Vertical exaggeration 2.5. For location of section shown see figures 5 and 11.

Figure 13

| | |
|---|---|
| **Proposed Site:** Lau 1<br><br>**General Area:** South-Western Pacific, West Side Lau Ridge<br>**Position:** 21°36.2'S 179° 29.9'W<br>**Alternate Site:** Lau 1A<br>21° 32.46'S 179°40.74'W | **General Objective:** Determine the nature of the c underlying Lau Ridge and the geologic record st in its overlying sediment cover. Determine if ment is uplifted & modified South Fiji Basin cr or a fragment of West Melanesian arc crust rift from the west.<br>**Thematic Panel interest:** SOHP, Tectonics, Lithosph<br>**Regional Panel interest:** Westpac |

**Specific Objectives:** 1. Obtain samples of basement for radiometric dating, mineralogy, petrology, paleomagnetic investigation. Purpose is to determine the nature of the crus upon which the central region of Lau Arc has been built (West Melanesian Arc fragment vs. modi South Fiji Basin crust). 2. Obtain a complete overlying sedimentary section to determine the volcanic, petrologic, & vertical tectonic history of Lau Arc. Objective 1 & 2 together will cl the position of the rift that split the Tonga-Lau arc to form Lau Basin (did the Tonga-Lau Arc in the forearc, backarc, or along the volcanic axis?).

**Background Information:**

**Regional Data:**

Seismic profiles: Both multichannel and single channel records are available. See Fig 2,3,4

Other data: Some proprietary multichannel reconnisance data may be available, gravity, magne refraction, and bathymetric data available along tracklines shown in Fig 2.

**Site Survey Data - Conducted by:**

Date:

Main results:

**Operational Considerations**

Water Depth: (m) 2100 (alt site 2025) Sed. Thickness: (m) 1300 (600) Total penetration: (m) ≈ 1400 (700)

HPC X Double HPC X Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Oligocene - recent

Weather conditions/window: Volcaniclastic & Hemipelagic sedimentary sect overlying Eocene-Oligocene metamorphosed arc volcanic & sed. rocks.

Territorial jurisdiction: Within 200 mm proposed EEZ of Fiji-closest land is southermost Lau Island currently within international waters.

Other:

**Special requirements** (Staffing, instrumentation, etc.)

None

Proponent: Andrew J. Stevenson
345 Middlefield Road MS 999
Menlo Park, CA 94025

Date submitted to JOIDES Office:

Rev. C

Proposed Site: Western Edge of Lau Basin
Lau 2

General Objective: Obtain oldest sediment deposits in southern Lau Basin. Date inception of spreading in southern Lau Basin.

General Area: Southwest Pacific, East Side of Lau Basin
Position: 22° 10.6'S 177° 40.9'W
Alternate Site:

Thematic Panel interest: Tectonics, SOHP? Lithosphere
Regional Panel interest: Westpac.

Specific Objectives: Angular unconformity in sedimentary section along western side of Lau Basin (see Figure 7). This may represent the initial phase of Lau Basin opening & debris shed from the eastern flank of Lau Ridge. Dating this unconformity could constrain the time of opening of southern Lau Basin which may have proceeded differentially with time. The tephrocronology of the section above and below the unconformity will record the petrologic evolution of volcanism on the waning Lau Arc and emerging Tofua Arc. Basement age and chemistry will define the age and nature of early back arc spreading in Lau Basin.

Background Information:
Regional Data:
Seismic profiles: See Figure 2.5 for trackline coverage, some industry multichannel reconnisance data may be available to the north of the proposed site.
Other data: Gravity, magnetics, bathymetery, refraction, and 3.5 KH2 Data available on tracklines. Seabeam coverage expected in 1986.
Site Survey Data - Conducted by:
Date:
Main results:

Operational Considerations

Water Depth: (m) 2700 Sed. Thickness: (m) 680 Total penetration: (m) 780 ?

HPC X Double HPC X Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Ash & fine grained volcaniclastics & hemiplagics overlying basalt

Weather conditions/window:

Territorial jurisdiction: Within Tonga territorial waters.

Other:

Special requirements (Staffing, instrumentation, etc.)

None.

Proponent: Andrew J. Stevenson
345 Middlefield Road MS999
Menlo Park, CA 94025

Date submitted to JOIDES Office:

Proposed Site: Tonga Terrace 1

General Area: Southwest Pacific, Tonga Forearc
Position: 21° 45.73'S 174° 36.07'W
Alternate Site: 21° 48.55'S 174° 32.02'W

General Objective: History of the vertical tectonics of the Tonga Ridge forearc terrace & adjacent summit platform. Effect of "oblic subduction of a seamount chain along a south migrating point. Basement sample to determir character & extent of preOligocene basement exposed on 'Eua Island
Thematic Panel interest: Tectonics, SOHP, Lithosph
Regional Panel interest: Westpac

Specific Objectives: Hole is sited to drill a forearc terrace sedimentary section that may inc a foundered sector of the 2-4 km. thick summit platform section. Objective 1 is to determine actual vertical tectonic history of the terrace and that of the adjacent summit platform. Obj tive 2 is to obtain a basement section for comparison with the pre-Oligocene section on 'Eua Island to determine the aerial extent of that pre-arc basement (West Melanesian fragment). Ob tive 3 is to obtain information on the paleodepth changed of the ridge's summit region and fc arc terrace to evaluate the effect of subduction of Louisville Ridge under this site approxim 3-4 Ma.

Background Information:
Regional Data:
Seismic profiles: See Fig (5), also some oil company data available to the north.

Other data: Bathymetery, magnetics, gravity, & refraction data along multichannel lines, some dredged rocks from a similar geomorphic position to the South. Possible seabeam in 1

Site Survey Data - Conducted by:
Date:
Main results:

Operational Considerations

Water Depth: (m) 3450 Sed. Thickness: (m) 1100m Total penetration: (m) 1300 ?

HPC X Double HPC X Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Limestones (Platform) and medium-fine grained volcaniclas overlying arc volcanic flows/intrusions

Weather conditions/window:

Territorial jurisdiction: Within Tonga territorial waters.

Other:

Special requirements (Staffing, instrumentation, etc.)

None

Proponent: Richard Herzer
NZ Geological Survey
D.S.I.R.
P.O. Box 30-368
Lower Hutt, New Zealand

Date submitted to JOIDES Office:

Rev.

Proposed Site: Tonga lower trench slope 1

General Objective: Sample basement underlying the lower slope to determine the nature & history of its basement rocks and evaluate the effects of subduction erosion & the passage of the Louisvill Ridge past this area. Compare vertical tectonic history with site Tonga Terrace 1.

General Area: Southwest Pacific, Tonga Forearc
Position: 21° 59.2'S 174° 18.6'W
Alternate Site:

Thematic Panel interest: Tectonics,SOHP,Lithospher
Regional Panel interest: Westpac

Specific Objectives: Rocks dredged from the Tonga lower trench slope consist of loose rubble of arc affinity rocks, but outcrops of basement rocks cannot be established. If the recovered rubble is from nearby outcrops, tectonic erosion of the forearc area is implied. A drill hole is essential to confirm the nature of the basement rock types of the lower slope. This hole wil also help extend the search for the extent of the West Melanesian Arc terrane. In one dredge to the south of this site shallow water carbonates and other pelagic deposits of Late Cretaceous age, presumed to have been accreted to the dorearc from a subducted seamount, were recovered. Similar rocks could be encountered here.

Background Information:
Regional Data:
Seismic profiles: See Figure (5) for multichannel and single channel coverage. Some oil company multichannel coverage to the north may be available.
Other data: Gravity, magnetics, refraction, and bathemetric and high resolution data along tracklines, some dredge data, seabeam data possible in 1986.
Site Survey Data - Conducted by:
Date:
Main results:

Operational Considerations

Water Depth: (m) 4350 m    Sed. Thickness: (m) 160 m    Total penetration: (m) 300 ?

HPC X    Double HPC ____    Rotary Drill X    Single Bit X    Reentry ____

Nature of sediments/rock anticipated: Thin recent hemiplagics overlying plutonic and volcanic arc 16 igneous rocks

Weather conditions/window:

Territorial jurisdiction: within Tonga territorial waters

Other:

Special requirements (Staffing, instrumentation, etc.)

None

Proponent: Richard Herzer
as on Tonga Terrace 1

Date submitted to JOIDES Office:

Rev. 02

Proposed Site: Tonga Terrace 2

General Objective: Companion hole to Tonga Terrace 1 (see terrace 1)

General Area: Southwest Pacific, Tonga Forearc
Position: 25° 54.4'S, 176° 12.9'W
Alternate Site:

Thematic Panel interest: Tectonics, SOHP, Lithosphe
Regional Panel interest: Westpac

Specific Objectives: Obtain section for correlation with Tonga terrace 1. Vertical respons to seamount subduction, which occurred at site 1 3.5 Ma. should be occurring at this site r Other objectives are the same as objectives 1 and 2 on Tonga terrace 1.

Background Information:
Regional Data:
Seismic profiles: See Fig. 2,5 for multichannel and single channel seismic lines, some indu data in the area (multichannel) may be available.
Other data: Gravity, magnetics, refraction, 3.5 KHz high resolution seismic, and bathymet on tracklines seabeam coverage expected in 1986. Some nearby dredges
Site Survey Data - Conducted by:
Date:
Main results:

Operational Considerations

Water Depth: (m) 3524 Sed. Thickness: (m) 1200 Total penetration: (m) 1300 ?

HPC X Double HPC X Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Volcanisclastics, platform and reefal limestones, hemi-plagics, overlying Arc volcanic flows intrusions.
Weather conditions/window:

Territorial jurisdiction: within Tongan territorial waters

Other:

Special requirements (Staffing, instrumentation, etc.)

None

Proponent: DAVID W. SCHOLL
345 Middlefield Road
Mail Stop 99
Menlo Park, CA 94025

Date submitted to JOIDES Office:

Rev

Proposed Site: Tonga trench slope 2

General Objective: Companion hole to Tonga trench slope 1

General Area: Southwest Pacific, Tonga Forearc
Position: 26° 14.6'S 175° 38.3'W
Alternate Site:

Thematic Panel interest: Tectonics, SOHP, Lithosphere
Regional Panel interest: Westpac

Specific Objectives: Same as slope 1 except offset to the south to evaluate the effect of subduction of the Louisville Ridge on the vertical tectonics of the forearc and the abrupt trench setback north of the ridge-trench intersection which implies removal or compression of the lower trench slope during subduction of the ridge. The two holes together examine the interactions of the forearc with large edifices during and after subduction (seamount subducted about 3 Ma. at site 1). The second hole on the lower trench slope further investigates the extent of the 'Eua basement terrane and allows for a test of either the presence or absence of pelagic debris accreted to the framework of the lower slope.

Background Information:

Regional Data:

Seismic profiles: See Fig. 2,5 for single channel and multichannel seismic coverage, some industry reconnisance multichannel data may also be available.

Other data: Gravity, magnetics, refraction, 3.5 KH2 seismic, and bathymetery along trackline, some nearby dredge data, seabeam data expected in 1986.

Site Survey Data - Conducted by:

Date:

Main results:

Operational Considerations

Water Depth: (m) 5650 Sed. Thickness: (m) 70 ? Total penetration: (m) 270 ?

HPC X Double HPC ____ Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Distal volcaniclastics and hemiplagics overlying Arc volcanic flows, dikes, and intrusions.

Weather conditions/window:

Territorial jurisdiction: within Togan territorial waters

Other:

Special requirements (Staffing, instrumentation, etc.)

None

Proponent: David W. Scholl
345 Middlefield Road MS-99
Menlo Park, CA 94025

Date submitted to JOIDES Office:

Rev. 02!

# Tonga Trench - Lau Basin Site L-5

Location: 20°00'S 173°30'W
broad forearc high near trench-slope break

Technical objective: Basement penetration and recovery; recovery of overlying sedimentary section; 50-100 m of basement penetration

Scientific objectives:

1. determine the composition and minimum age of the forearc basement
2. examine the uplift/subsidence history of the outer forearc recorded in the sediments
3. examine the petrologic and chemical variability in the forearc basement and compare to units on the active and remnant arcs

Subduction erosion has been postulated as an important process in both the Mariana and Japan Trenches. Two key pieces of evidence for this are the occurrence of arc volcanics in the forearc basement, as old or older than units on the active and remnant arcs, and the recovery of sedimentary sections whose paleodepth curves show extensive subsidence of the outer forearc. Evaluating the importance of subduction erosion in a particualr arc-trench system requires 1. identification of the petrologic character of the forearc basement, 2. examining the subsidence history of the forearc recorded in the sediments overlying that basement, and 3. determining a minimum age for the basement. All of these objectives can be met only by drilling. Dredging along the landward slopes of the trench can provide some information on the composition of the outer forearc basement. While there can be a problem in determing if dredged samples are representative of the local exposures, many more sites can be sampled by dredging than drilling, and the dredge may recover some units missed or avoided in drilling (for example serpentinite/gabbro exposures in the outer Mariana forearc). A complete study of a particular forearc area is best completed by a combined program of drilling, dredging and geophysical studies, as was the case in the 18°N transect of the Marianas. Drilling however is essential to provide in-situ samples of the forearc basement and to provide some age and tectonic information on that basement.

It is not at all clear how important a process subduction erosion is in intraoceanic subduction zones. Other intraoceanic subduction zones need to be studied in some detail if we are to understand how these regions develop. If it proves that erosion has occurred in many of these areas we may need to rethink many of our models of subduction processes. The forearc of the Tonga Trench is a logical place to search for evidence of subduction erosion. It is in many ways similar to the Mariana system - grossly similar geometries, similar convergence rates and similar histories of convergence and volcanism. A great deal can be added to our understanding of this margin by drilling a hole into the forearc basement. The easiest place to accomplish this objective, as was the case at 458 and 459, is near the trench-slope break where the forearc basin sediments thin substantially.

The most extensively sampled area on the landward slope of the Tonga Trench (excepting the northern strike-slip portion of the trench, dredged by Soviet workers) is at 20°10'S. R.L. Fisher and C. Engel have collected 10 dredges on the nearshore slope and two on the offshore slope, and completed a detailed wide-beam survey (figure 1, 2). There has been extensive petrologic and geochemical work on these samples. SEABEAM surveys indicate that the trench axis here is part of a graben in the offshore plate (Lonsdale, pers. comm.); the plate boundary is at about 9000 m on the landward slope. Both sides of this graben yield N- and T-type ocean-ridge basalts; there is a zone of peridotite exposures at 8000-9000 m. Shoaler than 8000 m only volcanic rocks and volcanoclastic sediments were recovered. The volcanic samples are either arc-like in their composition or are of indeterminate origin. No samples with an N- or T-type ocean-ridge composition were recovered. The samples are small and few in number and it is not clear that they represent pieces of local outcrop; there is clearly however no evidence of an oceanic type basement. Bottom photographs (52-C, 20°00'S, 173°24'W, 4500 m) near the trench-slope break clearly show igneous-appearing outcrop. A single channel seismic line crossing the southern part of the areaa (from 20°20'S on the left to about 20°30'S on the right) shows relatively thin sediment cover on the upper slopes. A site on one of the broad highs along the trench-slope break here should have a high probability of reaching and recovering forearc basement; it has the added advatage of having an extensive dredge collection nearby.

This site clearly requires an extensive site survey, particularly for high-quality seismic reflection data. There is a proposal in preparation by Bloomer and Fisher for SEABEAM surveys and extensive dredge sampling of this and other portions of the landward slopes.

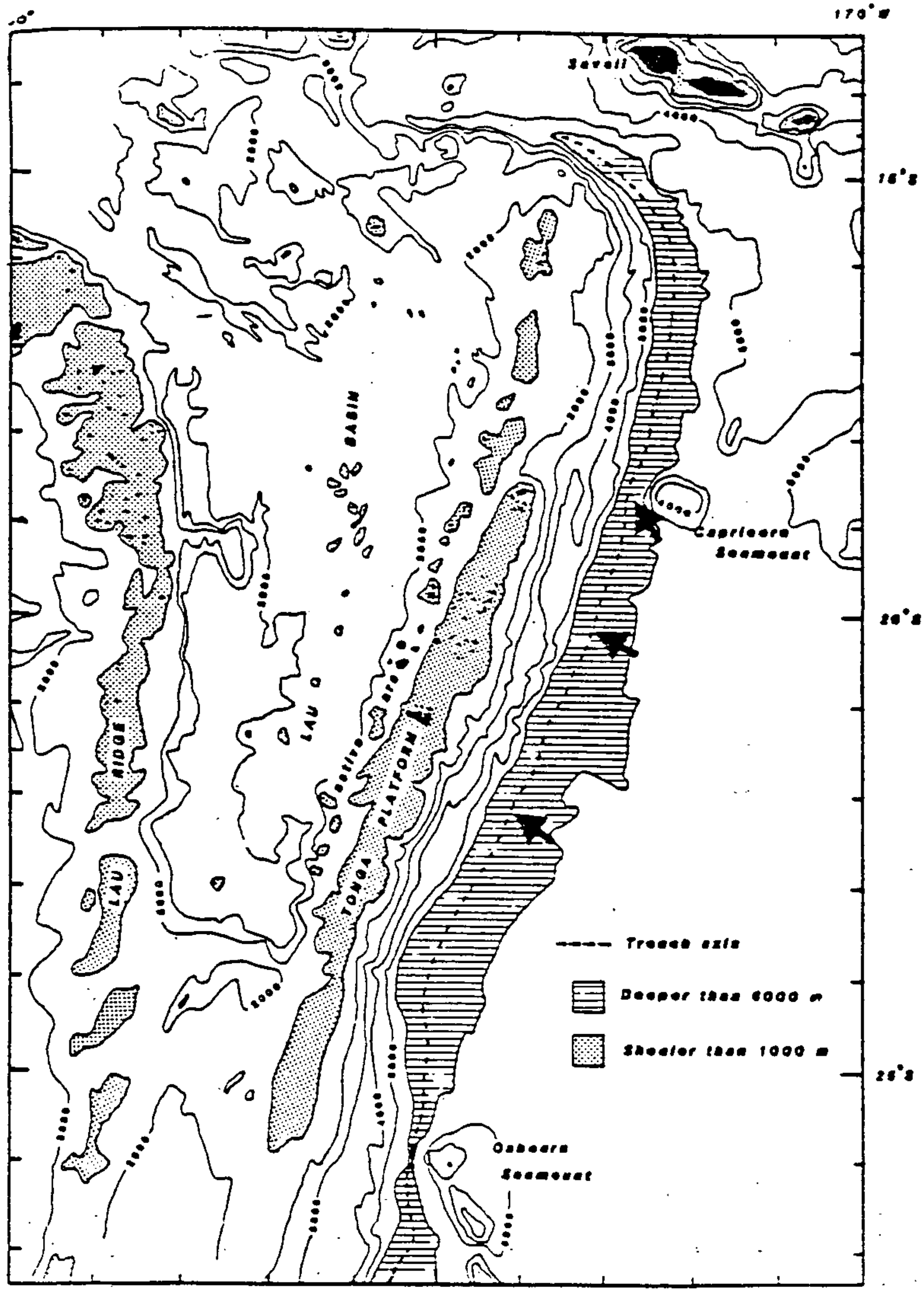
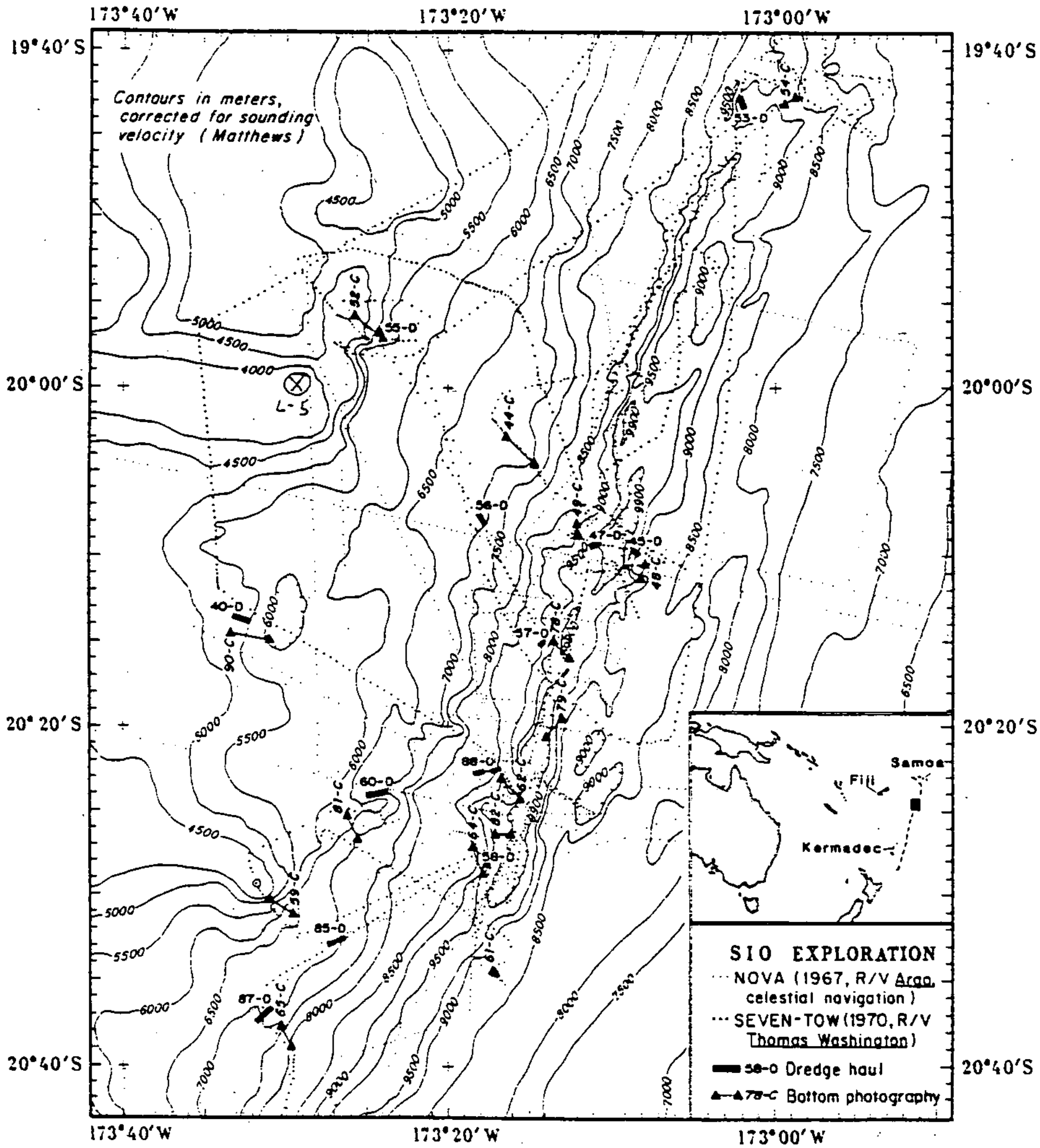
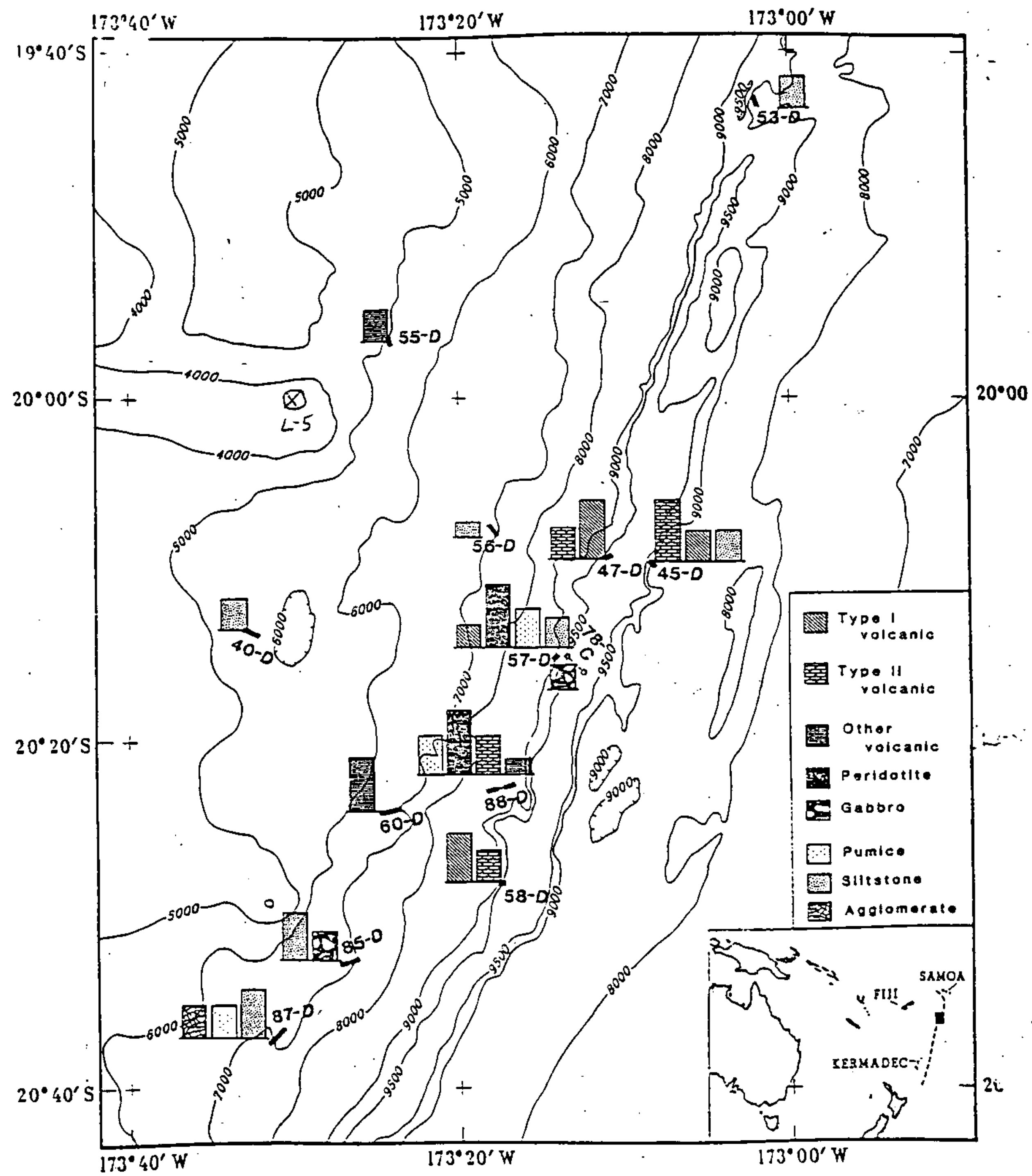



Figure 1 Sketch map of the principal bathymetric features in the Tonga region; note the change in the trench axis to the north.




Ⓧ site of L-5

Figure 2



173°40′ W
173°20′ W
173°00′ W
19°40′S
20°00′S
20°20′S
20°40′S
20°00
55-D
L-5
56-D
47-D
45-D
40-D
57-D
78-C
60-D
88-D
58-D
85-D
87-D
53-D
Type I volcanic
Type II volcanic
Other volcanic
Peridotite
Gabbro
Pumice
Siltstone
Agglomerate
SAMOA
FIJI
KERMADEC


Figure 3

103

**…sed Site:**

forearc Tonga Trench
20°00'S 173°30'W L-5

**…eral Area:** Tonga Trench

**…tion:** 20oS 173o30' W

**…ernate Site:** 19°53' S 173°22' W

**General Objective:**

identification of forearc basement
arc or accreted crust
uplift/subsidence history of trench slope break

**Thematic Panel interest:** Active margins

**Regional Panel interest:** Western Pacific

**…ific Objectives:**

Drill broad high near trench slope break. Principal objective is basement recovery to identify type of volcanic basement in outer forearc and its minimum age of emplacement. Data places important constraints on models of erosion and/or accretion in the forearc. Recovery of overlying sediment section will be important to evaluate history of vertical motions on the trench slope break.

**…kground Information:**

**…gional Data:** 13 dredges from trench slopes at this latitude, extensive chemical

**…eismic profiles:** data indicates possible arc exposures on upper slopes; one single channel analog reflection line across southern part of area

**…ther data:**

detailed seismic reflection survey needed

**…te Survey Data - Conducted by:**

…ate:

…ain results:

**…erational Considerations**

…ter Depth: (m) 4000 m  Sed. Thickness: (m) 200-400 m  Total penetration: (m) 100 m into basement

…C ____ Double HPC ____ Rotary Drill xx Single Bit ____ Reentry xx

…ture of sediments/rock anticipated: principally volcanoclastic sediments, basaltic basement

…ather conditions/window: none

…rritorial jurisdiction: Kingdom of Tonga

…her:

**…ecial requirements** (Staffing, instrumentation, etc.)

none

**…oponent:** S.H. Bloomer
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Box 6729 College Station
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Durham N.C. 27708

**Date submitted to JOIDES Office:**

July 31, 1985

## VI. MARIANA ARC SYSTEM STUDIES

The Mariana Arc system comprises the Mariana Trench; an outer arc ridge formed in part of serpentinized peridotite diapirs and uplifted blocks of oceanic crust/serpentinized mantle peridotite; the islands of Guam and Saipan, which represent arc volcanic rocks capped by limestone, and the limestone islands of Rota and Tinian which presumably have the same type of volcanic basement as Guam; there is a well developed forearc basin; the volcanic island arc comprises a number of emergent volcanoes some of which (e.g. Pagan) are still active; a backarc basin; and a remnant volcanic arc. The Mariana Trough backarc basin probably is less than 5 my old. The remnant arc, West Mariana Ridge, was active until about 7 Ma., and the active Mariana Arc is believed to be younger than the beginning of opening of the Mariana Trough.

The Mariana Arc system was the focus of DSDP studies on the drilling transect at 18 North and there are extensive data from the islands and from a number of marine expeditions. The main reason for continued work in the Marianas is because there are a number of new problems that have been identified (e.g. the serpentinite diapirs) and because there is the beginning of an understanding of the three dimensional aspects of the geology of this convergent margin system that can be greatly improved with the proposed program.

# DEEP SEA DRILLING TARGETS NEAR FOREARC SERPENTINITE DIAPIRS

Patricia Fryer

## Introduction

Recent work in the fore-arc region of the volcanic Mariana Island Arc, including extensive bottom sampling and swath-mapping using the SeaMARC II side-scan sonar and bathymetric system, has presented new interpretations of tectonics in a forearc regime. The most dramatic features studied are large (up to 2500 m high and 30 km in diameter), cone-shaped seamounts that occur on the outer fore-arc from near the trench slope break to within 100 km of the volcanic arc. These seamounts were probably caused by uplift of forearc material, and by intrusion, and in some cases eruption of diapirs of serpentinized, arc-affiliated, ultramafic rock (Fryer, et al., 1985). Elsewhere in the vicinity of these huge diapirs we have mapped fields of seafloor hummocks whee individual mounds have dimensions on the order of 100 m in diameter and elevations of less than 50 m. We speculate that these mounds may be the expression of hydrothermal vents possibly associated with diapirism.

We propose two holes at a site on one of these seamounts using the D/V RESOLUTION to investigate the detailed stratigraphy and structure of one of the large diapiric seamounts. We intend to observe detailed structures, including fracture patterns, faults, and flow structures on the seamount, to study the history of tectonic uplift associated with emplacement of the diapir by examining the sediment stratigraphy on the flanks of the seamounts, and to determine if there is associated hydrothermal activity.

## Geologic background and proposed drill sites

Most recent models of the structure and tectonic development of the inner trench walls and fore-arcs of both continental regions and oceanic island arcs invoke uplift and accretion of oceanic plate sediments and crust (e.g., Seeley, 1979) or subsidence, brought about by tectonic erosion of the overriding plate (e.g., von Huene et al., 1980), to explain observed features. In most cases it is apparent that fore-arcs can be the product of episodes of tectonic erosion and accretion brought about by variable modes of convergence and subduction (Uyeda, 1982). Furthermore, the tectonic style of a given trench system may vary between erosion and accretion along its length as well as through time.

The Mariana Island arc system (Figure 1) is a good example of a purely oceanic island arc arising where the Pacific oceanic plate is being overridden by the Philippine oceanic plate. Uyeda (1982) uses the Mariana convergent margin as the model for one type of subduction, the "Mariana-type" margin charcterized by a pervasive tensional stress regime, seafloor spreading in the back-arc region, subsidence of the inner trench wall, and tectonic erosion of the outer fore-arc wedge. The lack of an appreciable accretionary prism throughout most of the central (17-20°N) Mariana fore-arc has been noted, based on geophysical surveys (LaTraille and Hussong, 1980; Hussong and Fryer, 1981; Mrozowski et al., 1981), dredging (Bloomer and Hawkins, 1980), and deep drilling (Hussong and Uyeda, 1981), suggesting that tectonic erosion may be dominant in this portion of the arc. On the other hand, in the southern Mariana arc (south of 14°S) Karig and Rankin(1983) note evidence for uplift and construction of the fore-arc that could be attributed to accretion of oceanic plate materials onto the overriding fore-arc. Further complicating the once simple interpretation of the structure of the fore-arc is the occurrence of large (up to 2 km relief), often very conical, seamounts near the trench slope break. The morphology of these seamounts is reminiscent of volcanic seamounts which occur in the arc. However, Hussong and Fryer (1981) point out that while these seamounts resemble volcanoes, they occur too close to the trench axis to fit existing models of arc magma generation. Subsequent sampling of these outer fore-arc seamounts by ourselves and by a Scripps Institution of Oceanography cruise (Hawkins et al., 1979) yielded a variety of serpentinized and tectonized gabbros and ultramafic rocks which discounted the possibility of a volcanic origin for these seamounts. Bloomer (1983) interprets the fore-arc seamounts as the products of diapirism brought about by serpentinization of arc-derived ultramafic rocks along deep faults in the landward trench wall. The origin and emplacement of these diapirs is related to the tectonic setting of the Mariana arc and convergence zone (Fryer et al., in press, see attached preprint).

As part of a study of the entire northern Mariana arc and back-arc we completed a SeaMARC II side-scan sonar and bathmetric mapping survey (KK83-01-16-04) of the fore-arc from 19° to 20°N, an area which includes two particularly spectacular fore-arc seamounts. A sketch showing the major features related to the drilling targets and the tectonic setting of this northern Mariana fore-arc survey is presented as Figure 2 (prepared from our surveys, including Hawaii Institute of Geophysics cruises KK 810626 and KK 830116, and U.S. Navy bathymetric data).

The trench-slope break in the region occurs at a depth of approximately 4.2 km,. which is typically reached about 25 km from the trench axis. The axis of arc volcanism is about 200 km west of the trench axis. The outer 100 km of the fore-arc is disrupted by the numerous large (up to 30 km in diameter and 2 km elevation above regional depths) seamounts that we plan to further investigate, while the half of the fore-arc that is closer to the volcanic arc is essentially featureless.

The corrected SeaMARC II side-scan mosaic of the main drilling area is shown as Figure 3. The images are printed so that the higher amplitude reflections are darker gray to black. The amplitude of each reflection is a function of the energy from back-scatter from seafloor relief on the order of a few centimeters (the wave-length of the sonar signal is about 10 cm) in addition to specular reflections from large bottom surface areas that are nearly perpendicular to the angle of incidence of the sonar signal. The data are discarded for the first 200 m from each side of the ship's track and the resultant strip along the track is represented by a mottled gray stripe. Navigation is controlled by satellite, LORAN C, and the overlap of the side-scan data to provide an absolute position accuracy of better than 150 m.

The SeaMARC II bathymetry of the whole area is shown as Figure 4. The contours have been smoothed by hand from computer-generated plots that are also at a 100 m interval. The depths are calculated assuming a sound speed in water of 1500 m per second. The depths are accurate to about 50-100 m, and have been spot checked and verified against previously available high-resolution multibeam data in the area.

Pac-Man Seamount. The most striking feature in the survey region is a seamount rising 1500 m above the seafloor, with a base over 30 km in diameter (Figures 4 and 5). The seamount has an open-jawed shape, apparently caused by the collapse of its eastern flank, which has prompted us to call it Pac-Man Seamount.

The summit of Pac-Man rises to a depth of less that 2700 m (Figure 5), and is a broad dome scarred by numerous small (relief of probably only a few meters) ridges and fractures. The upper portion of the eastern slope of Pac-Man is covered by what we interpret to be a recently emplaced series of large, viscous, flows emanating from an area located at a depth of 3050 m, 4 km east-south-east of the summit. The flows cover a nearly circular region of the steeply sloping flank of the seamount and extend down over 8 km to a 4200 m depression. Based on the SeaMARC II bathymetry, the flow has an apparent relief of over 100 m above regional contour trends. Seimic reflection records do not show any coherent reflectors in this region, so can not be used to determine flow thicknesses.

A smaller flow sequence is observed at a depth of 3400 to 3500 m on the lower southeastern flank of Pac-Man. This sequence comes from what appears to be a small conical vent, extends for 3 to 5 km, and covers a tongue in the local bathymetric trends that rises 200-300 m above regional depths. This flow has not been sampled, but its morphology suggests that it may be a smaller scale analogy to the upper slope flow. The western slope of Pac-Man appears to be covered with several more flows that yield more muted reflections (outlined, but not shaded in Figure 5) than those just described. We believe the muted images occur when the flows are covered with thin sediments that partially mask the small scale relief (on the order of 10 cm) to which SeaMARC II is most responsive, so that the flows acoustically fade with age as they are dusted with pelagic sediments.

During an earlier cruise we completed 3 dredge stations on the eastern flanks of Pac-Man, one of which sampled the flow. This dredge yielded highly altered and serpentinized ultramafic and mafic plutonic rocks. Based on these samples and the morphology of the flow we interpret it to be a cold and viscous eruption of deep-seated rocks that were perhaps remobilized by tectonic activitiy and serpentinization and brought up by subsequent diapirism. Lacking stratigraphic control over the sampling, it is impossible to determine whether there is any substantial difference in composition within the flow. A series of 14 dives in the region have been scheduled for 1987. With these dives the stratigraphy of the eastern flank exposed in the graben will be studied.

Material recovered in our dredges is very similar to clasts contained in "serpentinized sediment" flows in the Wilbur Creek area of the Franciscan terrain north of San Francisco. Chris Carlson of the USGS in Menlo Park has mapped this area and interprets the serpentinized flows to be similar features to those on Pac-Man. The comparison of the subaerial flows to those which we hope to sample with drilling will be useful.

Conical Seamount. A second large seamount with a very conical shape, a summit depth of less than 3100 m, and a base about 20 km in diameter, is situated a little over 40 km northwest of Pac-Man. Flows emanating from the summit of this seamount (Figure 6) are apparently more fluid than those from Pac-Man, and have sinuous and braided courses that have greater extent down-slope. This conical seamount is also not as fractured in appearance as Pac-Man, and has no associated depressions, collapse features, or observable flank vents. The side-scan image suggests that the cone may be partially composed of concentric low-relief ridges, best observed on the southeastern flank. These ridges may relate to vertical motion of the seamount caused by uplift related to diapiric intrusion.

We do not know what kind of material comprises the flows on the flanks of the seamount. A dredge station near the summit of the conical seamount yielded only consolidated sediments, mostly vitric siltstones. Either the flows are composed of this material or they are composed of remobilized unconsolidated sediments. It is possible that uplifted related to diapiric intrusion coupled with emanations of fluids from the diapiric body could remobilize the sediments on the flanks of the seamount. As these sediments sluff off the upper slopes they may expose the more consolidated material beneath.

The morphology and limited samples from the conical seamount suggest that it is generally similar to Pac-Man, but is in an earlier stage of development. The deeper plutonic material that produces the viscous flow on Pac-Man may not have reached the surface at the conical seamount, but the latter is being actively uplifted by deep-seated diapirism.

A drill site on this volcano would help to test this possibility and would enable us to study the timing of uplift of this seamount.

Mounds. Many small sediment mounds are observed throughout the side-scan image in Figure 3. Some of the largest of these mounds are in the saddle between Pac-Man and the conical seamount, are on the order of a kilometer in lateral extent, and have relief on the order of 100 to 200 m. More typical, however, are smaller mounds that occur in numerous fields throughout the region. These fields are often located near the flanks of the seamounts.

With little direct evidence, we can only speculate on two possible causes of the fields of mounds. A likely cause of at least some of the mounds is overpressuring of underlying sediment horizons cause by local tectonic activity (the larger mounds in the saddle between Pac-Man and the conical seamount). The collapse of large areas of the fore-arc which causes depressions such as on the eastern flank of Pac-Man, and the very large depression that occupies the entire center of the survey region, would cause tilting, flow, and instability of deeper sediment layers that could easily produce mud lumps and mud volcanoes. In fact, the most obvious groupings of the larger mounds are adjacent to the southwest and northeast bounds of the large fore-arc depression. Thus, we suggest that the large mounds are mud lumps. None of the mounds, however, have the character of mud volcanoes which we have extensively mapped with SeaMARC II in eastern Indonesia.

A second, potentially more interesting, possibility is that some of the fields of smaller mounds may be caused by outflow of fluids that may be associated with the serpentinite diapirism. A drill site on the flank of the Pacman diapir would help identify the origin of some of these mounds. ALVIN dives are planned to examine the surface expression of these features in 1987.

If these fore-arc mounds are shown to have a hydrothermal origin, several very important implications arise. In contrast to rise crest hydrothermal vents, similar features on the fore-arc might be a part of a relatively stable process that would permit them to exist in the same place for many millions of years. Even if the amount of fluid flux is relatively small, and the fluids are not as hot as presently known vent areas, the longevity of diapir-related vents might make them geologically important. Under these conditions fore-arc hydrothermal vents might, for instance, be important as a mechanism for formation of ore bodies. They would also represent a significant component of the worldwide flux of elements related to plate tectonic activity.

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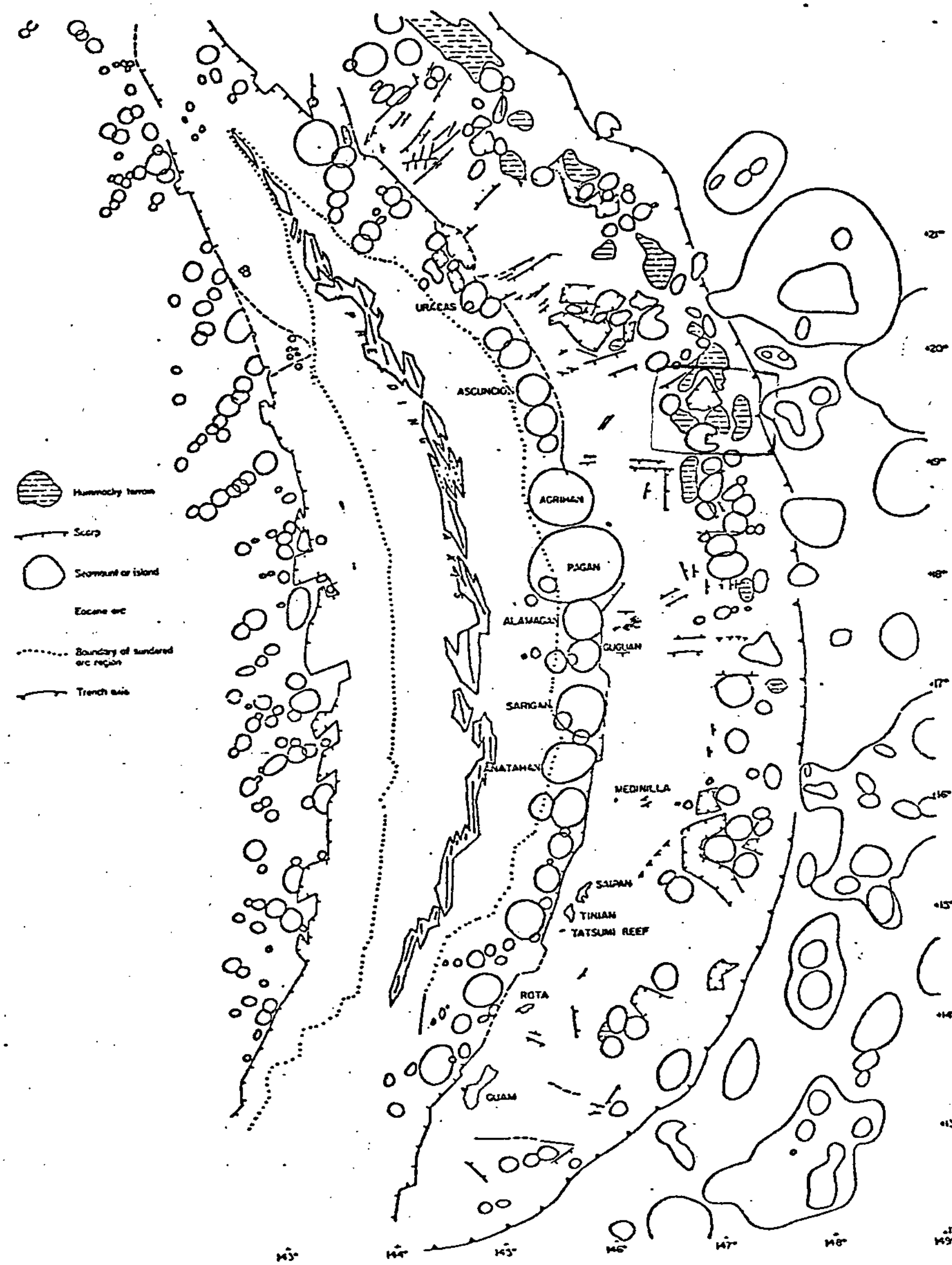
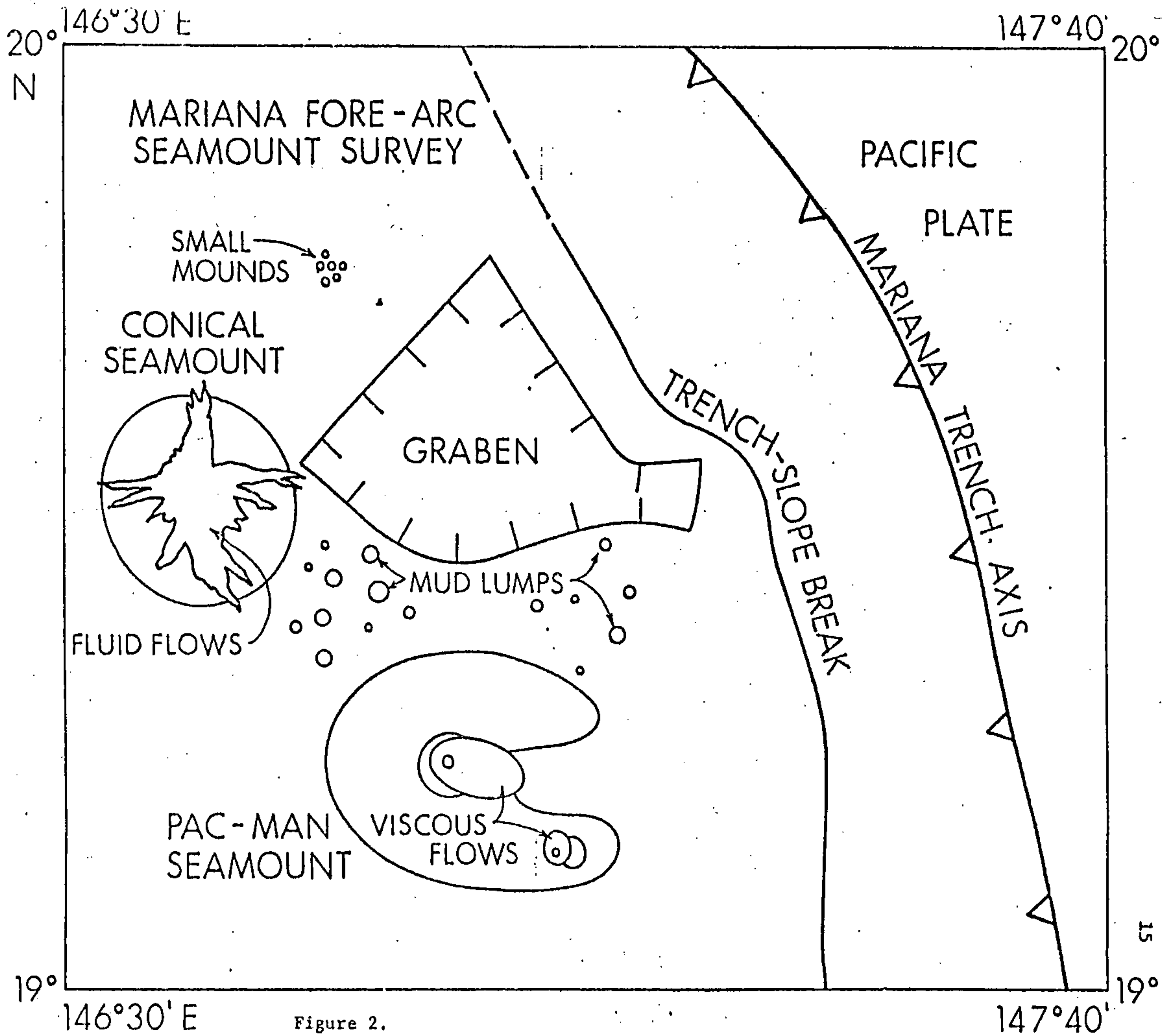

Hummocky terrain
Scarp
Seamount or island
Eocene arc
Boundary of sundered arc region
Trench axis
AGRIHAN
PAGAN
ALAMAGAN
GUGUAN
SARIGAN
MEDINILLA
SAIPAN
TINIAN
TATSUMI REEF
ROTA
GUAM

Figure 1.


146°30' E
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MARIANA FORE-ARC
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GRABEN
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Figure 2.

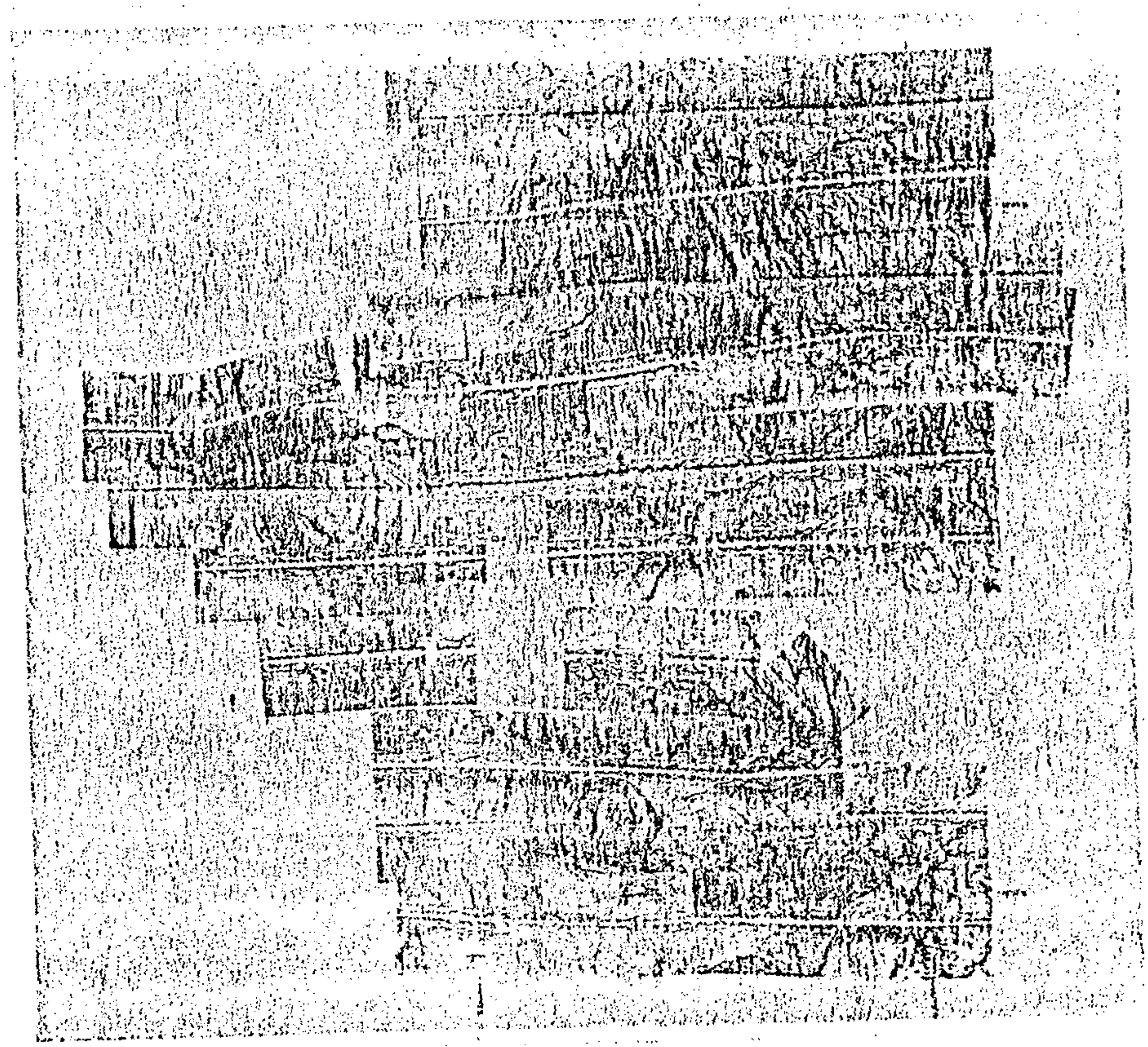


Figure 3.

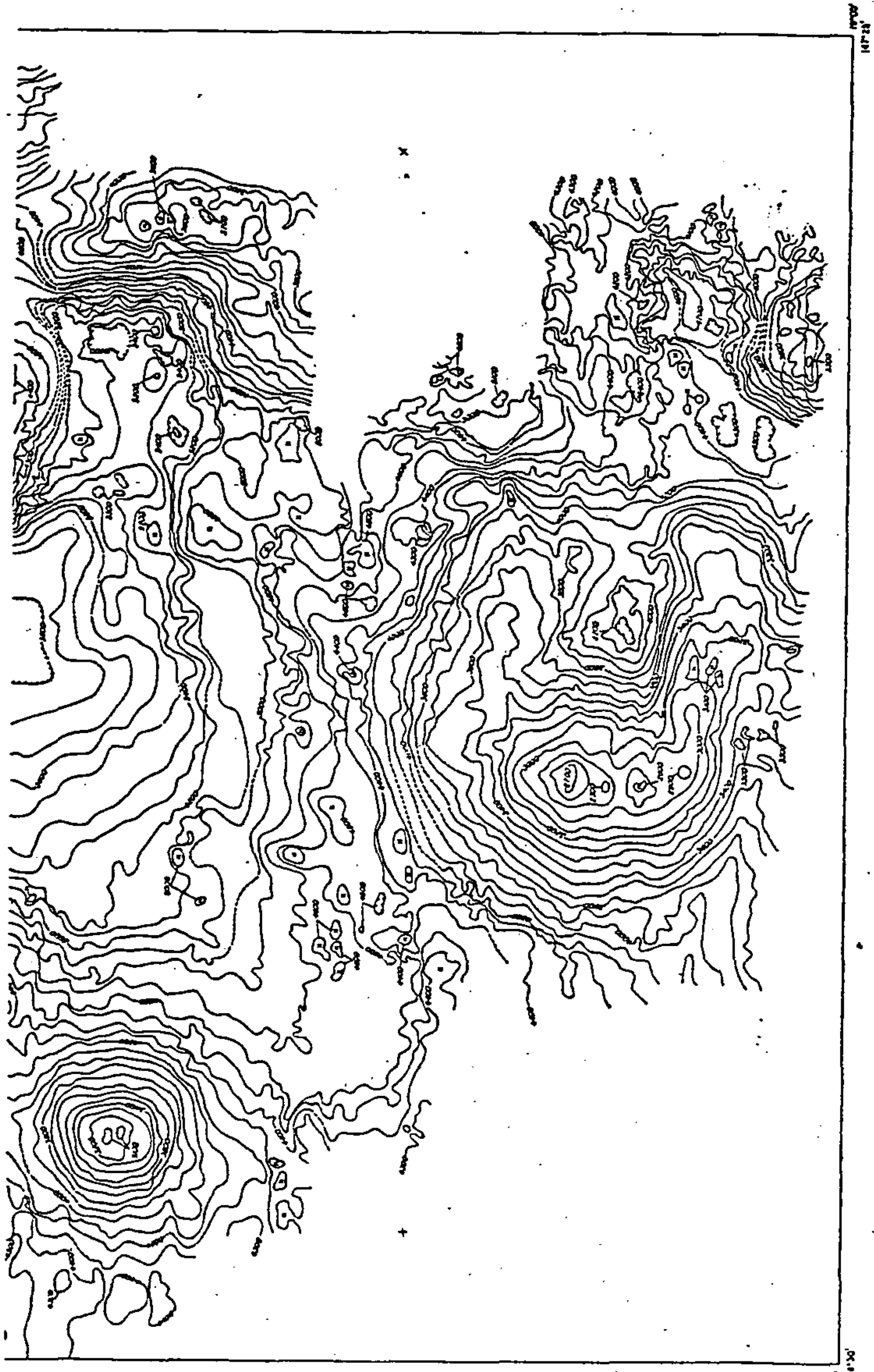


Figure 4.

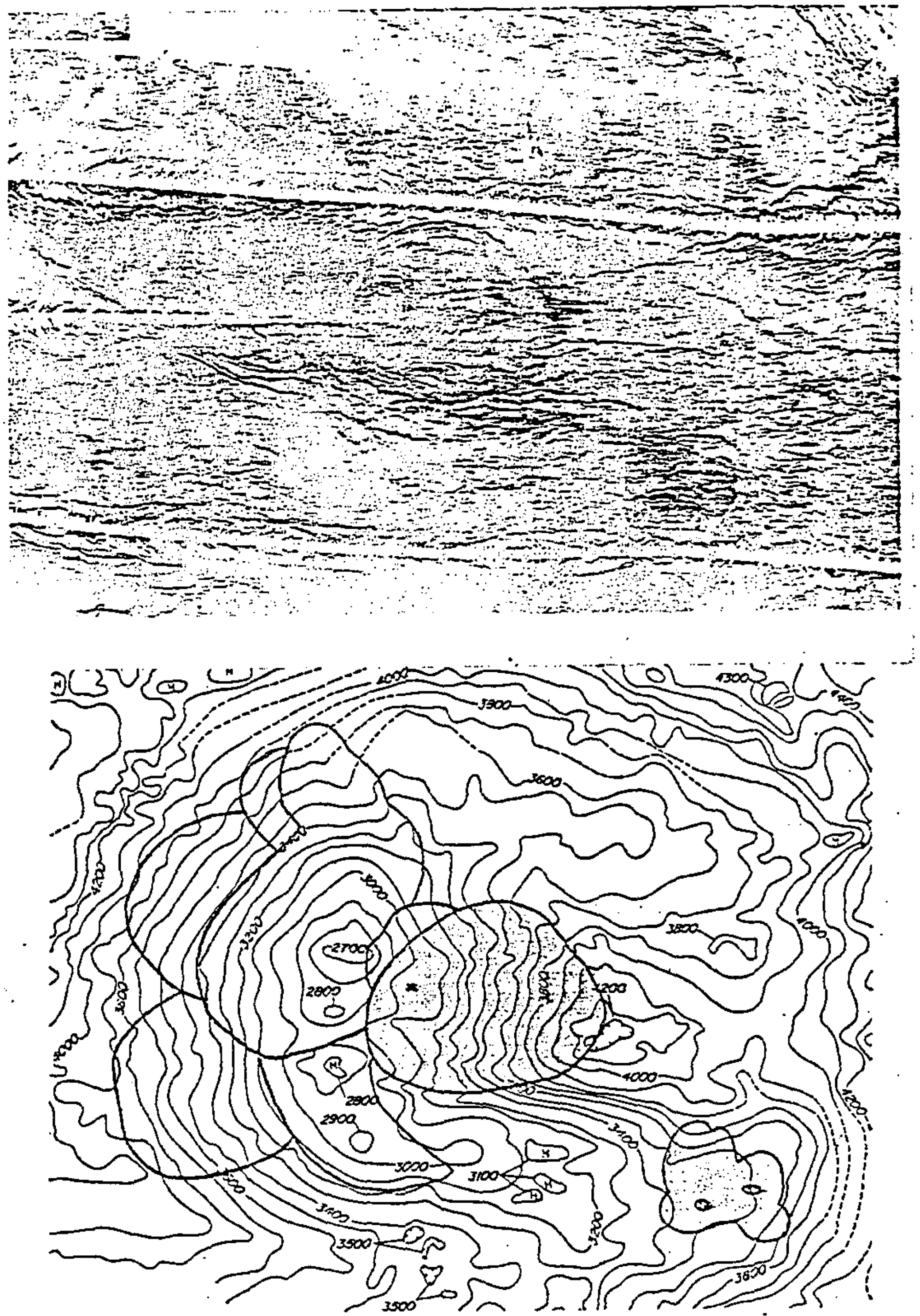
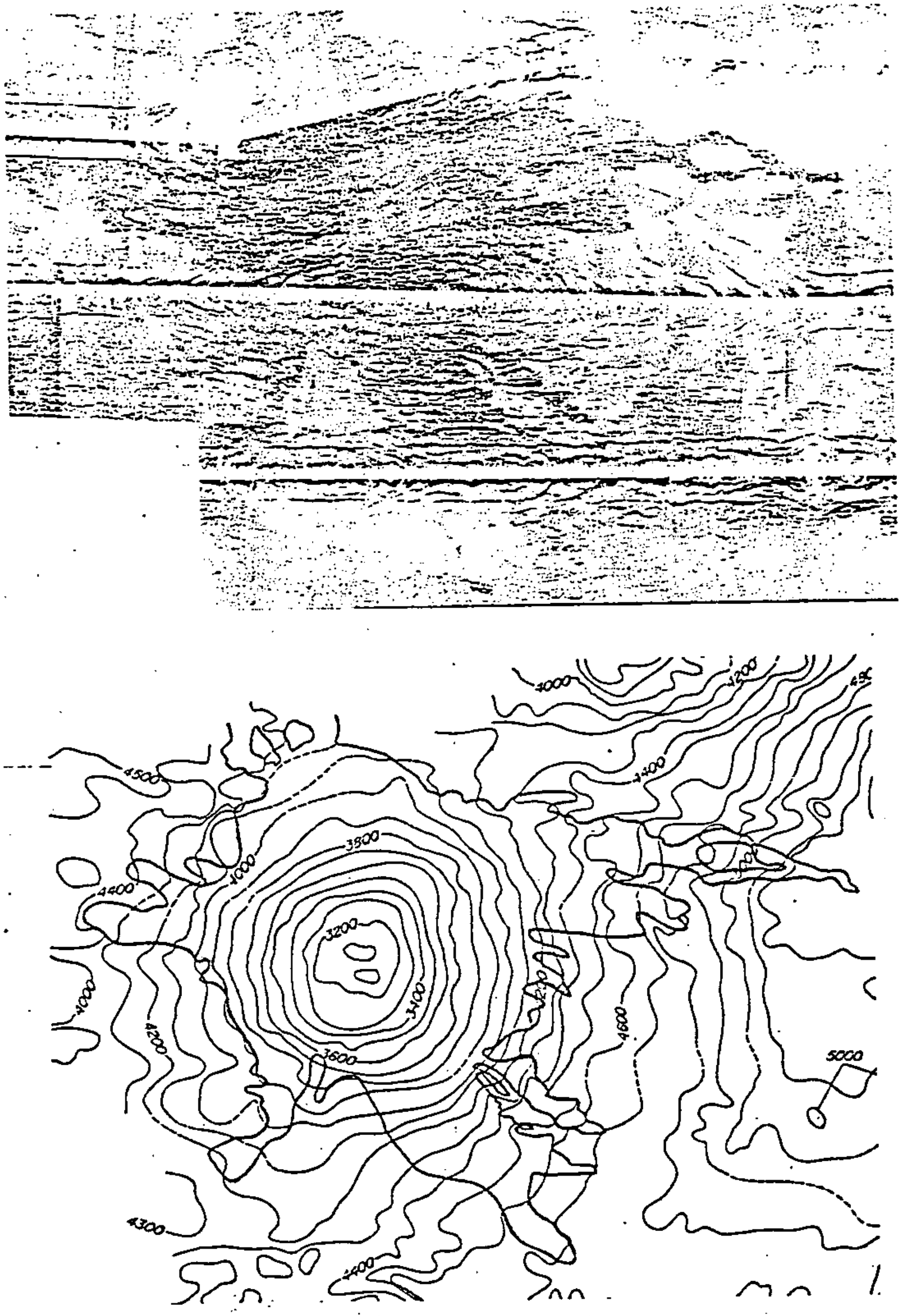



Figure 3.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4600
5000
4300
4400

Figure 8.

118

Proposed Site: Serpentinite Diapir on the Mariana Forearc (three holes) MF-1, 2, 3

General Area: breached diapir at approx 19°N

Position: 19°15'N 147°E, 19°20'N 146°54'E,

Alternate Site: 19°30'N, 146°41'E

General Objective: Mode of emplacement and timing of the serpentine diapirism in the outer Mariana forearc

Thematic Panel interest: Lithosphere, Tectonics

Regional Panel interest: Western Pacific

Specific Objectives: To determine stratigraphy of interbedded sediments and serpentinite flows (to date flows). To investigate small scale deformation of sediments associated with emplacement of the diapirs. To recover matrix material of flows (presumed lost duri: dredge recovery). To investigate possible hydrothermal alteration of sediments by fluids associa· with diapirism. To determine internal deformational characteristics of serpentinite flows. To determine rate of uplift of diapir from sediment history near and on the seamount.

Background Information:

Regional Data: Bathymetry, seismic reflection and refraction, Gravity, magnetics, dredge samples, SeaMARC II.

Seismic profiles: See attached.

Other data: Will have 14 dives with ALVIN completed in 1987 on this seamount and in vicinity.

Site Survey Data - Conducted by: KK81-06-26-03, KK83-01-16-04, D. Hussong and P. Fryer

Date: 27 Aug - 16 Sept 81, 20 Apr - 17 May 83

Main results: data described above collected.

Operational Considerations

Water Depth: (m) 4,500 Sed. Thickness: (m) approx. 500m Total penetration: (m) to refusal

HPC _____ Double HPC _____ Rotary Drill _____ Single Bit x Reentry _____

Nature of sediments/rock anticipated: vitric clay, siltsone, interbedded with serpentine flows.

Weather conditions/window: APR-JULY optimum; MAR-SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent: Patricia Fryer

Date submitted to JOIDES Office: July 9, 1985

Rev. 02

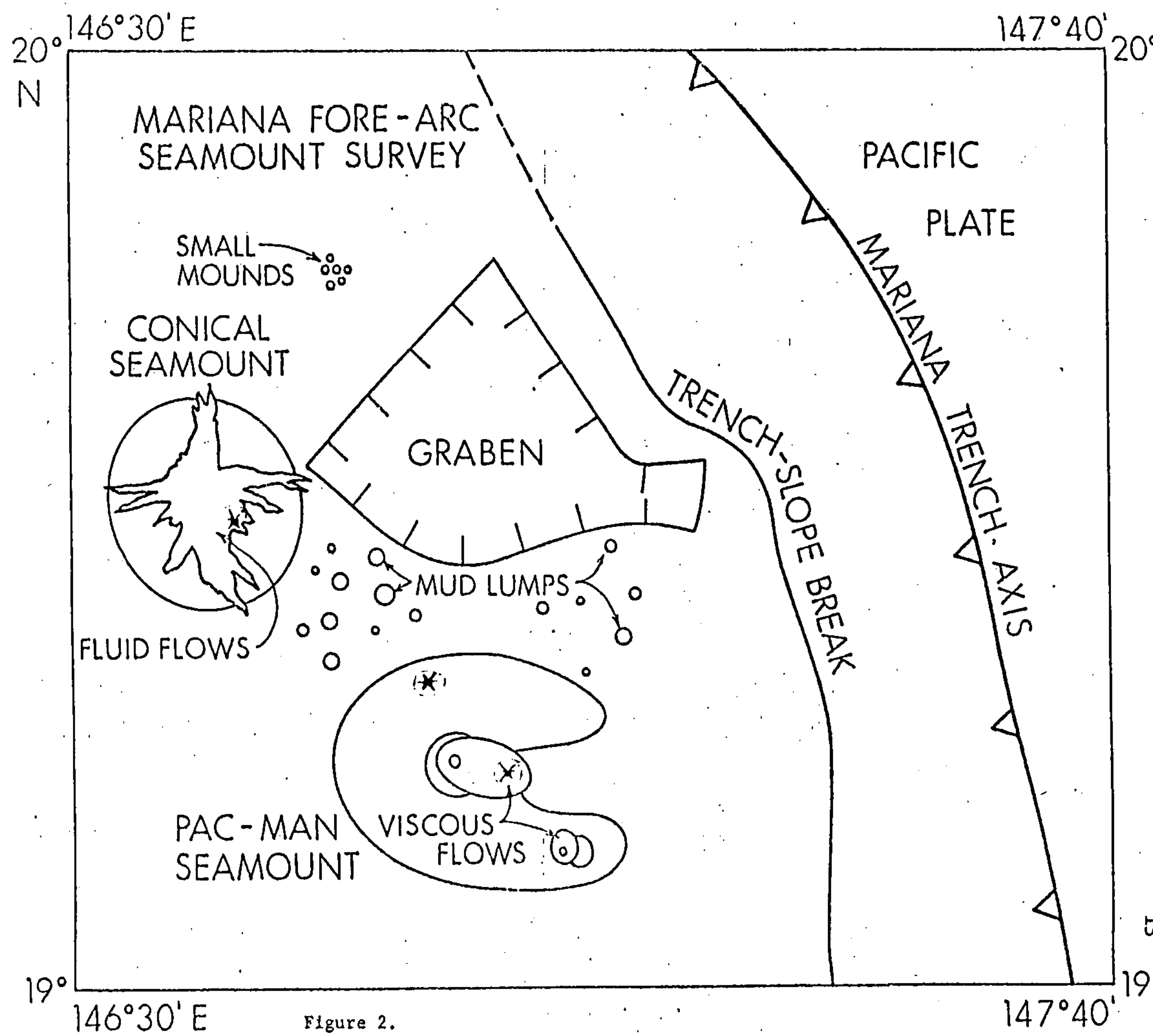
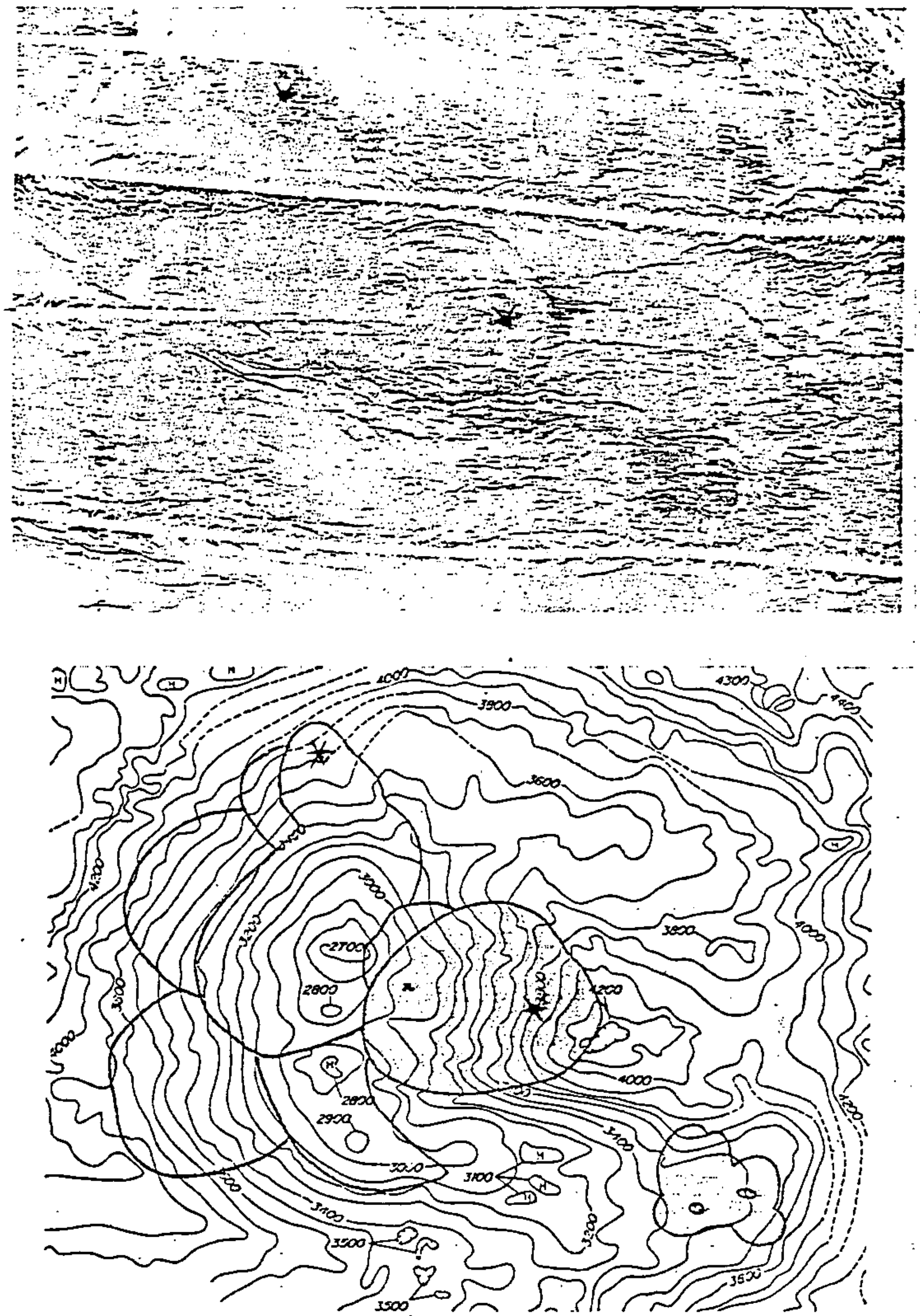

20° N
146°30' E
147°40'
20°
MARIANA FORE-ARC
SEAMOUNT SURVEY
PACIFIC
PLATE
MARIANA TRENCH. AXIS
TRENCH-SLOPE BREAK
SMALL
MOUNDS
CONICAL
SEAMOUNT
GRABEN
MUD LUMPS
FLUID FLOWS
PAC-MAN
SEAMOUNT
VISCOUS
FLOWS
19°
146°30' E
19°
147°40'

Figure 2.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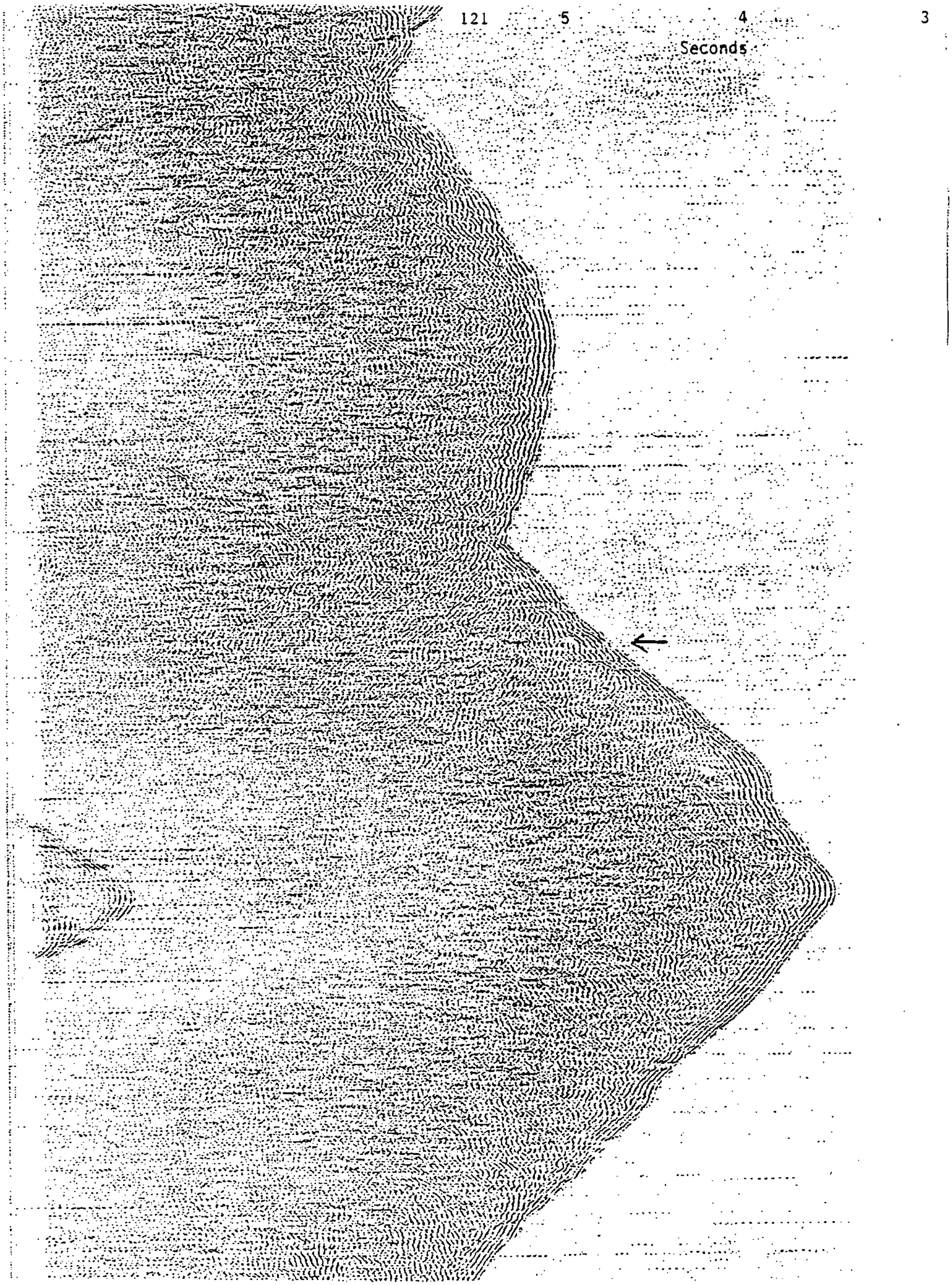
3200

Figure 3.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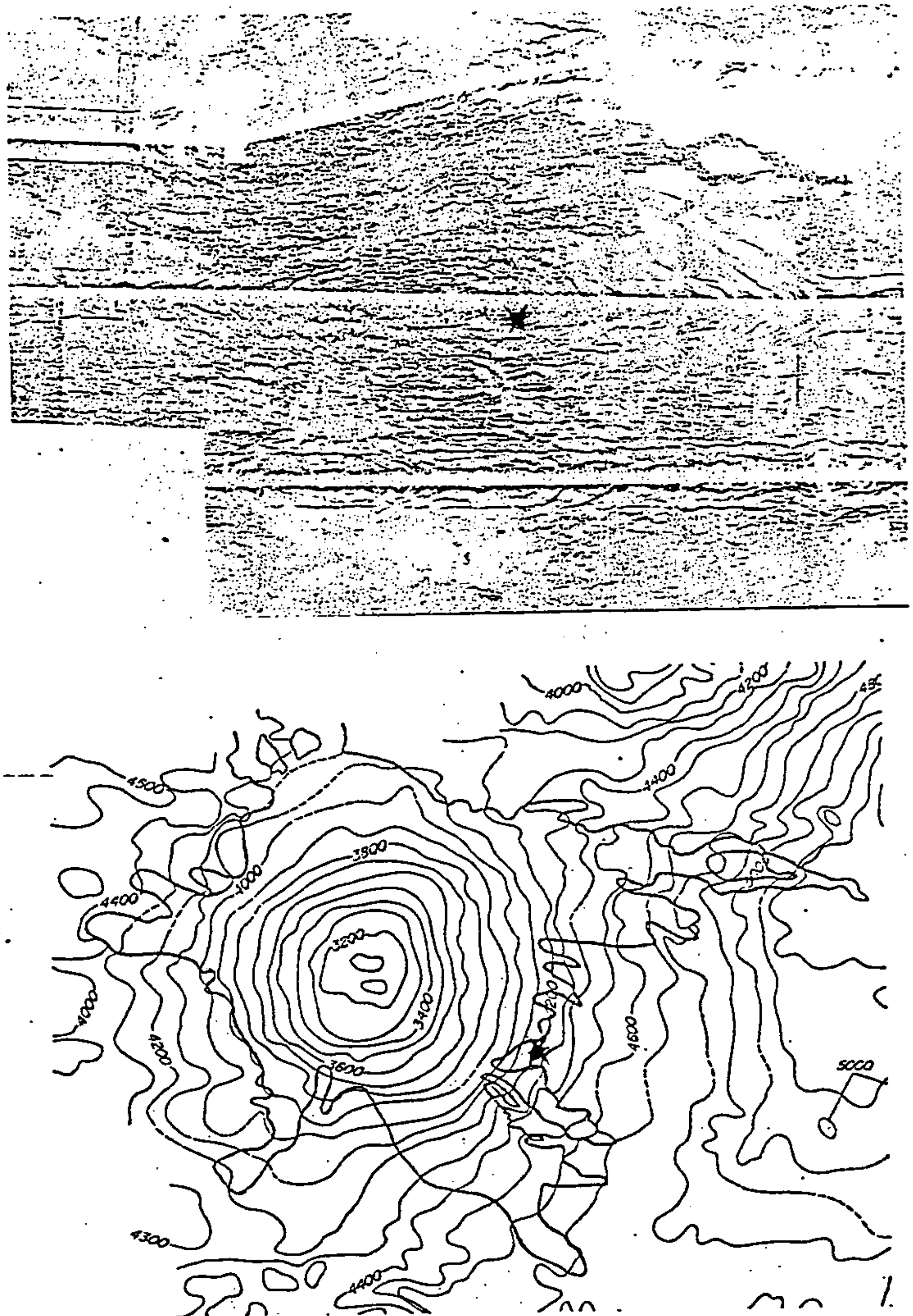
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Figure 8,

## Drilling in the Northern Mariana Backarc Basin

Patricia Fryer

The following four sites are proposed to address the problems of the early stages of arc rifting. On DSDP Leg 60 a series of holes was drilled in the central latitudes (18°N) of the Mariana backarc basin. At the latitude of this transect the basin is widest and exhibits a well-developed mid-ocean rift system at about the center of the basin. The objective of this transect was to investigate backarc basin processes in a portion of the basin that would show the greatest variation in age. The sites proposed here would enable us to study the youngest portion of the basin and to determine the history of opening of the basin.

### Geologic Setting

The western margin of the Mariana basin all along the length of the basin shows a morphology that is distinct from the magmatic rift system that exists in the center of the basin from latitude 14°N to 21°N (Fryer et al., submitted). By contrast with the ridges and troughs that run parallel to the central rift system, the western margin of the basin shows a horst and graben structure, similar in many respects to the basin and range province of the western U.S. It is probable that this horst and graben structure is the precursor to development of ridge systems in young backarc basins. It is probably formed by stretching and rifting of the arc massif, which causes thinning of the arc prior to the beginning of localized magmatic intrusions. The localization of magmatic intrusions result in formation of a stable spreading ridge system in the backarc basin. This process is described in Fryer et al. (submitted) for the Mariana backarc basin, but has also been suggested to be occuring in the Izu-Bonin arc (Fryer et al., 1985; Taylor, et al., 1985) and may have occured in the Lau Basin, as well as in others.

This early rifting stage is apparently devoid of surface fissure eruptions of any magnitude in the northern Mariana backarc basin (unpub. SeaMARC II data) and in the Izu arc (unpub. SeaMARC II data). Such fissure eruptions wouldbe associated with development of a mid-ocean spreading rift system in a backarc basin. At the early stage of opening of the northern Mariana basin magmatic activity of the backarc rifts may be limited to intrusion of arc magma along fractures forming in the basin. However, along localized fractures which run essentially perpendicular to the strike of the arc in the Izu rift grabens we have collected rocks which are similar in trace element compositions to the backarc basin basalt collected in the central part of the Mariana back arc basin at 18°N (Fryer et al., 1985). This indicates that while a rift system may not have developed in the young backarc basin, it is still possible to see the eruption of magmas that are distinct in composition from the magmas being erupted in nearby arc volcanoes. Studies of the magma types in the Lau and Mariana backarc basins have led Hawkins to suggest that there is a progressive transition from arc through backarc basin to MORB lava types, as these basins mature. This is a refinement of a similar suggestion offered by Tarney et al. (1977). This kind of distribution of magmatic types has never been investigated in detail in any backarc basin. It would be impossible to sample such a proposed distribution of magma types if the new backarc magmas are emplaced as intrusions along fault planes between horst and graben blocks in the incipient or young backarc basin. Such igneous bodies would have to be sampled by drilling. Furthermore, drilling would be the only way in which to document the subsidence history of the young backarc basin.

Northern Mariana Backarc Basin Site 1 (NM-1)

The first of the northern Mariana backarc basin crust sites we propose (see attached Site proposal sheet) is aimed at documenting the history of the rifting of the Mariana backarc basin. With a site located here it is expected that we will be able to determine the history of subsidence of the arc, the level of volcanic activity during early rifting stages of this portion of the arc, the influence of possible secondary intrusive activity on the sediment column and on igneous basement, and the effects of any hydrothermal activity associated with intrusions. The history of subsidence of this part of the arc would help to answer the questions regarding the timing of opening of the northern Mariana backarc basin. It is still not known whether the northern part of the basin has been opening at a very much slower rate since the beginning of opening of the Mariana backarc basin at 18°N (about 10 ma), or whether opening of the basin is propagating northward. In the latter case the subsidence of the arc in the northern part of the basin might have begun within the last two or three million years.

Northern Mariana Backarc Basin Site 2 (NM-2)

Site two (see attached site proposal sheet) is of interest for a number of reasons. Paramount among these is to study the nature of the earliest true spreading rift in the Mariana backarc basin. We know from the sidescan data collected at this site that the rift axis lies in the depression immediately west of the site we have chosen. There is no thick sediment cover obvious on the sidescan records of the rift axis itself. Since bare rock drilling is so time consuming, we have chosen to select a drill site as close as possible to the rift axis which does show sufficient sediment cover. Dredge samples will be collected in Oct. 1985 by R. Stern and S. Bloomer at sites along the active spreading ridge. If sampling goes as planned, it will be possible to compare the variation in composition of the rift lavas along strike with the composition of the off axis lavas collected from the drill site. This is also the most likely site for the development of Koroko type deposits in the basin. The rift axis is close to a source of sediment (Fukujin Seamount) and is apparently rapidly burried by debris. In addition to the questions of basement composition and development of economic deposits it will also be possible to determine whether the volcanism on Fukujin Seamount, a large submarine volcano has experienced any periodicity which might be related to the rifting of the arc to form the backarc basin. One of the still debated questions regarding the development of backarc basins in general is whether the initiation of backarc spreading causes a cessation of arc volcanism. The timing of volcanism on Fukujin may also be related to the development of the forearc graben in which the volcano is situated. By determining the history of volcanism at this site it may be possible to relate the timing of the formation of the forearc graben to initiation of the volcano.

Northern Mariana Backarc Basin Site 3 (NM-3)

The third of the sites proposed for the backarc basin is situated at a distance of about 13 km east of site 2 (see figure attached to site proposal sheet). The thickness of the sediment cover at this site is similar to that at site 2. However, the site is much further away from the rift axis and is located at a position which should be underlain by rifted arc crust, assuming symmetric spreading of the basin about the currently active rift axis. There are apparent piercement structures in the sediment of this part of the basin and the origin of these structures is not clear. They may be intrusions of arc magmas, in which case the setting is potentially excellent for the development of Koroko type deposits.

Northern Mariana Backarc Basin Site 4 (NM-4)

The fourth site proposed is an attempt to address two very important aspects of the development of backarc basin crust which have not been investigated and which are of tremendous significance to the understanding of the petrogenesis of backarc basin lavas. The first of these aspects deals with the influence of arc magmas in the backarc basin as it is related to local tectonics within the basin. The second aspect deals with the composition of the ancient arc foundations.

Geologic and geophysical studies of backarc basins have concentrated on developing models for the tectonic history of the regions. Specific studies of the backarc basins have done much to clarify the mechanism by which these features develop. However, a critical component of the backarc basin picture has been left untouched. To date, no attempt has been made to study, using deep sea drillling techniques, the ubiquitous chains of submarine volcanoes cross-cutting the arcs and extending into the backarc basins. These volcanoes are composed of arc lavas. They are actively erupting these lavas even at distnces of 50 km from the line of volcanoes that are situated along the strike of the arc. What effect the presence of these cross-chain volcanoes may have on the distribution of magma types in the backarc basin is unknown. It has been shown that some backarc basin lavas have a unique composition similar to MORB, but are overprinted by an arc component. Spatial variations in the composition of backarc basin basalt (BABB) have been suggested to be related to size of a given basin and distance of the spreading axis from the strike of the related arc (Tarney et al., 1977; Hawkins, 1984). However DSDP results from Site 456 in the Mariana trough and results of studies of dredge samples from the spreading axis at 18°N showed that arc magmas may occur quite close to the spreading axis of a backarc basin. Site 456 is located along the trend of one of the Mariana cross-chains. Variations in composition of dredge samples from the spreading rift in the Mariana backarc basin at 18°N suggest a distribution controlled by fracture zone/rift axis interaction (Fryer and Sinton, in prep.). If the cross-chain volcanism can influence composition of the rift axis lavas, as dredge results indicate, it is highly probable that the backarc basin crust adjacent to a given cross-chain may be contaminated by lavas leaking out laterally from the cross-chain into the backarc basin. Leaking of this sort would necessitate a network of fractures adjacent to the cross-chains. Studies of basin morphology (sidescan and bathymetry data) revealed the presence of mid-ocean ridge spreading fabric in the vicinity of one of the northern basin cross-chains. Sidescan data indicate the presence of fractures on the basin floor which parallel the spreading axis of the basin. Whether distribution of cross-chain lavas is influenced by the presence of such fabric is unknown. However, until the distribution of arc lavas in the backarc basin can be evaluated, no comprehensive model for the development of backarc crust can be defined.

The cross-chains occur on the east side of the basins. They extend from the line of the active arc toward the center of the basin. Previous efforts to drill close to the active arc have met with limited success. A deep blanket of volcaniclastic sediments covers the lower submarine slopes of the arc volcanoes. This material was nearly impossible to penetrate with existing drilling equipment in 1978 (site 457). Bathymetry data and SeaMARC II sidescan images suggest that less volcaniclastic debris has been deposited north of Uracas in the Mariana arc. The arc volcanoes north of Uracas are relatively small, with the exception of Fukujin Seamount (see Figure 1). They are quite deep and are unlikely to have erupted subaerially. Thus, they probably have produced much less debris than the larger seamounts and islands of the southern Mariana arc. The largest cross-chains in the Mariana backarc basin occur near 21°N. The seamounts in one of these chains have large areas of exposed lava flow fields and smaller areas of volcaniclastics (see sidescan image attached to site proposal). The basin floor around these seamounts appears to have sediment cover and also to display fracture patterns which may be related to the spreading fabric generated in the backarc basin rift axis. It appears from bottom morphology south east of the cross-chain that ridges between the rift scar of the arc and the prospective sites may provide barriers to volcaniclastics that might have been produced in the arc. This implies that the basin floor near the cross-chain may be free of the coarser kind of sediment that might give problems for drilling.

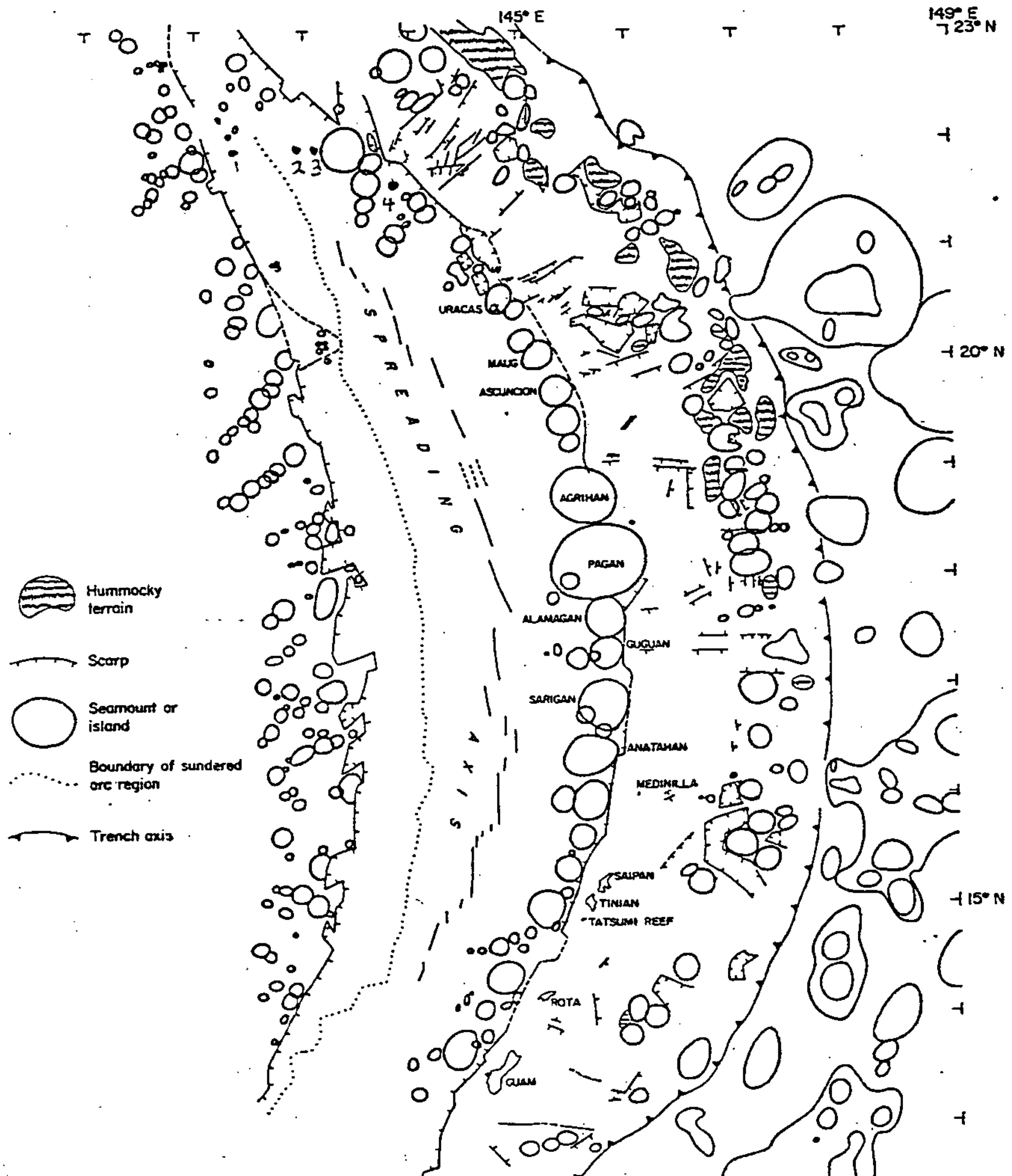
In order to evaluate the degree to which cross-chain magmas may have influenced the composition of the backarc basin crust we propose a drill site on the eastern side of the cross-chain in the basin described above. We shall have data from dredge samples along the rift axis near the cross-chain with which to evaluate the influence of the magmas from this chain on the magmas being erupted in the rift. The objective of the drill site will be, in part, to give a third dimension of control to our understanding of this complex interaction.

This site will also satisfy the requirements of the need to understand the nature of the arc crust upon which the major volcanic edifices develop. We do not know what underlies the arc volcanoes. Dredging of scarps of the arc in the vicinity of this site and exploration of similar scarps with ALVIN dive programs are planned for the next two years. However, these types of studies will only allow us to examine the forearc basement near the sites of major arc volcanoes. Neither dredging nor submersible work can be used to address the problem of determining the foundation of the arc basement along strike of the arc, because most arc volcanoes develop within the backarc basins, on the margin between the basin and the unrifted forearc. We cannot sample this region in any other way but by drilling. The objectives of looking at the arc between major volcanoes will be to examine the history of development of the arc as a whole and to compare the forearc near the arc volcanoes, that is exposed in fault scarps, with the subsurface arc foundations between arc volcanoes.

The studies we propose to pursue with information from this site are applicable to many other backarc basins. The development of cross-chains for instance is by no means unique to the Mariana backarc basin. Such chains of volcanic edifices are numerous on the West Mariana ridge, occur extending west from the Palau-Kyushu Ridge, and very well-developed, large chains extend into the Shikoku basin from the Izu-Bonin arc. In addition, similar linear volcanic chains are numerous in arcs on land (Central America, Japan, New Britain, etc.). The Philippine Islands apparently show exposures of dike systems within backarc basin terrain, which appear to be related, at least spatially, to the arc half of the basin sequence. The origin of these dike systems is unknown at present. It is obvious that cross-chains of arc volcanoes in backarc basins settings must be an important component of any model developed to explain the evolution of the arcs and backarc basins.

Applicability of Northern Mariana Backarc Basin Studies to Other Areas

The information gathered from the drilling project proposed here will be able to be applied to many arcs, and indeed the study of the early opening history of the arc, the development of the arc foundations and of the influence of cross-chain volcanism need not necessarily be attempted only at the sites proposed here. It is obvious, however, that drilling in the Mariana backarc basin has the advantage of considerable supporting data. Numerous geophysical and geological sampling cruises to the area, completed DSDP Leg 60 as a basis for comparison, SeaMARC II reconnaisance data, as well as scheduled ALVIN dive programs will considerably facilitate ultimate understanding of data from this proposed drilling program.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MAUG
ASUNCION
AGRIHAN
PAGAN
ALAMAGAN
GUGUAN
SARIGAN
ANATAHAN
MEDINILLA
SAIPAN
TINIAN
TATSUMI REEF
ROTA
GUAM
Hummocky terrain
Scarp
Seamount or island
Boundary of sundered arc region
Trench axis

~~sed~~ Site: Northern Mariana Backarc Basin Crust Site 1

NM-1

General Area: northern Mariana backarc basin
Position: 21°41'N 142°26'E
Alternate Site:

General Objective: To study early stages of su ing of arc during backarc basin formation.

Thematic Panel interest: Tectonics, Lithosphe
Regional Panel interest: Western Pacific

Specific Objectives: To investigate the history of tectonic movement (arc stretching and ri during the early stages of backarc basin opening. To examine basement composition in a port the backarc basin which has experienced no apparent (on sidescan images) mid-ocean rift mag in order to test the possibility that the basement is composed of sundered arc material. To possible intrusive phenomena associated with graben formation. To study the history of sedi and nature of sediments in this part of the basin for the tephrachronology studies as well subsidence history. To test the chronology of opening of the Mariana Trough by comparison DSDP Leg 60 results.

Background Information:
Regional Data: SeaMARC II sidescan and bathymetry, seismic reflection, gravity, magnetic
Seismic profiles: See Attached

Other data: dredge samples and geophysical data will be collected by R. Stern & S. Bloome October 1985.

Site Survey Data - Conducted by: SeaMARC II survey conducted 1984, P. Fryer and D. Hussong
Date: June 1984
Main results: The regional data described above was collected.

Operational Considerations

Water Depth: (m) 3450 Sed. Thickness: (m) approx. 400 Total penetration: (m) to refusal

HPC _____ Double HPC _____ Rotary Drill _____ Single Bit x Reentry _____

Nature of sediments/rock anticipated: vitric silt, mud, siltstone, pumice, basalt

Weather conditions/window: APR-AUG optimum; MAR-SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special requirements (Staffing, instrumentation, etc.)

none

Proponent: P. Fryer, R. Stern, S. Bloomer

Date submitted to JOIDES Office: July 9, 1

Re

Basin Crust Site 2

NM-2

General Area: Northern Mariana backarc basin
Position: 21°40'N 143°19'E
Alternate Site:

Thematic Panel interest: Lithosphere, Tectonics
Regional Panel interest: Western Pacific

Specific Objectives: To examine a part of the actively rifting Mariana backarc basin where the rift formation process is very young, in order to test the possibility that the eastern side of the basin was formed by magmatic intrusion, rather than by stretching of arc crust. To determine composition of basement, to examine tectonic history in sediments in a location where sediments appear undisturbed, close to the active rift axis. To determine nature of possible hydrothermal activity associated with a young backarc rift in an area with thick sediment cover that is apparently little disturbed (similar to Koroko environments).

Background Information:
Regional Data: SeaMARC II sidescan and bathymetry, seismic reflection, gravity magnetics.
Seismic profiles: See Attached.

Other data: dredge samples and geophysical data will be collected by R. Stern & S. Bloomer, October 1985.
Site Survey Data - Conducted by: SeaMARC II survey conducted 1984, P. Fryer, D. Hussong
Date: June 1984
Main results: Data described above was collected.

Operational Considerations

Water Depth: (m) 3000 m Sed. Thickness: (m) approx. 400 Total penetration: (m) to refusal
HPC _____ Double HPC _____ Rotary Drill _____ Single Bit x Reentry _____

Nature of sediments/rock anticipated: vitric silt, mud, siltstone, pumice, basalt

Weather conditions/window: APR — AUG optimum MAR — SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special requirements (Staffing, instrumentation, etc.)

none

Proponent: P. Fryer, R. Stern, S. Bloomer, J. Gill, J. Natland

Date submitted to JOIDES Office: July 9, 1985

Rev. 028

ʼsed Site: Northern Mariana backarc basin crust near the active arc
Site 3. NM-3

General Objective: To study near arc, backarc basin crust in a young backarc rift

132

neral Area: Northern Mariana backarc basin
sition: 21°40'N 143°30'E
ternate Site:

Thematic Panel interest: Lithosphere, Tectonics
Regional Panel interest: Western Pacific

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cific Objectives: To determine sediment history of backarc basin in order to examine tectonic history of rifting, tephrachronology of nearby arc volcanoes (if possible). To determine basement composition to test possibility that the near arc basement is sundered arc crust or alternatively is composed of newly formed backarc crust (implying asymmetric spreading). To examine extent to which arc magmatism may be associated with backarc rifting near the active arc. To study possible hydrothermal activity associated with rifting in an area of thick sediment which appears undisturbed (similar to Koroko environments).

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ckground Information:
egional Data: SeaMARC II sidescan and bathymetry, seismic reflection
Seismic profiles: See Attached.

Other data: R. Stern & S. Bloomer will collect additional geophysical data and samples in Oct 1985.

ite Survey Data – Conducted by: SeaMARC II survey conducted 1984, P. Fryer, D. Hussong
Date: June 1984
Main results: Data described above was collected.

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erational Considerations

ater Depth: (m) 3000 m Sed. Thickness: (m) approx. 400 Total penetration: (m) to refusal

PC ____ Double HPC ____ Rotary Drill ____ Single Bit x Reentry ____

ture of sediments/rock anticipated: vitric silt, mud, siltstone, pumice, basalt

eather conditions/window: APR—AUG optimum MAR—SEPT acceptable

rritorial jurisdiction: Northern Mariana Territory

her:

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ecial requirements (Staffing, instrumentation, etc.)

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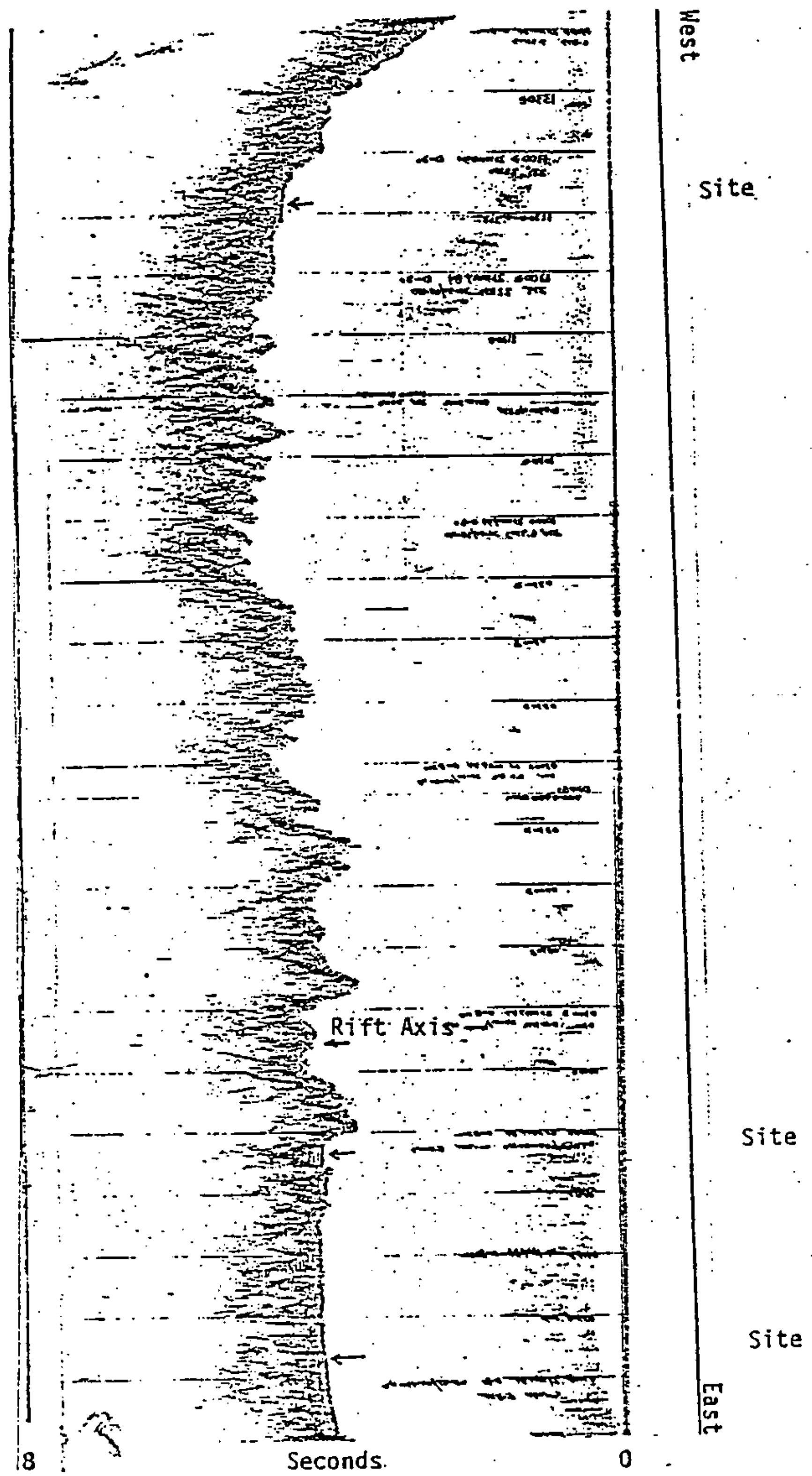
oponent: P. Fryer, R. Stern, J. Gill, J. Natland

Date submitted to JOIDES Office: July 9, 1985

Rev. 028


West
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Rift Axis
Site
Site
East
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Seconds
0

/ sed Site: , Near large chain of volcanoes in the Mariana back arc basin Site 4

NM-4

General Objective: volcanism between volcanic cross-chains in a ba arc setting and inter-volcanic backarc basin cr on the arc side of the backarc basin

134

General Area: Northern Mariana Backarc Basin
Position: 21°39'N 143°53'E
Alternate Site: 21°40'N, 143°30'E (see Northern Mariana Backarc Basin Crust, Site 3)

Thematic Panel interest: Tectonics, Lithosphere
Regional Panel interest: Western Pacific

Specific Objectives: To investigate the degree to which arc magmas contaminate the backarc basin crust by injection into preexisting crust along fractures. To examine backarc basin crust of the eastern margin at a site between volcanic centers and not along cross fractures. To test possibility that the Mariana backarc basin has spread assymmetrically, and thus may be compose of primarily sundered arc material on the western half and of newly formed (by ridge spreading basaltic magmatism on the eastern half.

Background Information:

Regional Data: SeaMARC II sidescan and bathymetry, seismic reflection, gravity magnetics in n vicinity.
Seismic profiles: None. See sidescan image attached.
S. Stern and S. Bloomer will augment available geophysical data and samples in 1
Other data: ALVIN diving is scheduled for 1987 for vicinity additional geophysical data wil collected on transit to dive sites.
Site Survey Data - Conducted by: will be collected on 1987 ALVIN cruises.
Date: 1985, 1987
Main results: Will collect data described above.

Operational Considerations

Water Depth: (m) 3400 Sed. Thickness: (m) unknown at present Total penetration: (m) to refusal

HPC ____ Double HPC ____ Rotary Drill ____ Single Bit x Reentry ____

Nature of sediments/rock anticipated: vitric silt, mud, siltstones, pumice, basalt

Weather conditions/window: APR-AUG optimum, MAR-SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

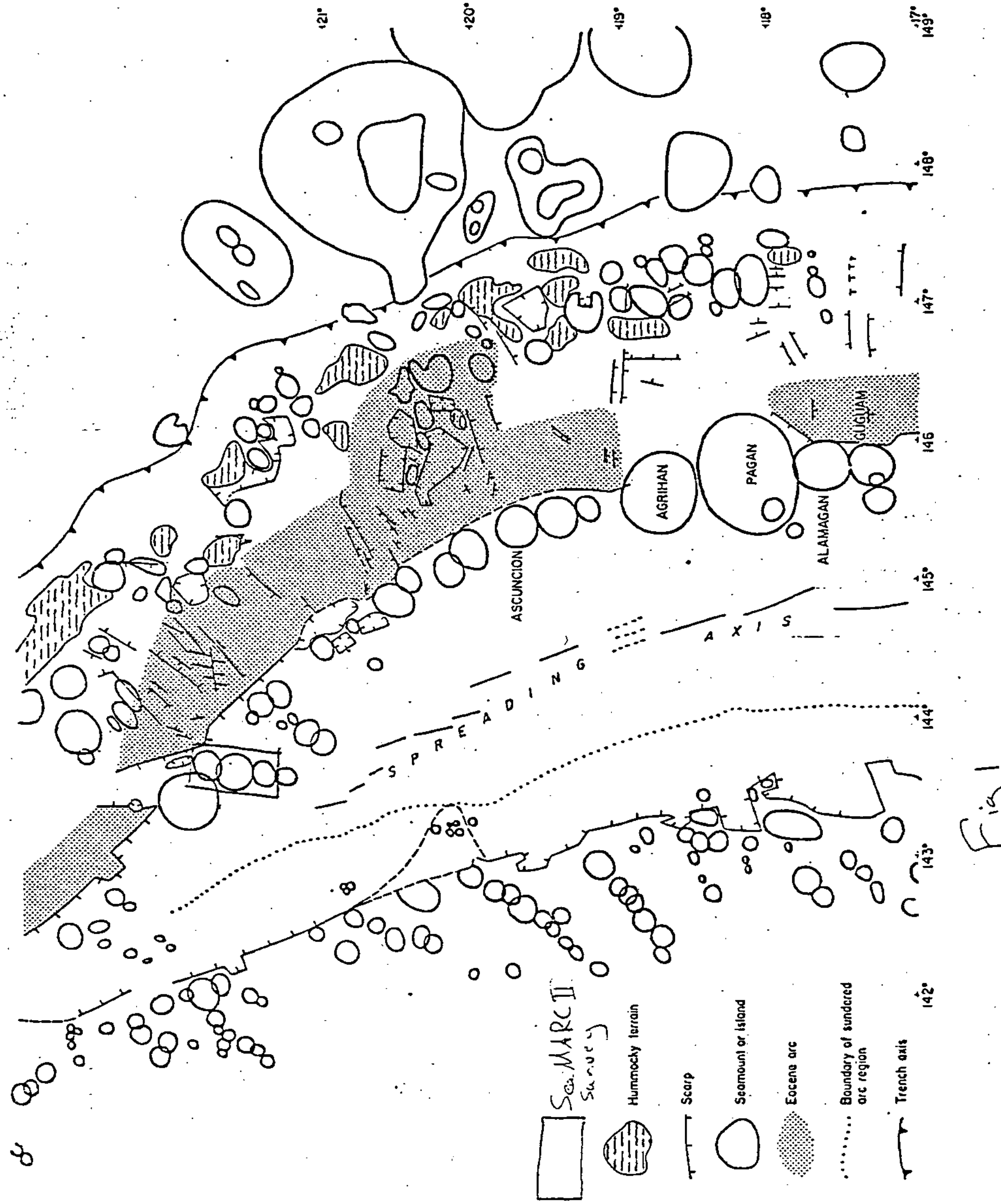
Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent: Patricia Fryer, J. Gill R. Stern

Date submitted to JOIDES Office: July 9, 1985

Rev.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AGRIHAN
PAGAN
ALAMAGAN
GUGUAM
ASCUNCION
SPREADING AXIS
Sea MARC II survey
Hummocky terrain
Scarp
Seamount or island
Eocene arc
Boundary of sundered arc region
Trench axis

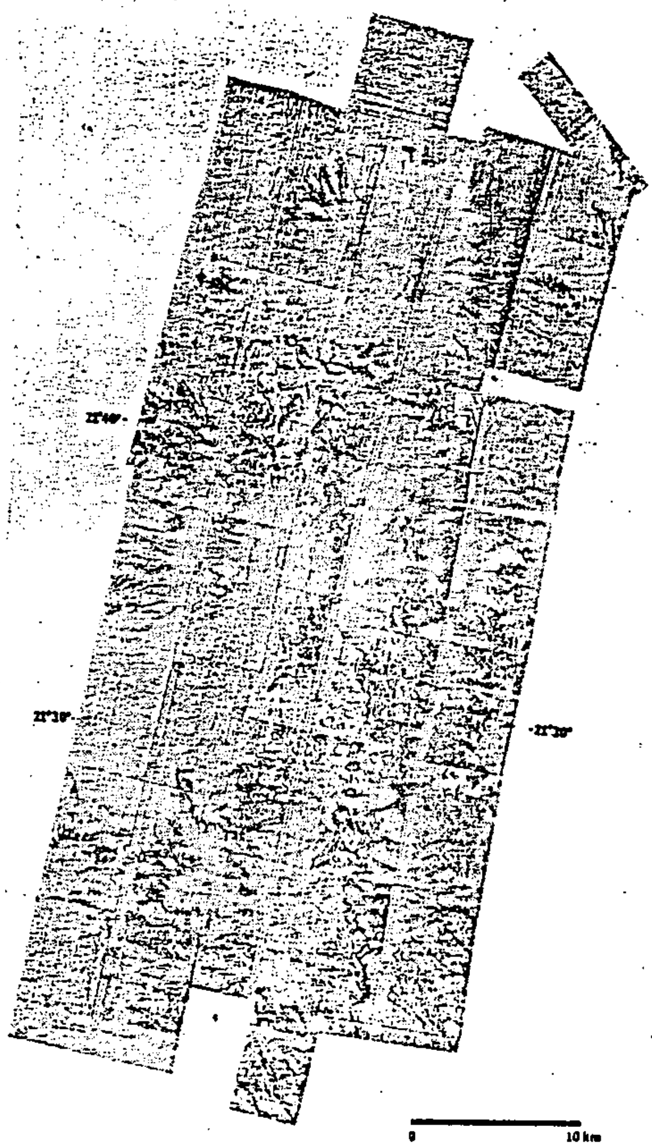
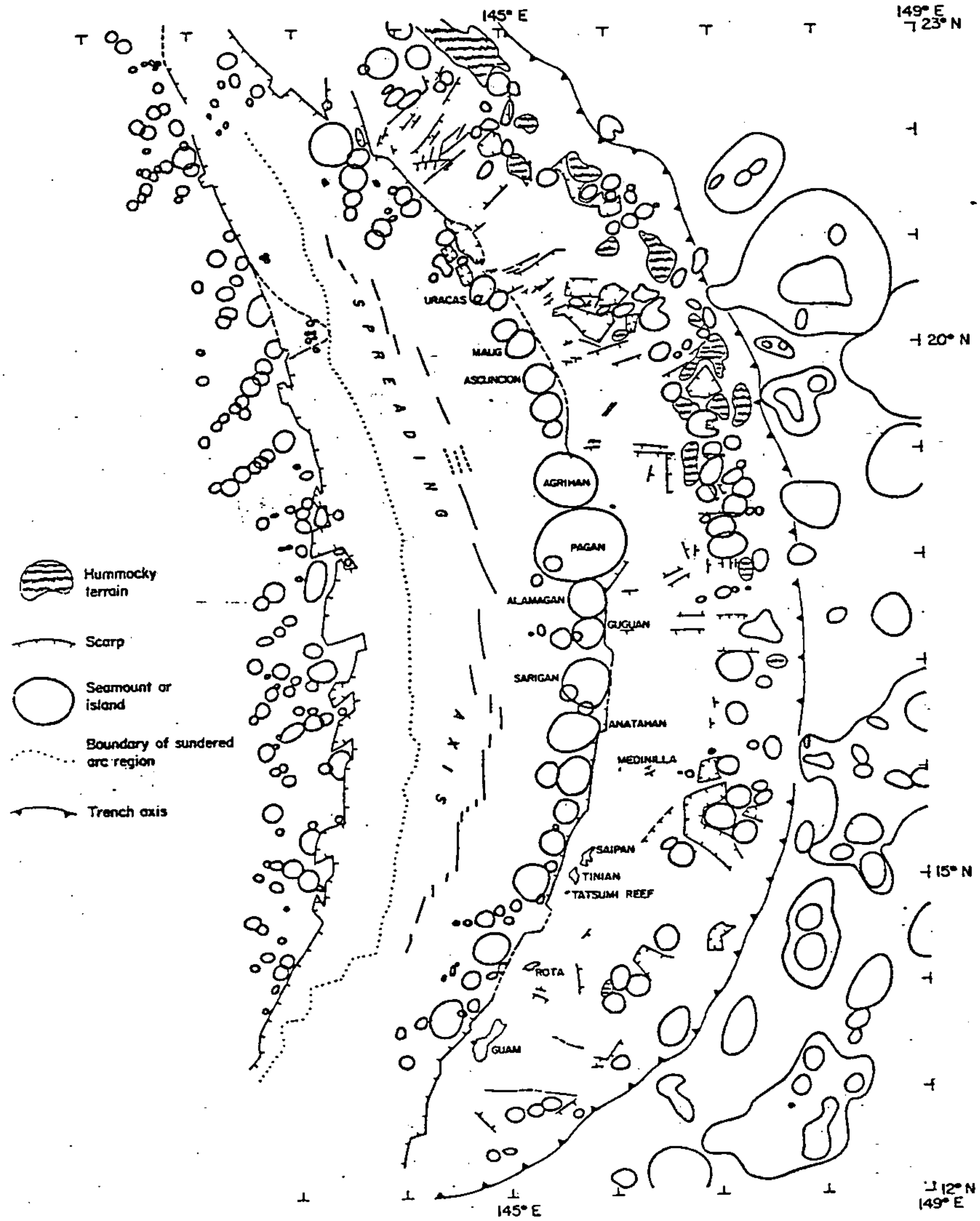



Fig 2 SeaMARC II side-scan image



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SPREADING
AXIS
URACAS
MAUG
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AGRIHAN
PAGAN
ALAMAGAN
GUGUAN
SARIGAN
ANATAHAN
MEDINILLA
SAIPAN
TINIAN
TATSUMI REEF
ROTA
GUAM
Hummocky terrain
Scarp
Seamount or island
Boundary of sundered arc region
Trench axis


Fig 3

# DEEP SEA DRILLING TARGETS IN THE NORTHERN MARIANA ARC

Patricia Fryer

The following two proposed sites are intended to address the problems of the tectonic history, structure, and composition of the arc at sites close to the active arc. The first area suggested for drilling is located in a portion of the arc which has probably had a lower rate of inFlux of volcanogenic sediments than elsewhere in the arc. At this site the arc volcanoes are small and occur within the backarc basin. The volcanoes are separated from the forearc in this region by a 2 km-high scarp (Figures 1 and 2), an effective barrier to any volcanigenic detritus that might have been generated in response to local arc volcanism. The forearc here may record a full section of arc tectonic history in a very thin sediment section. It is likely that basement close to the line of active arc volcanoes would be reached more rapidly here than in any other portion of the arc. In addition to these considerations, the site suggested shows evidence of tectonic movement. The relative age of this disturbance is not known. It is of considerable interest to the study of stress fields of the arc to determine whether the fracturing of the forearc in this region is ancient or recently active. Recent tectonic activity is possible along some of the faults seen on SeaMARC II data from this area. A small volcanic cone exists on one of the fault traces at the base of the fault scarp bounding the back arc basin. This volcano appears young. It has more highly reflective back scatter characteristics as compared with the surrounding basin floor and with the fault scarp itself. If volcanism occurs along fault scarps in this part of the arc, there are obviously avenues for migration of magmatic and possibly for metalogenic fluids. Note also (see Izu/Bonin arc sites, Taylor) that numerous small young-appearing volcanic cones are seen on SeaMARC II data between major volcanic centers in the Izu arc at about 31° N, 140° E. No assessment of the economic potential of such areas in arcs has ever been attempted.

The second forearc site we propose is directed toward solving a different set of problems. The forearc graben north of Fukujin seamount is one of the largest grabens in the Mariana arc. Some of the largest seamounts of the arc are situated along the trend of this graben. While the volcanoes are composed of arc lavas, they are situated either parallel to or along strike of the backarc rift axis. It is conceivable that the distribution of these volcanoes is controlled by local tectonic processes of back arc extension. If so, the large graben in the forearc may also be related to back arc rifting processes. It may represent a locus of rifting which has managed to propagate through the arc to some extent. It is clear (data from Izu/Bonin arc and the Coriolis Trough of the New Hebrides) that backarc rifting can occur in the forearc, between the line of active volcanoes and the trench axis, in a given arc system. However, in the case of the Izu/Bonin and Coriolis rift grabens, the tectonic setting is one of incipient rifting, lacking a well-developed magmatic spreading ridge. In the case of the site proposed here, there exists the unusual opportunity to study tectonic processes associated with forearc rifting that may be the arcward extension of a mid-ocean ridge type of backarc spreading center. Some shallow-focus earthquakes have been located in the vicinity of this graben. However, locations for these earthquakes are not well determined by the global seismic network for this region. Fryer, Ambos and Duennebier intend to propose in 1986 an OBS study of this part of the Mariana arc for 1987 or 1988. We would prefer to do this study in conjunction with the drilling of this site if approved, in order to incorporate downhole OBS data with the data from the OBS array we intend to deploy. The downhole data would enable us to determine the structure of the forearc in this region in greater detail. The greater coupling capability of the downhole OBS and its greater sensitivity is required in order to distinguish the variations in anisotropy, which would be expected in this region if propagation of rifting through the arc had occurred. If the graben is fault-controlled or if dikes are associated with it, the extent of this faulting or dike intrusion could be detected by combining data from the downhole instrument with the seafloor array. The objective of such a study would be to determine the extent of forearc fracturing associated with graben formation, to distinguish between volcanigenic and tectonically generated seismic activity, and to examine the extent and distribution, if possible, of dikes associated with Fukujin Seamount.

Sediment history in this graben will record timing of graben formation and the history of volcanism of this portion of the arc, and composition of these sediments would help to determine the possible extent of hydrothermal activity associated with formation of the graben or of mineralization associated with either volcanism at Fukujin Seamount or igneous activity associated with graben formation. The most likely type of mineralization we could expect to be associated with this region is that typical of Koroko type deposits. Much discussion of the formation of this type of deposits has centered around their originating in the backarc environment. If, as in the Izu/Bonin arc and the Coriolis Trough of the New Hebrides, forearc rifting has occurred or is occuring in the Northern Mariana arc, then the possible extent of Koroko type deposits may be much greater than currently anticipated. These deposits may occur in the backarc, the arc, and the forearc environments.

/ ..d Site: Large forearc graben 22°N in the Mariana Arc.

General Objective: Forearc rifting processes.

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..neral Area: Northern Mariana Forearc MF-4
..sition: 22°55'N 143°45'E
..ternate Site:

Thematic Panel interest: Lithoscphere, Tectonics
Regional Panel interest: Western Pacific

..ecific Objectives: To determine the tectonic history of formation of the large graben northeast of Fukujin Seamount. To determine relative timing of formation of this and a smaller graben close by to the south. To examine nature of active tectonic movement in the forearc; to determine composition of the inner forearc basement in a region of suspected low sedimentation (few large arc seamounts nearby). To test the possibility of propagation of backarc spreading rifts through the arc massif by examining the composition of basement material in the rifts, to determine whether hydrothermal activity is associated with rifting. To test the possibility of recent arc magmatism associated with rift formations. (see attached)

..ckground Information:

..egional Data: SeaMARC II sidescan and bathymetry data, gravity, magnetics, seismic reflection.
Seismic profiles: See attached.

Other data: ALVIN Diving will be conducted in vicinity in 1987 additional geophysical data will be collected the. R. Stern and S. Bloomer will provide additional geophysical data in Oct '85
..ite Survey Data - Conducted by: will be acquired.
Date:
Main results: Will have geophysical data, seismic reflection, gravity, magnetics.

..erational Considerations

..ater Depth: (m) 2800 Sed. Thickness: (m) unknown at present Total penetration: (m)

..PC to refusal Double HPC ____ Rotary Drill ____ Single Bit ____ Reentry X

..ture of sediments/rock anticipated:

..eather conditions/window: APR-AUG optimum; MAR-SEPT acceptable

..rritorial jurisdiction: Northern Mariana Territory

..her:

..ecial requirements (Staffing, instrumentation, etc.)

Downhole OBS and OBS array deployed by second ship.

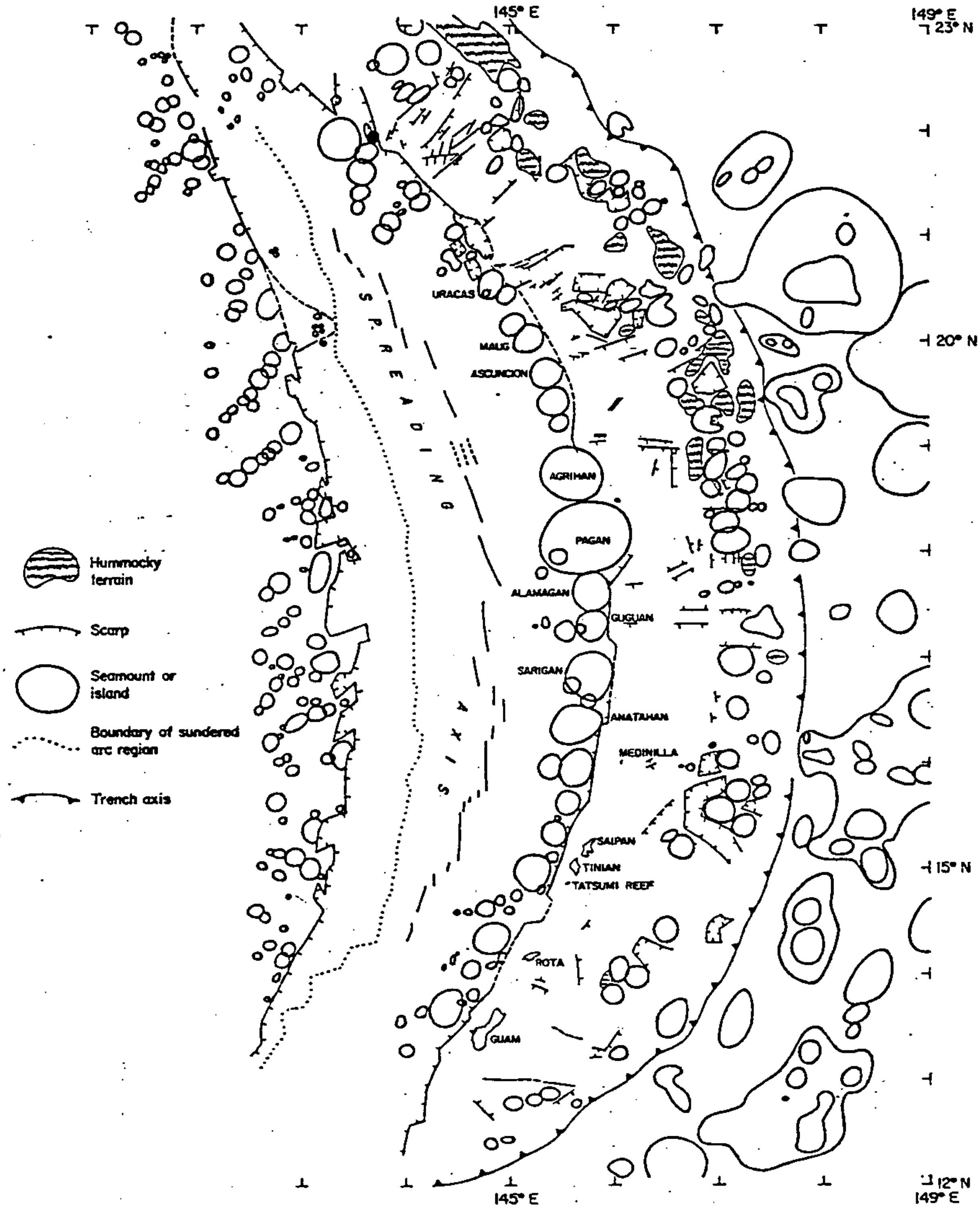
..oponent: P. Fryer, B. Ambos, F. Duennebier

Date submitted to JOIDES Office: July 9, 1985

Rev. 0284

SPECIFIC OBJECTIVES (continued)

To determine the level of seismic activity associated with the rift region. To study fine scale structure of the rift in an attempt to distinguish between propagation of backarc rifting through the arc and fracturing of the arc in response to regional forearc stresses (anisotoropy controlled by dike or fracture orientation). To study the structure of this part of the arc in conjunction with deployment of an OBS array. Very similar objectives could be addressed at the alternate site although no ALVIN studies are planned in this area.


145° E
149° E
23° N
20° N
15° N
12° N
URACAS
MAUG
ASUNCION
AGRIHAN
PAGAN
ALAMAGAN
GUGUAN
SARIGAN
ANATAHAN
MEDINILLA
SAIPAN
TINIAN
TATSUMI REEF
ROTA
GUAM
S P R E A D I N G
A X I S
Hummocky terrain
Scarp
Seamount or island
Boundary of sundered arc region
Trench axis

Proposed Site: small graben near active arc between active submarine volcanoes of the Northern Mariana Arc.

General Area: Northern Mariana Arc MA-5
Position: 21°39'N, 144°16'E
Alternate Site:

General Objective: To determine the nature of basement of the forearc close to the active To determine recent history of forearc rifti

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Thematic Panel interest: Lithosphere, Tectonics
Regional Panel interest: Western Pacific

Specific Objectives: To determine stratigraphy of forearc sediments in region presumed to have a low sedimentation rate (few and small volcanoes). To examine the nature of active tectonic movement in the forearc. To determine the compositions of the forearc basement between arc volcanoes and determine whether forearc fracturing is associated with recent emplacement of igr material. To examine the sedimentologic history of the forearc in a region close to the arc, bu where sedimentation rates are low (few large active seamounts nearby).

Background Information:

Regional Data: SeaMARC II sidescan and bathymetry data, seismic reflection, gravity, magnetic

Seismic profiles: See attached

Other data: Additional geophysical data will be collected by R. Stern and S. Bloomer in Oct.

Site Survey Data - Conducted by: KK83-01-16-04, D. Hussong and P. Fryer
Date: 20 April - 17 May 1983
Main results: Data described above was collected.

Operational Considerations

Water Depth: (m) 2600 m Sed. Thickness: (m) approx. 400m Total penetration: (m) to refusal

HPC _____ Double HPC _____ Rotary Drill _____ Single Bit x Reentry _____

Nature of sediments/rock anticipated: vitric silt and mud, siltstones, pumice, basaltic basement

Weather conditions/window: APR-AUG optimum; MAR-SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent: Patricia Fryer

Date submitted to JOIDES Office: July 12, 198

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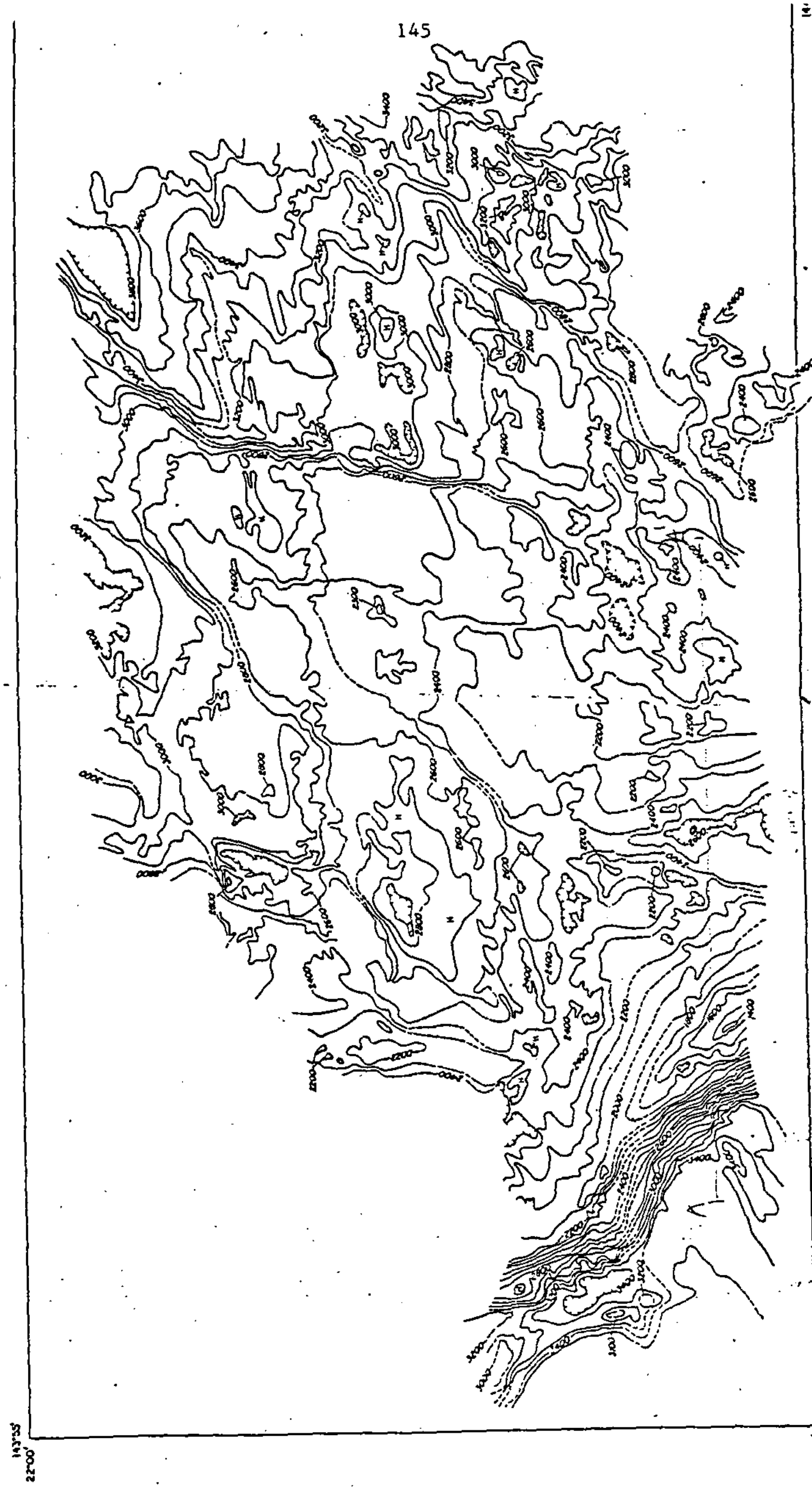

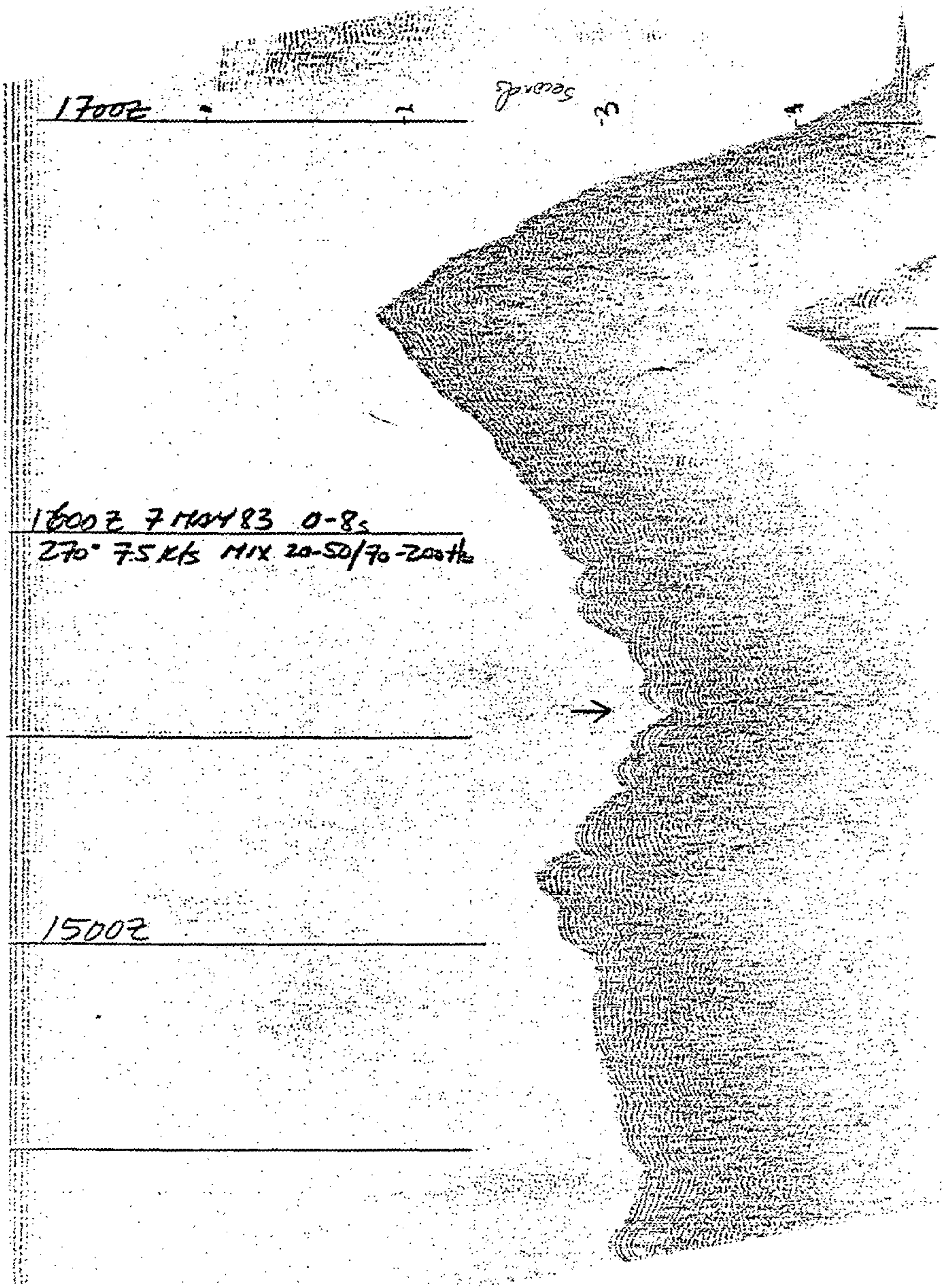
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1
Seconds
3
4
1600Z 7 MAY 83 0-8s
270° 7.5 Kts MIX 20-50/70-200Hz
1500Z

***ODP SITE PROPOSAL SUMMARY FORM***
(Submit 6 copies of mature proposals, 3 copies of preliminary proposals)

| Proposed Site: MA-7 | General Objective: Composition of arc volcanic rocks between arc volcanoes. |
|---|---|
| General Area: N. Mariana arc<br>Position: 144.5°E, 21.2°N (locations 7 & 7B in Figs.)<br>Alternate Site: 144°E, 21.5°N | Thematic Panel interest: LITHP, DMP<br>Regional Panel interest: WPP |



Specific Objectives: 1) To find out if the submerged, deep flanks of an intraoceanic arc volcano are the same composition as, or are different from, the 0.5% of the arc above sea level; 2) to study the lithology, structure, etc. of exclusively submarine arc eruptives; 3) to ascertain deep structure beneath an arc away from major edifices; 4) assorted geothermal objectives.

Background Information (indicate status of data as outlined in the Guidelines):

Regional Geophysical Data:

Seismic profiles: some HIG data near alternate site

Other data: SeaMARC II data near alternate site. Primary site slightly preferable as being most distant from islands and near-sea-level arc volcanoes.

Site Specific Survey Data:

Seismic profiles: Locate sediment ponds, if any, along or near major arc ridge at both primary and alternate sites.

Other Data: Core same, measure heat flow in same. SEABEAM or SeaMARC determination of distribution of lavas, volcano alignment, etc. For such a deep hole, seismic refraction to relate to downhole measurements, etc.

Operational Considerations:

Water Depth: (m) 3,000–3500 m Sed. Thickness: (m) ? Tot. penetration: (m) 0.5–1.5 km

HPC X Double HPC ____ Rotary Drill X Single Bit ____ Reentry X

Nature of sediments/rock anticipated: Arc volcaniclastics, basalts, andesites.

Weather conditions/window: APR–AUG optimum; MAR–SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special Requirements (staffing, instrumentation, etc.):
Hole will have geothermal interest, therefore proper pore-fluid sampling procedures, packer, etc. Oblique seismic experiment or equivalent. Good place for downhole long-term seismometer.

Proponent:
Address & phone number:

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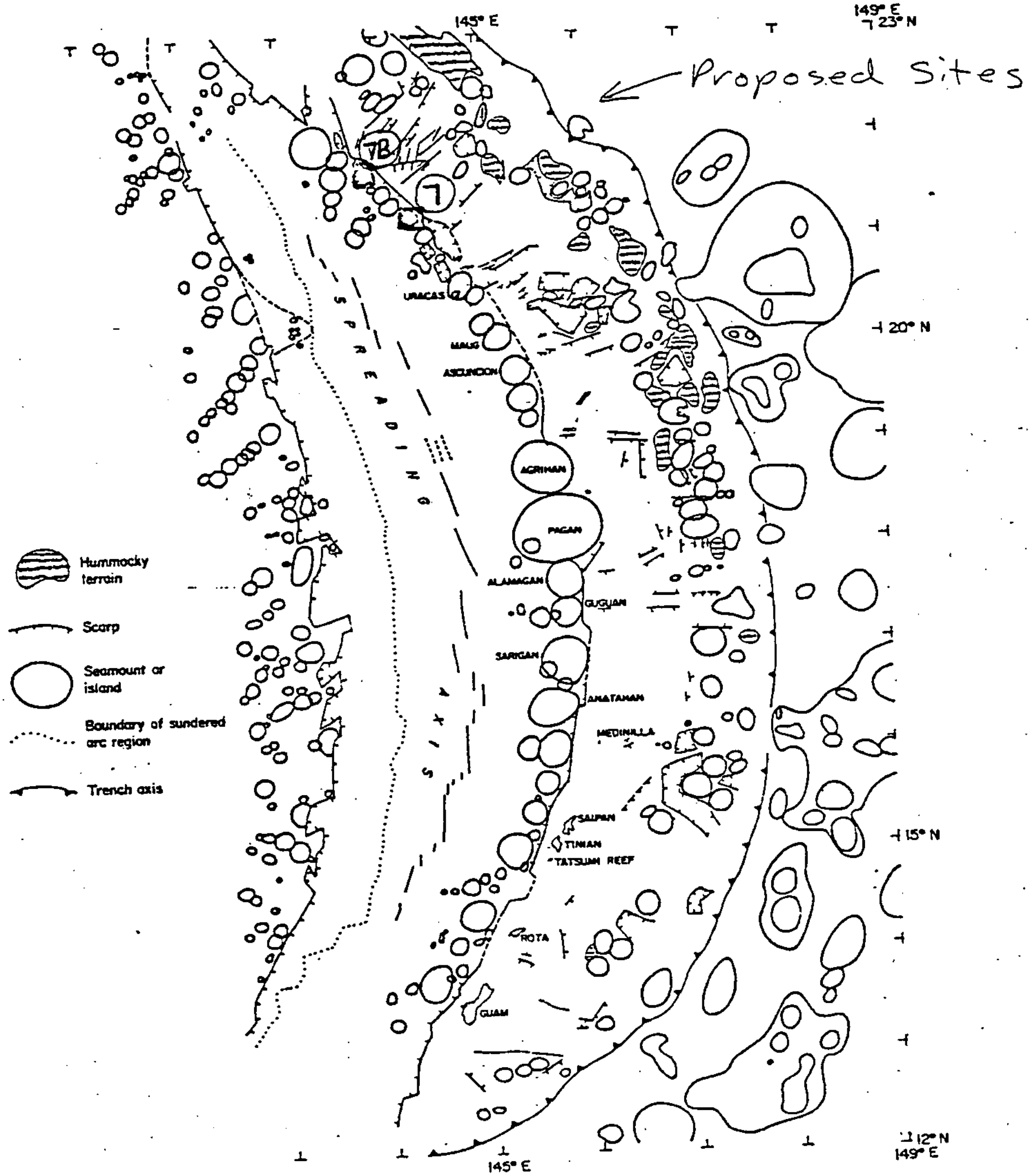
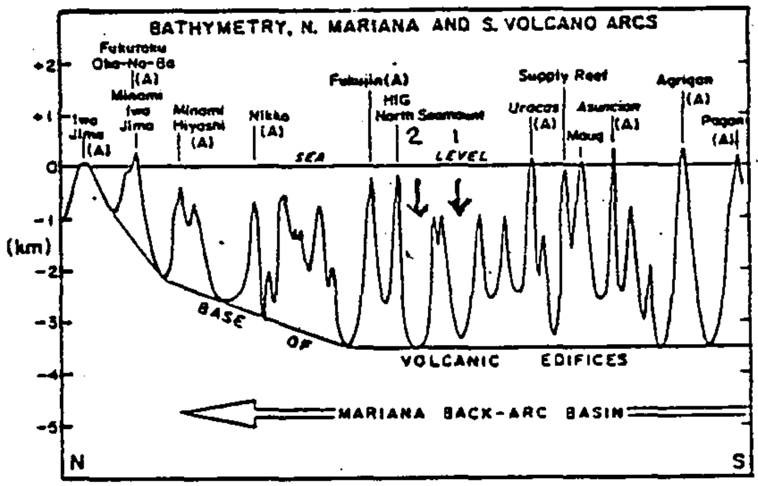
R.J. Stern
Program in Geosciences
U. Texas, Dallas
Richardson, TX 70580

(619) 452-3538
J. Natland
DSDP A-031
Scripps Institution of Oceanography
La Jolla, CA 92093

FOR OFFICE USE:
Date received:
Classification no.:
Panel allocation:


145° E
149° E
23° N
Proposed Sites
7B
7
URACAS
MAUG
ASUNCION
S P R E A D I N G
A X I S
AGRIHAN
PAGAN
ALAMAGAN
GUGUAN
SARIGAN
ANATAHAN
MEDINILLA
SAIPAN
TINIAN
TATSUMI REEF
ROTA
GUAM
20° N
15° N
12° N
145° E
149° E
Hummocky terrain
Scarp
Seamount or island
Boundary of sundered arc region
Trench axis


BATHYMETRY, N. MARIANA AND S. VOLCANO ARCS
Fukutoku Oka-No-Ba (A)
Minami Iwo Jima
Iwo Jima (A)
Minami Hiyoshi (A)
Nikko (A)
Fukujin (A)
HIG North Seamount
2
1
Supply Reef
Uracas (A)
Maug
Asuncion (A)
Agrigan (A)
Pagan (A)
SEA LEVEL
+2
+1
0
-1
(km)
-2
-3
-4
-5
BASE OF VOLCANIC EDIFICES
MARIANA BACK-ARC BASIN
N
S

# *SITE M-8*

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*Department of Geological Sciences*

*University of Illinois at Chicago*

## *Introduction*

According to a diachronous spreading model for the Mariana Trough, the proposed site represents the locus of imminent rifting. Site M-8 is located where the inactive West Mariana and active Mariana ridges join to form the southern end of the Iwo Jima Ridge (Fig. 1). As delineated by the 3 km isobath, the northern tip of the Mariana Trough lies 125 km east-southeast of the site. Deep basement penetration (1-2 km) at this site should yield stratigraphic evidence for the transition from arc to backarc magmatic regimes, and a record of vertical movements and subaerial arc volcanism. Major objectives would be to seek chronologic geochemical patterns analogous to those at propagating mid-ocean rifts, and to study the question of synchronous versus asynchronous arc/backarc activity.

To avoid the risks of drilling 'pure arc' or 'pure backarc' crust, site surveys (surface heat flow, seismic, bathymetric, etc.) should aim to characterize and select transitional crust. If successful, drilling this site should provide insight regarding the genetic conditions for many ophiolite lava successions.

## *Location*

The proposed site would lie in the area between Lats. 23.5-24°N and Longs. 141-141.5°E, in water 1 to 1.5 km deep.

*Scientific Rationale*

Drilling this site would definitively test the hypothesis that the Mariana Trough is propagating northward [see pre-conference contributions by Flower and Rodolfo, and by Bob Stern. The same hypothesis is a basis for the cluster of more southerly sites M-4, -5, -6, and -7.] According to the hypothesis, deep penetration at M-8 should provide a unique section through pre-sundered crust, together with the magmatic products of incipient spreading. These products may take the form of eruptives and/or intrusives of relatively unfractionated zero-age basalt. Pre-sundered crust consisting of arc tholeiite, andesite, boninite, etc. could represent cycles of arc activity possibly ranging as far back as the Eocene [cf. Palau-Kyushu ridge, Guam, Saipan].

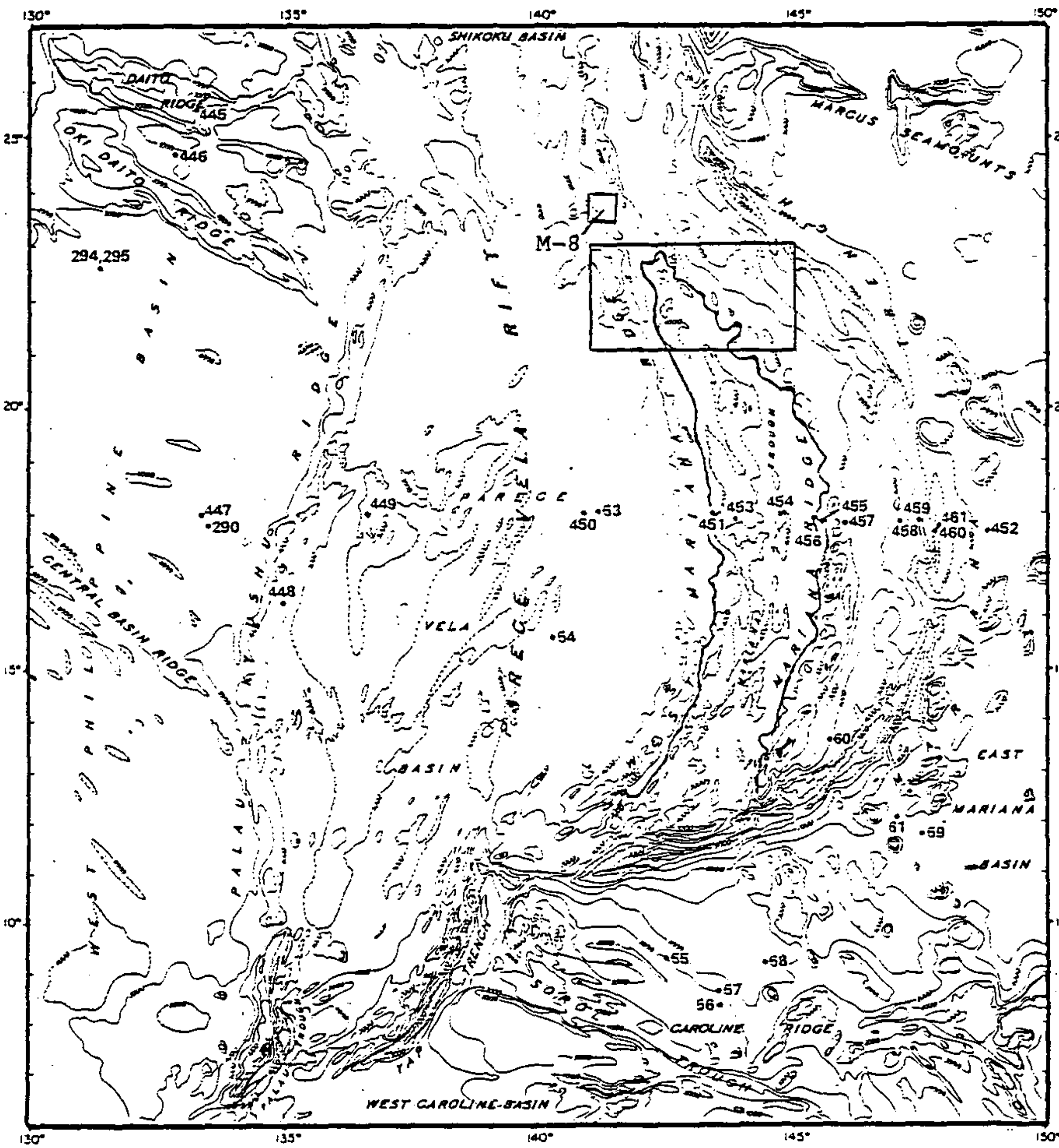
Complex lithologic and age relationships in basement should yield critical geochemical and geophysical data. Petrologic-geochemical studies should monitor changes in mantle-source character (eg. 'refractory' vs 'fertile'; possible metasomatism), magma system type ('open' vs. 'closed'), and changes in magmatic volatile content. Geophysical logging, downhole heat-flow, and seismic experiments should characterize the predicted transitional crust type, and the thermal conditions of incipient arc sundering. Magnetic polarity changes and paleo-inclinations should help distinguish eruptives and intrusives, and monitor tectonic deformations.

M-8 is a shallow site, well above CCD, and is probably accumulating calcareous oozes similar to the surface oozes and chalks cored at DSDP Site 451. At the very least, the M-8 sediments should yield an excellent biostratigraphic record, and a good record of paleodepths from benthic foraminifera. [Janet Haggerty's conference presentation is particularly relevant in this respect.] Hence the site should document and measure rates of vertical uplift from the postulated incipient rifting.

The sedimentary column at M-8 may well record events as far back as the Parece Vela spreading of middle Oligocene to early Miocene time. This may enable us to measure several earlier vertical motions of regional extent, including subsidences as well as uplifts, documented in Marianas exposures and in DSDP cores, e.g. (a) uplift immediately preceeding and accompanying initial Parece Vela Basin spreading during Middle Oligocene time; (b) regional subsidence during the (early Miocene) mature phases of this earlier backarc-spreading event; (c) uplift in the middle Miocene, and (d) subsidence in the late Miocene. Regardless of how far back the sedimentary record may reach, the evidence for vertical motions would have major tectonic significance for the whole Mariana region.

The site should provide a good tephrochronologic record of subaerial frontal-arc volcanism. Its crestal position, physiographic isolation, and distance from the active Mariana volcanoes should ensure that the tephra record span a long time interval and consist of discrete ashfall layers that are easy to date. It will, moreover, avoid the problems encountered on Leg 60 sites, where the volcaniclastic record was swamped by coarse, unlithified materials that in large part may have been epiclastic derivatives of quiescent volcanic terranes. The geochemistry of the tephras from this site should reflect the changes in frontal-arc volcanism accompanying the present, and possibly earlier sundering events. Stratigraphic correlation of the tephra with those of other DSDP and ODP sites would be valuable documentation of diachronic arc volcanism. [See pre-conference statement from Jim Natland.]

FIGURE 1. Location of proposed Site M-8 (small square). The larger rectangle contains proposed sites M-4, M-5, M-6, and M-7 [see figure from R. Stern's pre-conference contribution]. The 3-km isobath has been arbitrarily chosen and darkened to outline the Mariana Trough. Modified from Langseth and Mrozowski, 1980 (DSDP Vol. 59, p. 488).



sed Site: M-8: southern end of Iwo Jima Ridge

General Objective: Diachronous backarc spread of Mariana Trough; frontal-arc tephrochro logy.

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Thematic Panel interest: LITHP, SOHP
Regional Panel interest: Western Pacific

eneral Area: Philippine Sea
osition: Lats. 23.5-24.0°N
~~lternate Site:~~ Longs. 141.0-141.5°E

pecific Objectives:
1. Transition from arc to backarc magmatic activity
2. Thermal regime of incipient backarc rifting
3. Magmatic expression of rift propagation
4. Sedimentologic record of vertical tectonism
5. Tephrochronology of arc volcanism

ackground Information:
Regional Data:
Seismic profiles:

Other data:

Site Survey Data - Conducted by:
Date:
Main results:

perational Considerations

ater Depth: (m) 1-1.5 km  Sed. Thickness: (m) unknown  Total penetration: (m) 1-2 km

IPC X  Double HPC ____  Rotary Drill X  Single Bit ____  Reentry X

ature of sediments/rock anticipated: Calcareous oozes and chalks with airfall tephra and other volcaniclastics; arc tholeiite, andesite, boninite.
eather conditions/window: Period of major storms is from July to November.

erritorial jurisdiction:

ther:

pecial requirements (Staffing, instrumentation, etc.)

roponent: M.F.J. Flower and K.S. Rodolfo
Department of Geological Sciences
University of Illinois at Chicago

Date submitted to JOIDES Office:

Rev. 028

# PROSPECTS FOR GEOTHERMAL DRILLING IN ISLAND ARCS AND BACKARC BASINS

## Introduction

A major emphasis of ocean-crust drilling in the past has been to understand geothermal processes on the sea floor. Circulation of seawater in the crust is presumed to be the principal agent in the consolidation of magmas and cooling of the lithosphere. The elevation of the sea floor, patterns of heat flow, and the generation of polymetallic sulfides and metalliferous sediments are all aspects of circulation of seawater in the ocean crust.

This is a preliminary prospectus concerning the potential for geothermal drilling in island arcs and backarc basins when JOIDES RESOLUTION leaves the Indian Ocean for the western Pacific in a few years time. Island arcs and backarc basins are logical places to carry out drilling with geothermal or hydrogeological objectives. Several of the backarc basins in the western Pacific contain actively spreading ridges, many arc volcanoes are submerged or have submerged satellitic vents, and in some places arc volcanoes are built out well toward the spreading centers of the backarc basins. Pyroclastic debris shed from the volcanoes forms aprons which can lap even further toward the backarc spreading ridges, thus potentially modifying patterns of seawater circulation. Finally, forearc regions offer quite a different type of seawater-circulation system, one related to dewatering of subducting ocean crust and sediments. All of these regions therefore offer enticing targets for studying flow of water in various types of crust, and the influence of that water in cooling that crust and modifying the compositions of rocks.

## Background: Geothermal Drilling in the Principal Ocean Basins

Through drilling, we have been able to explore several more-or-less idealized examples of geothermal systems in the ocean crust. These are 1) a comparatively "hot" area of off-axis seawater circulation with thin sediment cover, namely the Galapagos Mounds hydrothermal field; 2) a more thickly sedimented area, still fairly "hot", but where measured heat flow is uniform and matches that predicted for conductive cooling of the lithosphere, namely Hole 504B near the Costa Rica Rift; 3) an area of recent rifting, with high heat flow, but rapid influx of terrigenous sediment, namely the Guaymas Basin in the Gulf of California; and 4) old ocean crust in the western North Atlantic, where low-temperature, oxidative alteration prevailed at a surprisingly early stage in the history of the crust.

The most dramatic manifestations of geothermal processes in the oceans, the hot-smoker fields at axial regions of the East Pacific Rise and Galapagos Rift, have until recently been impossible to approach through drilling because of the inability to spud into bare rock. With bare-rock drilling capability near at hand, however, plans are proceeding for drilling the axial regions of spreading ridges, and particularly a high-temperature vent area of the East Pacific Rise. The new spud-in capability will allow direct sampling of circulating fluids in the crust above presumed axial magma chambers, monitoring of seismicity related to movement of magmas (and heated seawater), and carrying out of precisely controled seismic refraction experiments to determine magma-chamber size, location and shape.

This capability, and the types of objectives that can be approached with it, need to be factored into planning for drilling of island arcs and backarc basins in the western Pacific.

Contrasts Between Geothermal Systems of Major Spreading Ridges, Island Arcs, and Backarc Basins

Space here is too limited to provided a detailed, and fully referenced, discussion on comparisons between seafloor geothermal systems in the normal ocean crust and those of arcs and backarc basins. At this stage, it is sufficient to note that all combinations of exploration techniques (submersible, deep-tow, dredging, ANGUS, drilling, etc.) have established the following.

In the open oceans, seafloor geothermal activity and the formation of metalliferous deposits is closely related to the size, shape, depth, and persistence of magma chambers, whether located at spreading ridges or within seamounts. We have managed to study an idealized succession of high- to low-temperature geothermal phenomena and relate these phenomena to the general cooling history of the ocean crust. High-temperavents and associated metalliferous deposits (including sulfides) are almost exclusively restricted in occurrence to active rift zones immediately atop axial volcanic ridges, for example at the East Pacific Rise. The metalliferous deposits formed here must eventually become buried with later lava flows, and come to reside near the base of the extrusive portion of the crust (e.g. the metalliferous stockwork in the dike-pillow transition zone of Hole 504B; Honnorez et al., 1985). Those later lava flows in turn are subjected to lower temperature stages of alteration, often themselves characterized by vigorous flux of formation fluids. However, so far as is known, only Fe-Mn oxyhydroxides and clay minerals, such as are found at the Galapagos Mounds field or more typically in basal sediments at DSDP holes, form in such circumstances. The combination of lithospheric cooling, reduction of the porosity of the uppermost crust (by means of collapse of voids and veining with secondary minerals), and capping with sediments bring to a halt geothermal circulation in the ocean crust, and any associated formation of metalliferous minerals.

In island-arc systems, a critical role in the circulation of seawater in the crust, and the formation of metalliferous deposits, must be assigned to the wide volcaniclastic aprons which flank arc volcanoes on both backarc and forearc crustal segments. In backarc basins, these will greatly modify the idealized sequence found so generally in the ocean crust. The geometry of heat sources will be less important than the fault structure affecting the aprons and underlying crust. Thus formation fluids heated either in the course of consolidation and cooling of backarc crust, or of arc volcanoes, will find no route to the sea floor through the impermeable sediments except along faults which break the impermeable sediment seal near the arc volcanoes and elsewhere. Comparatively high-temperature forms of alteration will characterize the uppermost crust in such circumstances, and metalliferous deposits will be selectively concentrated at structural transitions between spreading-types of crust (backarc or forearc), arc volcanoes, and the arc-derived sediment prisms. These relations are demonstrated in a minor way by drilling already carried out at Sites 453 and 456 in the Mariana Trough (Hussong, Uyeda et al, 1982, and chapters therein). High-temperature fluid flux, and associated alteration and deposition of minerals, will thus tend to occur favorably at high levels in, or in materials deposited atop, the forearc or backarc crust, as for example found in many ophiolites (e.g. Samail; Alabaster and Pearce, 1985). Where arc volcanoes and centers of backarc spreading are very close together, and where volcaniclastic sediment deposition nearly buries the latter, the extreme of high-level crustal alteration, and focusing of circulating fluids along fault zones can take place. This was probably an important factor in the formation of the Koroku deposits of western Japan during a narrow time interval in the Miocene, at a time of rapid opening of the Sea of Japan (e.g. Sillitoe, 1982).

The potential return on geothermal drilling in island-arcs and backarc basins is thus very high, provided such drilling occurs in geothermal systems differing from, thus not duplicating, those we have studied at the major spreading ridges. With this proviso, we should be able to add to conceptions of geothermal processes we have so far obtained by studying the major spreading ridges.

Some Objectives of Geothermal Drilling in Arc and Backarc Systems

It is too early to make a comprehensive list of objectives for geothermal drilling in island arcs and backarc basins; detailed planning is required for this. We can, however, summarize some of the important rationales for such drilling,

From a petrological perspective, an important problem is the possible involvement of fluids and entrained dissolved constituents derived from subducted materials in arc and backarc magmas, or their melt sources. Ideally, one perhaps would like to consider a transect within an individual arc and backarc system, where a trench-slope forearc region is drilled, to study hydrogeological processes related to initial dehydration of subducted crust and sediments; an active arc volcano is drilled, to study the arc portion of the system; and an axial spreading center in a backarc basin is drilled, to assess differences between it and the arc volcano. Here, an important reason for drilling would be sampling of fugitive constituents in pore fluids within sediments, or formation fluids within basement. Such constituents are not always present even in minor amounts in fresh lavas (let alone altered rock), but careful geochemical studies of fluids from boreholes in continental volcanic centers ave recently allowed discrimination of "mantle" versus "meteoric" components in some cases (e.g. Smith + Kennedy, 1985). A similar approach should be fruitful in submerged arc and backarc geothermal systems.

Practically, however, an idealized transect across a single arc system might not be feasible, either because of time constraints, or lack of appropriate targets. Other objectives for geothermal drilling might prove more attractive. However, at least in a hypothetical sense, the concept of a transect can be retained, as long as all three structural elements of an arc system - the forearc, an arc volcano, and a backarc basin, are targeted for this type of exercise somewhere. This may be a better way to approach it than by rigidly insisting that all three be drilled in one arc system.

From the perspective that arc volcanoes and aprons modify circulation patterns of seawater in the crust, additional types of drilling targets suggest themselves. A program on a youthful, ideally active, arc volcano, plus its flanking sediment apron, would establish the general properties of such structures in relation to circulating fluids. This drilling might require a bare-rock spud in capability; alternatively, an older, inactive seamount with sufficient sediment on it could be targeted to study the final consequences of high-level seawater circulation in an arc edifice. Here the objective would be altered rock, and ephemeral constituents in pore fluids would probably be long gone.

Backarc ridges with potential complications introduced by proximity of arc volcanoes (and arc-derived sediment aprons) are also likely candidates for geothermal exploration through drilling. Here, the extreme case of a very narrow backarc basin might be the most attractive, for the reasons outlined above. Probably it would be valuable to contrast this with a more isolated backarc spreading-ridge segment. Where sediments occur, of course, bare-rock spud in can be avoided. Where bare-rock drilling is attempted on a backarc spreading ridge, however, other aspects of the crustal generation process can be explored, for example by use of borehole seismometers or a long-term installation in the hole. If sediments lap onto the spreading ridge, though, such an installation can be contemplated without the compli-

***ODP SITE PROPOSAL SUMMARY FORM***
(Submit 6 copies of mature proposals, 3 copies of preliminary proposals)

Proposed Site: M-9

General Area: CENTRAL MARIANA TROUGH
Position: 145°E, 18°N
Alternate Site: similar locations between 14° and 20° N

General Objective: To study geothermal processes at an active, as-yet unsedimented backarc spreading ridge

Thematic Panel interest: LITHP, Dwnhole Msrmt
Regional Panel interest: WPP

Specific Objectives: To study the hydrology, pore-fluid chemistry, structure, physical properties, etc. of backarc crust in an area of active hydrothermal activity. Relationship of such processes to subjacent magma chamber, if such exists. Sample fluid contributions from diverse backarc, arc, mantle sources.

Background Information (indicate status of data as outlined in the Guidelines):
Regional Geophysical Data:
Seismic profiles: Pre Leg 60 Site surveys; SCAN Expedition surveys, etc. None too relevant, since this proposal is for a bare-rock site.

Other data:

Site Specific Survey Data:
Seismic profiles:

Other Data: seismic refraction for crustal structure in area of target; heat-flow distribution in nearby sediment ponds; near-bottom observations from projected ALVIN studies.

Operational Considerations:

Water Depth: (m) ca. 3500 Sed. Thickness: (m) 0 Tot. penetration: (m) 100 m. min; 500 m. bett

HPC ____ Double HPC ____ Rotary Drill ____ Single Bit ____ Reentry x (bare-rock

Nature of sediments/rock anticipated: basalts, variously altered; interbedded (?) volca clastic sediments (e.g. compare Site 454)
Weather conditions/window: APR-AUG optimum; MAR-SEPT. acceptable

Territorial jurisdiction: Northern Mariana Territory

Other:

Special Requirements (staffing, instrumentation, etc.):

Full-court press with logging, resistivity, downhole seismics, pore-fluid sampling, packer, long-term instrument installations, etc.

Proponent: J. Natland
Address & phone number: DSDP A-031
Scripps Institution of Oceanography
La Jolla, CA 92093
(619) 452-3538

FOR OFFICE USE:
Date received:
Classification no.:
Panel allocation:

*****ODP SITE PROPOSAL SUMMARY FORM*****

(Submit 6 copies of mature proposals, 3 copies of preliminary proposals)

**Proposed Site:** M-10

**General Objective:** Understanding geothermal processes in a backarc basin

**General Area:** Northern Mariana Trough
**Position:** 143°E, 21.5°N
**Alternate Site:** near DSDP 456, Mariana Trough 18°N transect, Leg 60

**Thematic Panel interest:** LITHP
**Regional Panel interest:** WPP

**Specific Objectives:** To determine the effects of partial burial of an active backarc basin with volcaniclastic sediments on the circulation of high-temperature fluids in and through the crust. Can be carried out in conjunction with petrologic, tectonic objectives of proposal by Fryer, Stern, and Bloomer.

**Background Information** (indicate status of data as outlined in the Guidelines):

**Regional Geophysical Data:**

**Seismic profiles:** Summary and profile given in proposal of Fryer, Stern, and Bloomer. Probably relevant profiles are also at SIO Data Center (SCAN Expedition).

**Other data:** SEA MARC II coverage of most of this area, showing distribution of open lava fields and areas covered with sediments; some seismic reflection, gravity magnetics, obtained 1984.

**Site Specific Survey Data:**

**Seismic profiles:** Sediment thicknesses need to be determined from existing profiles, and faults through sediments located.

**Other Data:** Should have a careful heat-flow survey, piston-coring to obtain surficial pore fluids.

**Operational Considerations:**

Water Depth: (m) 3450 Sed. Thickness: (m) up to 400 m Tot. penetration: (m) ______

HPC X Double HPC ______ Rotary Drill X Single Bit X Reentry ______

Nature of sediments/rock anticipated: volcaniclastic muds and sands above basalt

Weather conditions/window: APR-AUG optimum; MAR-SEPT acceptable

Territorial jurisdiction: Northern Mariana Territory

Other: As at Site 456, probably several holes near and away from faults, within a heat-flow survey grid will be necessary.

**Special Requirements** (staffing, instrumentation, etc.):

Packer, pore-fluid sampling devices, downhole heat flow, possibly high-temperature logging tools.

Proponent: J. Natland
Address & phone number: DSDP A-031, Scripps Institution of Oceanography, La Jolla, CA 92093
(619) 452-3538

FOR OFFICE USE:
Date received:
Classification no.:
Panel allocation:

# PROPOSAL FOR ODP SITES IN THE BONIN REGION ADDRESSING PROBLEMS OF INTRA-OCEANIC ARC-TRENCH DEVELOPMENT

## Scientific Objectives

1) Arc Rifting: Nascent Backarc Basins

Tectono-stratigraphic evolution of syn-rift passive margins in an arc environment. Major questions concern:

- models of stretching /subsidence.
- early rift volcanism and sedimentation.
- hydrogeology and formation of Kuroko-type massive sulphides.

2) Arc/Forearc Magmatism, Structure, Stratigraphy and Vertical Tectonics

Magmatism/Structure (basement objectives)

- initial stages of arc volcanism
- spatial and temporal migration of volcanism and changes in chemistry
- formation of 200 km wide arc-type forearc massif
- origin of boninites
- crustal structure and evolution of forearc ophiolites
- microstructures associated with forearc deformation

Stratigraphy/Tectonics

- timing of arc volcanism (tephrachronology)
- record and chemistry of explosive activity and pyroclastic flow deposits
- paleomagnetics: rotated (and exotic?) terrains
- development of the frontal arc forearc basin and outer-arc high
- differential uplift-subsidence across the forearc
- flexural loading by arc volcanoes and by coupling with the subducting plate

3) Outer Forearc "Diapirism"

- emplacement mechanism, petrology and structure of domal bodies of chloritised/serpentinised mafics and ultramafics. Relation to some alpine-type ultramafics.
- hydrogeology through outer forearc basement.
- timing of emplacement: ongoing, dormant, pre/post canyon formation?

Proposed Site: BON 1; Sumisu Rift

General Area: BONINS
Position: 30°55' N, 139°53' E
Alternate Site:

General Objective:
Rifting of an intra-oceanic island arc
- precursor to back-arc basin formation

Thematic Panel interest: Tectonics, Lithosphere, SOHP
Regional Panel interest: Western Pacific

Specific Objectives: To drill the inner rift graben to determine:
1. The nature of rift basement and extent of crustal stretching.
2. The age of initial rifting and history of subsidence.
3. The type of early rift volcanism and sedimentation.
4. Hydrothermal processes in a modern Kuroko-type setting.

Background Information:
Regional Data:
Seismic profiles: MCS by Japan National Oil Co., single channel by Geological Survey of Japan, Hydrographic Office of Japan, and Hawaii Institute of Geophysics.
Other data: SeaMARC II sidescan, SASS bathymetry, 2-D one-mile grid of 3.5 kHz, magnetics, gravity; abundant dredge and core samples, some heat flow and bottom camera data.
Site Survey Data - Conducted by: Geological Survey of Japan and Hawaii Institute of Geophysics, 1984.
Date: Geological Survey of Japan to collect MCS line in August 1985; ALVIN dives Spring, 1987.
Main results:

Operational Considerations

Water Depth: (m) 2270 Sed. Thickness: (m) 850 Total penetration: (m) 870

HPC x Double HPC ____ Rotary Drill x Single Bit ____ Reentry x

Nature of sediments/rock anticipated: Volcaniclastics and hemipelagics / basalts or andesites.

Weather conditions/window: Good spring through fall.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)
Re-entry required for long-term monitoring of (potential) hydrothermal fluids.

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
August, 1985

Rev. 0284

Proposed Site: BON 2; Sumisu Rift

General Area: BONINS
Position: 30°55'N, 140°00' E
Alternate Site:

General Objective:
Rifting of an intra-oceanic island arc
- precursor to back-arc basin formation

Thematic Panel interest: Tectonics, Lithosphere, SOHP
Regional Panel interest: Western Pacific

Specific Objectives: To drill the eastern horst block to determine:
1. The nature of arc basement between major arc volcanoes.
2. The history of vertical motion (compared to adjacent graben).
3. Pre-recent arc stratigraphy.

(The site is topographically isolated from recent submarine volcaniclastic flow deposits.)

Background Information:
Regional Data:
Seismic profiles: MCS by Japan National Oil Co., single channel by Geological Survey of Japa Hydrographic Office of Japan, and Hawaii Institute of Geophysics.
Other data: SeaMARC II sidescan, SASS bathymetry, 2-D one-mile grid of 3.5 kHz, magnetics, gravity; abundant dredge and core samples, some heat flow and bottom camera dat
Site Survey Data - Conducted by: Geological Survey of Japan and Hawaii Inst. of Geophysics, 1984.
Date: Geological Survey of Japan to collect MCS line in Aug., 1985; ALVIN dives Spring, 1987
Main results:

Operational Considerations

Water Depth: (m) 1100 Sed. Thickness: (m) 500 Total penetration: (m) 700

HPC x Double HPC ____ Rotary Drill x Single Bit x Reentry ____

Nature of sediments/rock anticipated: Volcaniclastics and hemipelagics/ basalts or andesites.

Weather conditions/window: Good spring through fall.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
August, 1985

Rev. 0284

Proposed Site: BON 3: Shinkurose Ridge

General Area: BONINS
Position: 31°32' N, 140°17.2' E
Alternate Site:

General Objective:
Intra-oceanic island arc/forearc development.

Thematic Panel interest: Tectonics, Lithosphere
Regional Panel interest: Western Pacific

Specific Objectives: To drill the Sumisu frontal arc to determine:

1. The age, petrochemistry and initial topography (w.r.t. forearc) of the igneous basement.
2. The history of vertical tectonics and arc volcanism (especially with regard to Shikoku Basin opening and recent rifting).
3. Paleolatitude through time.

Background Information:
Regional Data:
Seismic profiles: MCS by Japan National Oil Co., single channel by Geological Survey of Japan.

Other data: SASS bathymetry; magnetics, gravity, core and dredge samples.

Site Survey Data - Conducted by: To be done
Date:
Main results: (Requires crossing seismic line.)

Operational Considerations

Water Depth: (m) 1250 Sed. Thickness: (m) 600 Total penetration: (m) 650

HPC x Double HPC ___ Rotary Drill x Single Bit x Reentry ___

Nature of sediments/rock anticipated: Volcaniclastics and hemipelagics / basalts or andesites

Weather conditions/window: Good spring through fall.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
August, 1985

Rev. 0284

| Proposed Site: BON 4A; Inner Forearc Basin | General Objective: Intra-oceanic island arc/forearc development |
|---|---|
| General Area: BONINS<br>Position: 32°26.5' N, 140°22.5' E<br>Alternate Site: | Thematic Panel interest: Tectonics, Lithosphere, S(<br>Regional Panel interest: Western Pacific |

Specific Objectives: To drill the upper section of the thick inner forearc basin to determine:

1. The tephrachronology of arc volcanism, and the record and chemistry of explosive activ: and pyroclastic flow deposits.
2. The vertical tectonics of the inner forearc basin relative to the frontal arc highs al( strike, and the rest of the forearc across strike. Flexure of the inner forearc due t( volcano loading and/or Shikoku Basin rifting?
3. Sedimentology of forearc deposits with respect to distance from volcanoes, canyon-form: processes, paleoceanography.

Background Information:

Regional Data:

Seismic profiles: MCS by Japan National Oil Company
Single channel by Geological Survey of Japan and Hawaii Institute of Geophy

Other data: SeaMARC II sidescan, SASS bathymetry, 3.5 kHz, magnetics, gravity.

Site Survey Data - Conducted by: 1984 HIG SeaMARC II survey
Date: Requires crossing MCS lines
Main results:

Operational Considerations

Water Depth: (m) 1820 Sed. Thickness: (m) >1500 Total penetration: (m) 700

HPC x Double HPC ____ Rotary Drill x Single Bit x Reentry ____

Nature of sediments/rock anticipated: Volcanoclastics and hemipelagics

Weather conditions/window: Good spring through fall

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent: Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office: August, 1985

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Proposed Site: BON 4B; Inner Forearc Basin

General Area: BONINS
Position: 32°28.6' N, 140°22.5' E
Alternate Site:

General Objective:
Intra-oceanic island arc/forearc development

Thematic Panel interest: Tectonics, Lithosphere, SOHP
Regional Panel interest: Western Pacific

Specific Objectives: To drill the inner forearc basin lower section to determine:

1. The tephrachronology of arc volcanism, and the record and chemistry of explosive activity and pyroclastic flow deposits.
2. The vertical tectonics of the inner forearc basin relative to the frontal arc highs along strike, and the rest of the forearc across strike. Flexure of the inner forearc due to volcano loading and/or Shikoku Basin rifting?
3. Sedimentology of forearc deposits with respect to distance from volcanoes, canyon-forming processes, paleoceanography.
4. Age and petrochemistry of the igneous basement

(No previous oceanic forearc drilling has sampled the deep inner forearc sediments and basement)

Background Information:

Regional Data:

Seismic profiles: MCS by Japan National Oil Company
Single channel by Geological Survey of Japan and Hawaii Inst. of Geophysics

Other data: SeaMARC II sidescan, SASS bathymetry, 3.5 kHz, magnetics, gravity

Site Survey Data - Conducted by: 1984 HIG SeaMARC II survey
Date: Requires crossing MCS lines
Main results: Canyon provides access to deep section

Operational Considerations

Water Depth: (m) 2420 Sed. Thickness: (m) 950 Total penetration: (m) 1000

HPC x Double HPC ____ Rotary Drill x Single Bit x Reentry ____

Nature of sediments/rock anticipated: Volcanoclastics and hemipelagics/basalts and andesites.

Weather conditions/window: Good spring through fall

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
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Proposed Site: BON 5A; Forearc Basin

General Area: BONINS
Position: 32°26' N, 140°47' E
Alternate Site:

General Objective:
Intra-oceanic island arc/forearc developme

Thematic Panel interest: Tectonics, SOHP
Regional Panel interest: Western Pacific

Specific Objectives: To drill the forearc basin upper sedimentary section to determine:

1. The tephrachronology of arc volcanism and chemistry of explosive activity.
2. The vertical tectonics of the forearc basin relative to surrounding structural highs.
3. The microstructures associated with forearc basin deformation (seismic lines suggest dominantly normal faulting).
4. The rotation and paleolatitude of the forearc through time.
5. The sedimentology of forearc deposits with respect to volcano distance, canyon-forming processes, and paleoceanography.

Background Information:
Regional Data:
Seismic profiles: MCS by Japan National Oil Company
Single channel by Geological Survey of Japan and Hawaii Institute of Geoph
Other data: SeaMARC II sidescan, SASS bathymetry, 3.5 kHz, magnetics, gravity, piston cc

Site Survey Data - Conducted by: 1978 JNOC MCS line, 1984 HIG SeaMARC II survey
Date: May require crossing MCS line
Main results:

Operational Considerations

Water Depth: (m) 2700 Sed. Thickness: (m) > 1500 Total penetration: (m) 950

HPC x Double HPC ____ Rotary Drill x Single Bit x Reentry ____

Nature of sediments/rock anticipated: Hemipelagics and volcanoclastics (cf Mariana site 458)

Weather conditions/window: Good spring through fall

Territorial jurisdiction: Japan

Other: Rather than one deep hole, a series of shorter HPC holes down the nearby canyon wa could provide oriented cores for the complete section (for paleomagnetic studies o rotated forearcs).

Special requirements (Staffing, instrumentation, etc.)

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
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Rev. 0284

Proposed Site: BON 5B; Forearc Basin

General Area: BONINS
Position: 32°23' N, 140°48' E
Alternate Site:

General Objective:
Intra-oceanic island arc/forearc dvelopment

Thematic Panel interest: Tectonics, Lithosphere, SOHP
Regional Panel interest: Western Pacific

Specific Objectives: To drill the forearc basin lower sedimentary section to determine:

1. The age and petrochemistry of the igneous basement (addressing questions regarding the initial stages of arc volcanism, origin of boninites, migration of arc/forearc volcanism, formation of 200 km-wide arc-type forearc, forearc ophiolites).
2. The tephrachronology of arc volcanism and chemistry of explosive activity.
3. The vertical tectonics of the forearc basin relative to surrounding structural highs.
4. The microstructures associated with forearc basin deformation.
5. Rotation and paleolatitude of the forearc through time.

Background Information:
Regional Data:
Seismic profiles: MCS by Japan National Oil Company
Single channel by Geological Survey of Japan and Hawaii Institute of Geophysic
Other data: SeaMARC II sidescan, SASS bathymetry, 3.5 kHz, magnetics, gravity, piston cores

Site Survey Data - Conducted by: 1978 JNOC MCS line, 1984 HIG SeaMARC II survey
Date:
May require crossing MCS line
Main results: Canyon provides access to deep stratigraphic section and basement

Operational Considerations

Water Depth: (m) 3400 Sed. Thickness: (m) 900 Total penetration: (m) 950

HPC x Double HPC ____ Rotary Drill x Single Bit x Reentry ____

Nature of sediments/rock anticipated: Hemipelagics and volcanoclastics/basalts or boninites

Weather conditions/window: Good spring through fall

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent:
Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office:
August, 1985

Rev. 0284

| | |
|---|---|
| Proposed Site: BON 6; Outer-Arc High | General Objective: Intra-oceanic island arc/forearc development |
| General Area: BONINS<br>Position: 31°54'N, 141°06'E<br>Alternate Site: | Thematic Panel interest: Tectonics, Lithosphere, SO<br>Regional Panel interest: Western Pacific |

Specific Objectives: To drill the outer-arc high to determine the:

1. Age and petrochemistry of the igneous basement (to address questions of the initial stages of arc volcanism and the origin of boninites).
2. Vertical tectonics (due to flexural loading, tectonic erosion, underplating, thermal cooling?)—compare differential uplift-subsidence across the forearc, and to Bonin Islands along strike. Origin of outer-arc high?
3. Crustal structure of the forearc (to investigate the formation of the 200 km-wide arc-type forearc massif and for comparison with ophiolites).
4. Microstructures associated with outer forearc deformation.

Background Information:

Regional Data:

Seismic profiles: MCS by Japan National Oil Co. and Lamont-Doherty Geological Observatory. Single channel by Geological Survey of Japan and Hawaii Institute of Geophy

Other data: SASS bathymetry, SeaMARC II sidescan, magnetics, gravity.

Site Survey Data - Conducted by: To be done (requires crossing MCS line)

Date:

Main results:

Operational Considerations

Water Depth: (m) 2850 Sed. Thickness: (m) 950 Total penetration: (m) 1100

HPC x Double HPC ____ Rotary Drill x Single Bit ____ Reentry x

Nature of sediments/rock anticipated: Hemipelagics and volcanoclastics/boninites or basalt

Weather conditions/window: Good spring through fall

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Re-entry required for downhole and other seismic experiments to determine forearc crustal structure, and for subsequent (1990's) deep drilling into forearc basement.

Proponent: Brian Taylor, Hawaii Institue of Geophysics

Date submitted to JOIDES Office: August, 1985

Rev. 0284

| | |
|---|---|
| Proposed Site: BON 7: Lower Slope "Domes" | General Objective: Intra-oceanic island arc/forearc development |
| General Area: BONINS<br>Position: 30° 58'N, 141°48' E<br>Alternate Site: | Thematic Panel interest: Tectonics, Lithosphere<br>Regional Panel interest: Western Pacific |

Specific Objectives: To drill into the flank of a dome on the lower-slope terrace to determine the:

1. "Emplacement" mechanism, petrology and structure of the domal bodies of chloritised/serpentinised mafics and ultramafics. Are they a) diapirs of serpentinised forearc basement, b) local upwarps along a terrace of hydrolysed and remobilised forearc basement, c) downdropped outer-arc high material? How do they compare to the serpentised diapris in the Marianas and to certain alpine-type ultramafics?
2. Timing of emplacement: ongoing, dormant, pre/post canyon formation?
3. Hydrogeology through the outer forearc: slab dewatering through igneous outer-arc.

Background Information:

Regional Data:

Seismic profiles: MCS by Japan National Oil Co. and Lamont-Doherty Geological Observatory single channel by Geological Survey of Japan and Hawaii Institute of Geophysics.

Other data: SASS bathymetry, SeaMARC II sidescan, 3.5kHz, magnetics, gravity, dredges.

Site Survey Data - Conducted by: to be done

Date:

Main results: Requires crossing MCS lines, dredging and coring.

Operational Considerations

Water Depth: (m) 4650 Sed. Thickness: (m) 200 Total penetration: (m) 600

HPC X Double HPC ____ Rotary Drill X Single Bit X Reentry ____

Nature of sediments/rock anticipated: Hemipelagics/sheared silicate matrix, chloritised and/or serpentinised mafics and ultramfics.

Weather conditions/window: Good spring through fall.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Proponent: Brian Taylor, Hawaii Institute of Geophysics

Date submitted to JOIDES Office: August, 1985

Rev. 0284

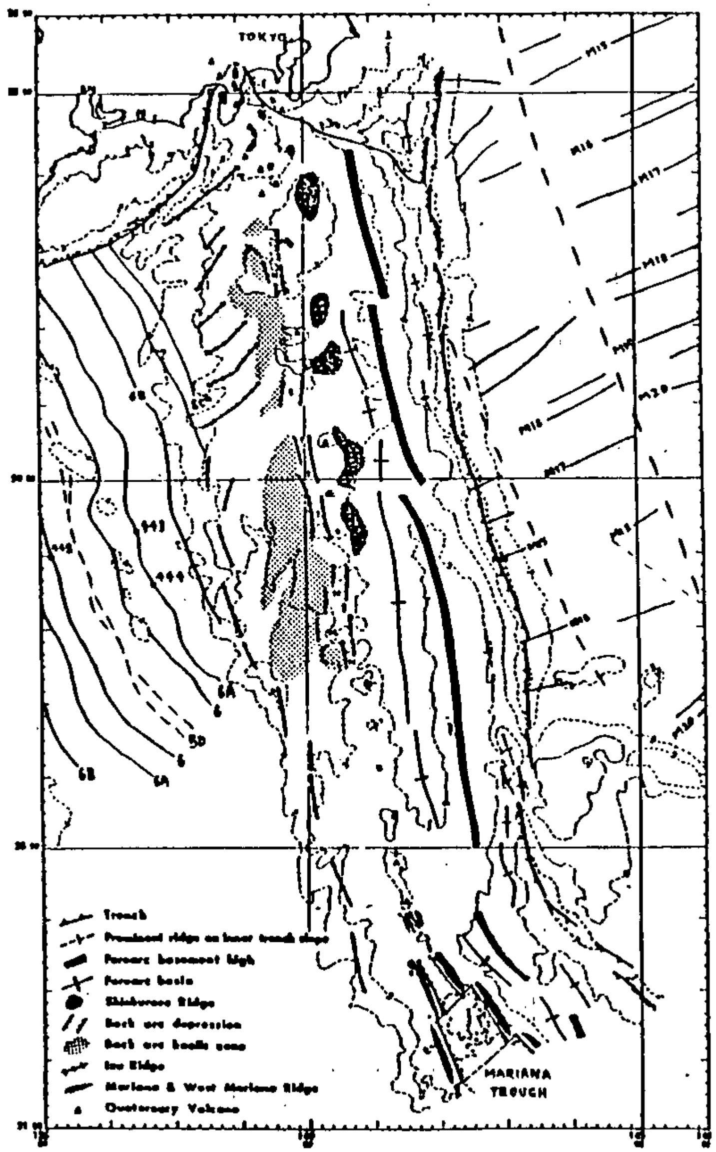


Figure 1a. Tectonic elements of the Bonin arc-trench system (modified after Honza and Tamaki, 1985).

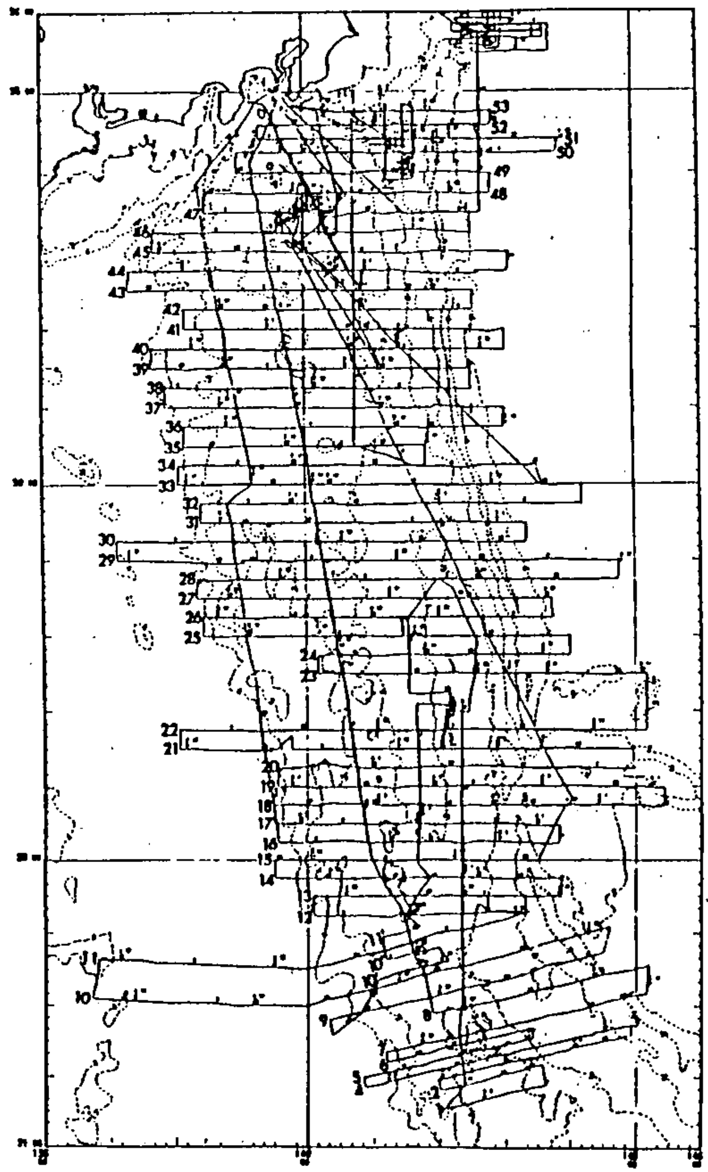

Figure 1b. Survey tracks by the Geological Survey of Japan (GH79-2, 3, 4, and GH80-3 cruises of R/V Hakurei Maru).

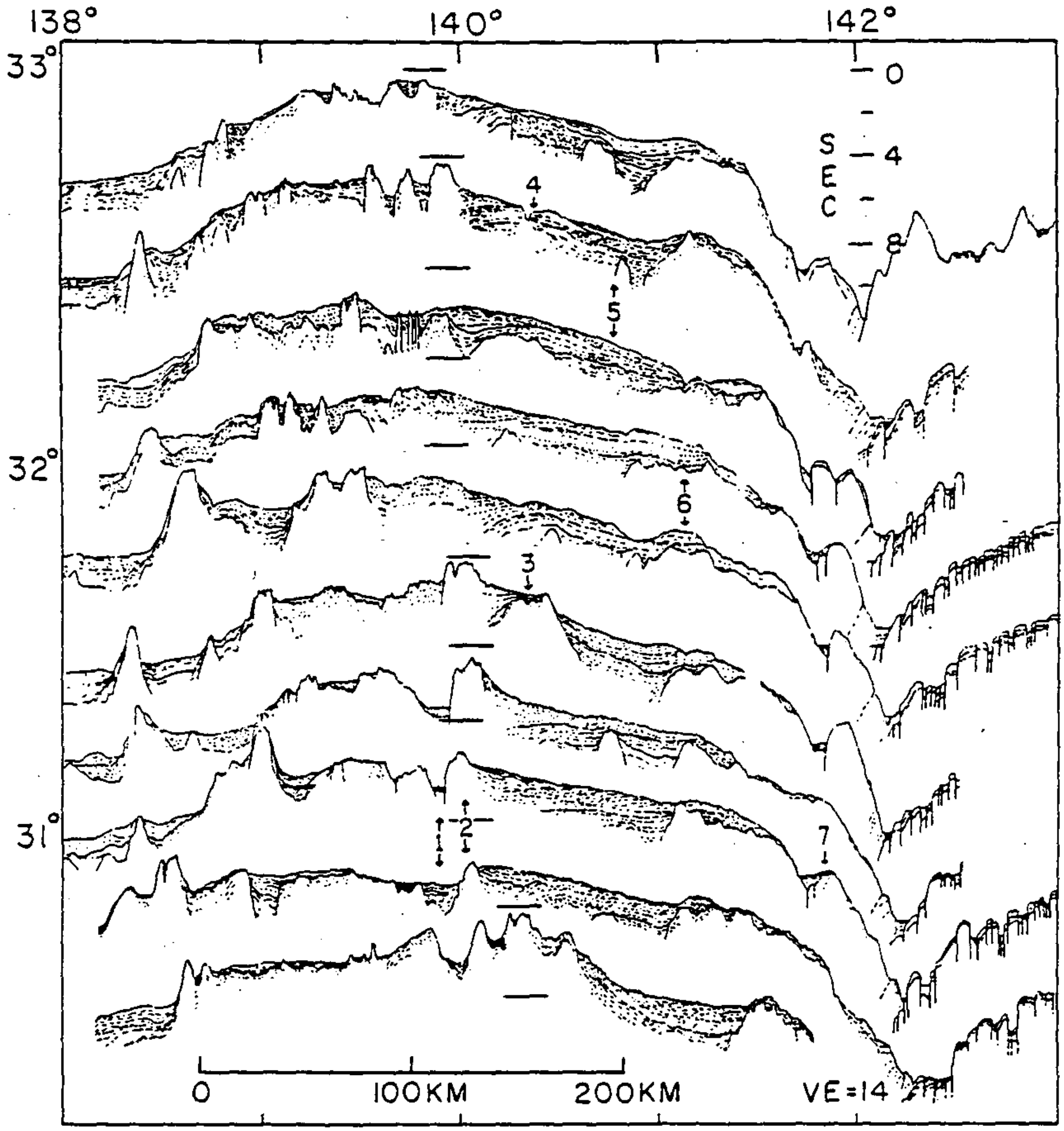


Figure 2. Line drawings of GH79 seismic reflection profiles across the Izu Arc-Bonin Trench system between 30.5° and 33° N(Honza and Tamaka, 1985). From east to west, the characteristic structural elements of this active margin include: (a) a lower slope terrace on the trench inner wall, (b) a thick forearc basin sequence which laps onto and thins over an outer-arc structural high, and (c) a broad arc platform with active volcanoes and rift basins on the east and older volcanic cross chains on the west. The seven proposed ODP sites on or between the seismic lines are indicated by single or double arrows respectively.

Figure 3 (overpage): 500m bathymetry and marine geophysical ship track coverage of the Bonin transect region. Aoga Shima canyon, Sumisu rift and the three lower slope "diapirs" south of 32° N have complete SeaMARC II coverage. Multichannel Seismic tracks of JNOC are not shown.

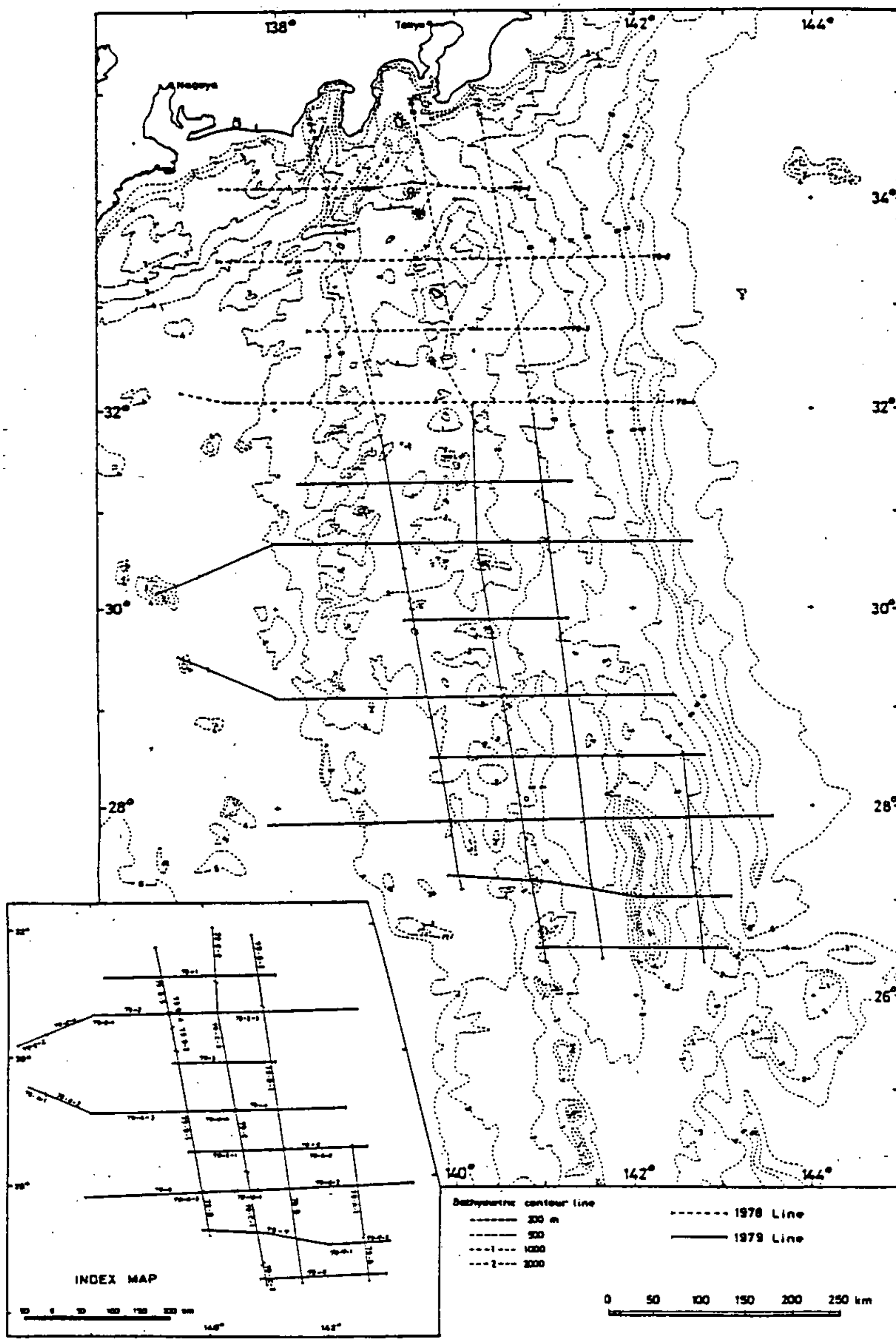


Figure 4. Japan National Oil Co. multichannel seismic lines in the Bonin region.

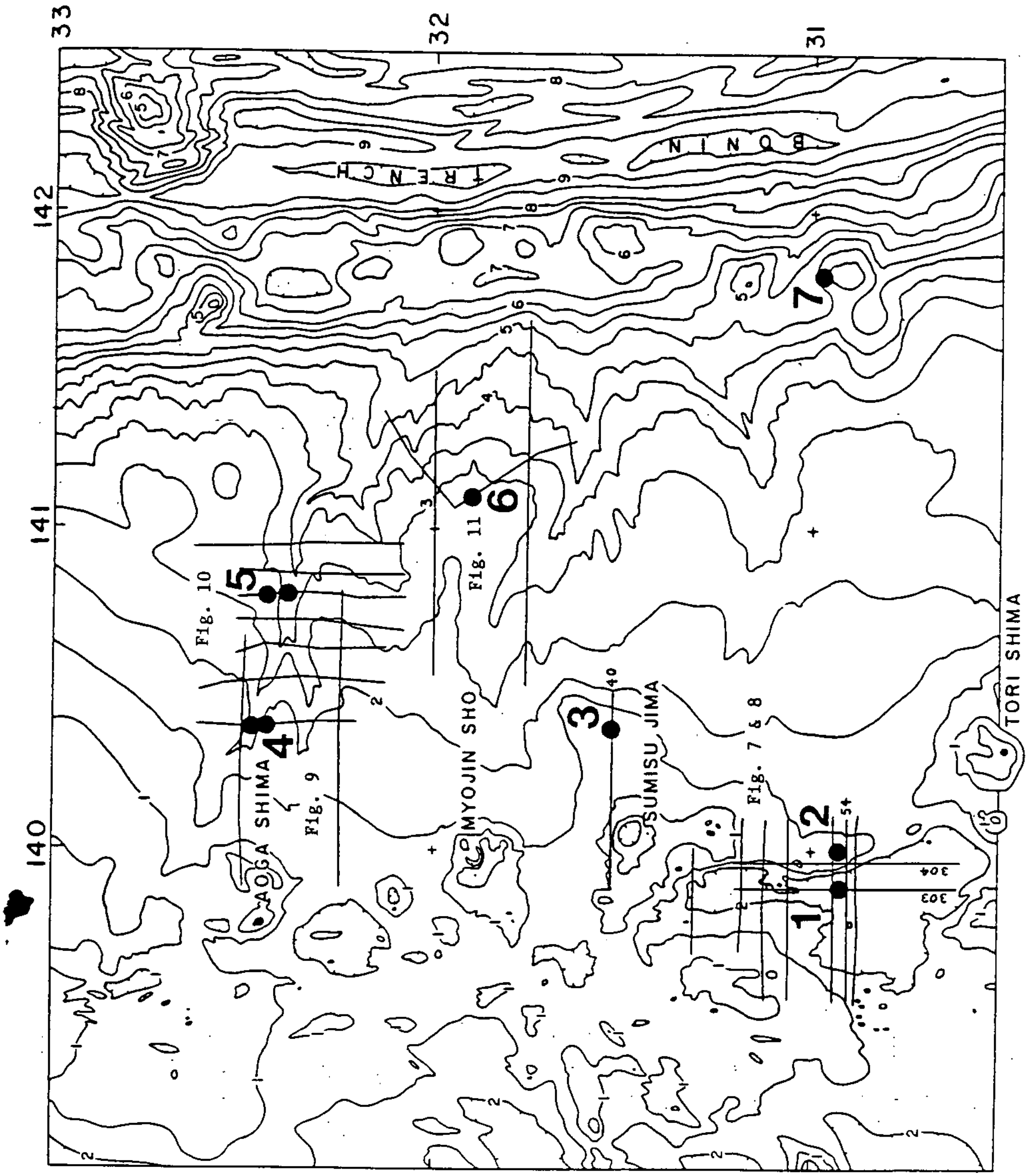


Figure 5. Location of proposed Bonin sites 1-7 together with those track segments whose seismic sections are illustrated in Figures 7-11.

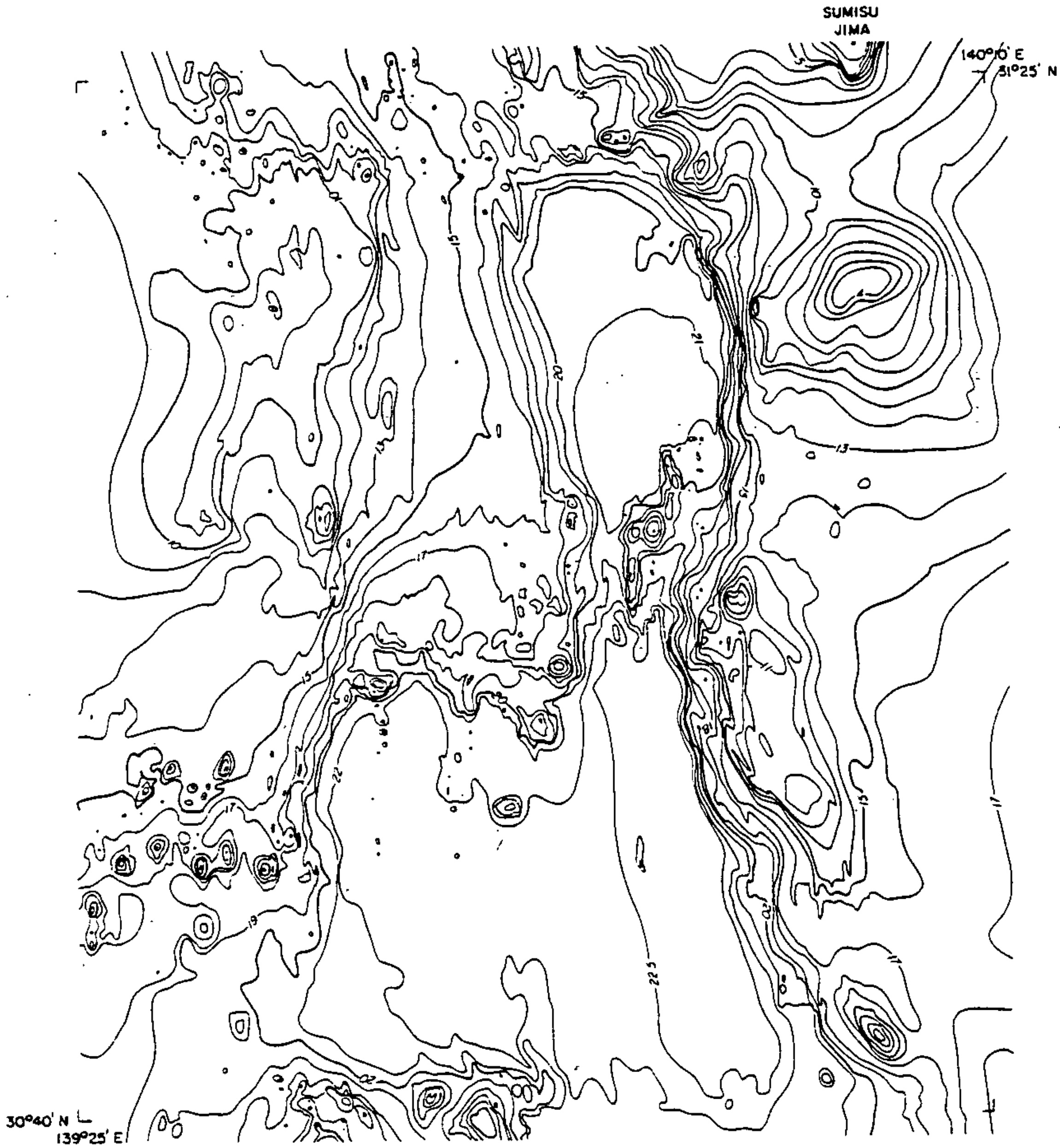


Figure 6a. SeaMARC II bathymetry (100 m contours) of the Sumisu rift.

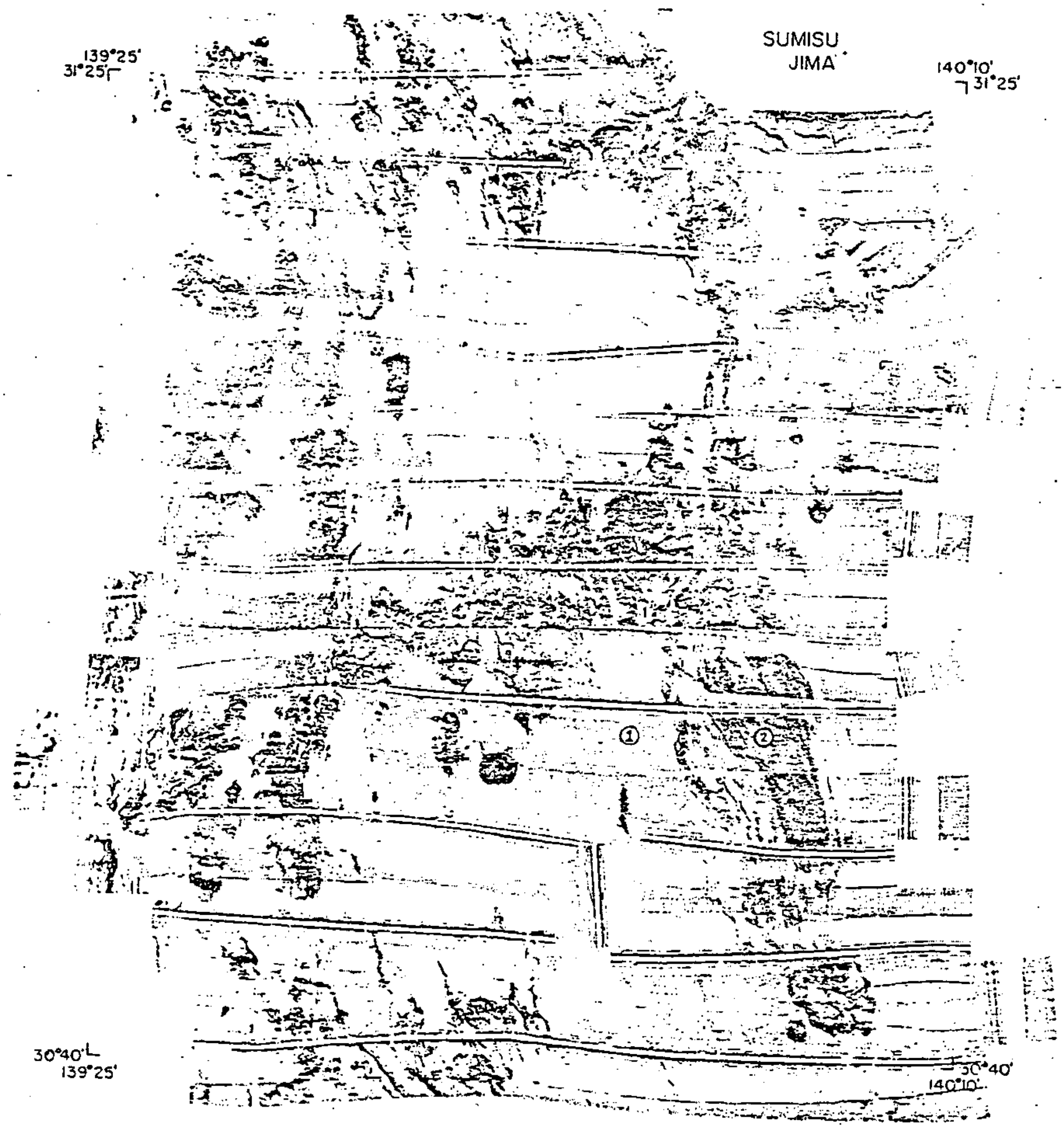


Figure 6b. SeaMARC II sidescan of the Sumisu rift. The original from which this poor page-size reproduction was made is approximately 4 ft. square.

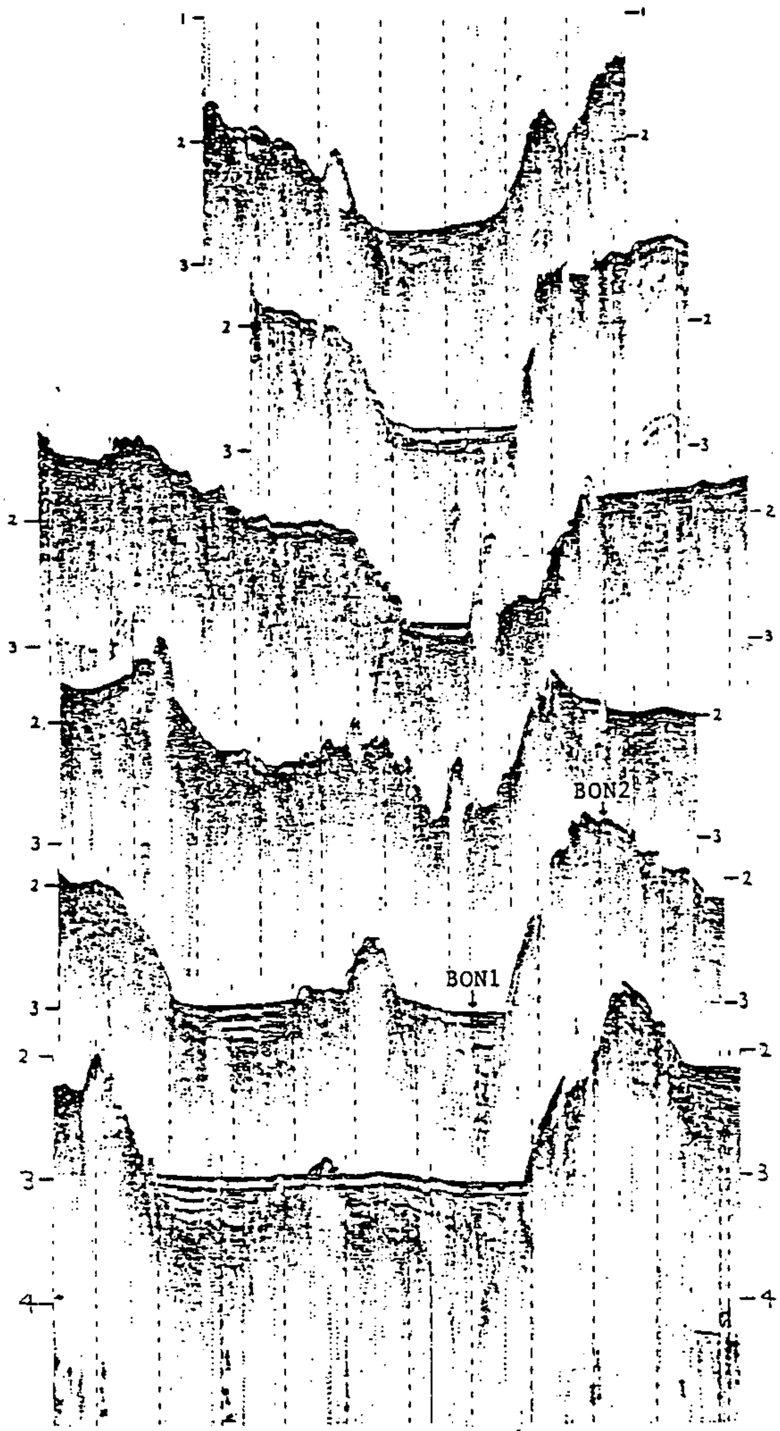


Figure 7. Geological survey of Japan unpublished seismic profiles across the Sumisu rift. V.E.=14

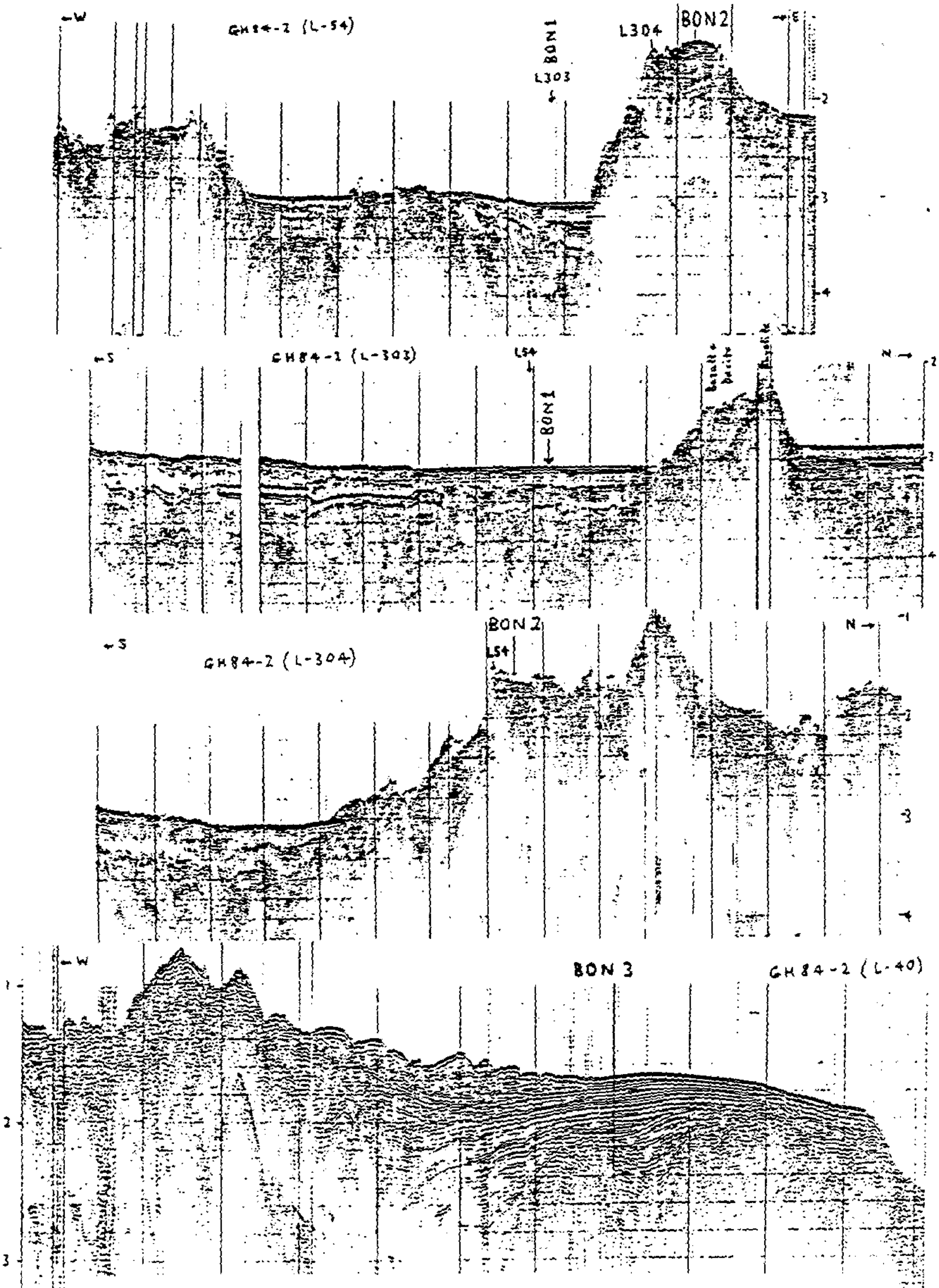


Figure 8. Sites BON 1 to 3 on or near Geological Survey of Japan single channel seismic profiles (located in Figure 5).

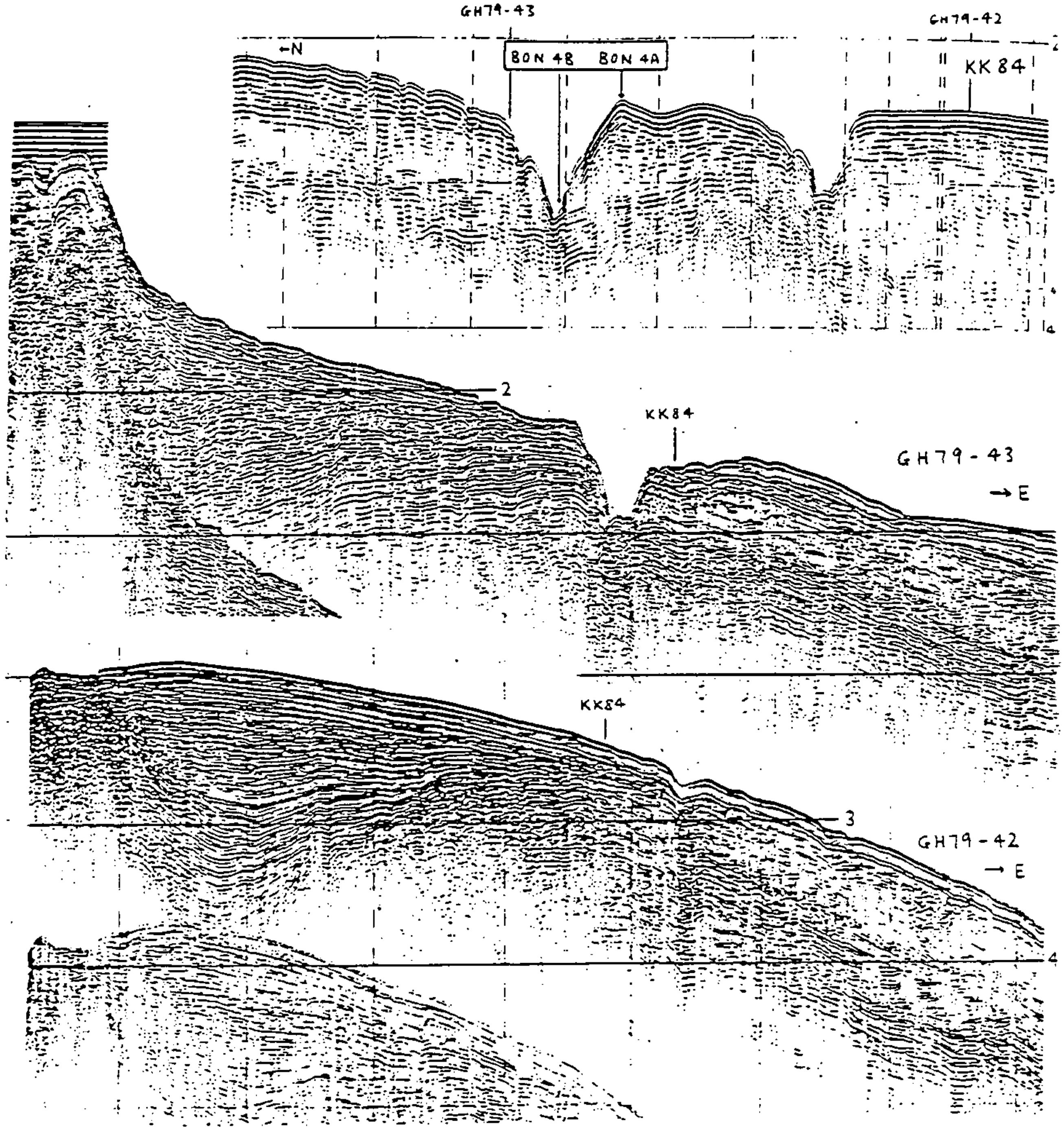


Figure 9. Sites BON 4A to 4B on HIG and between GSJ single channel seismic profiles (located in Figure 5).

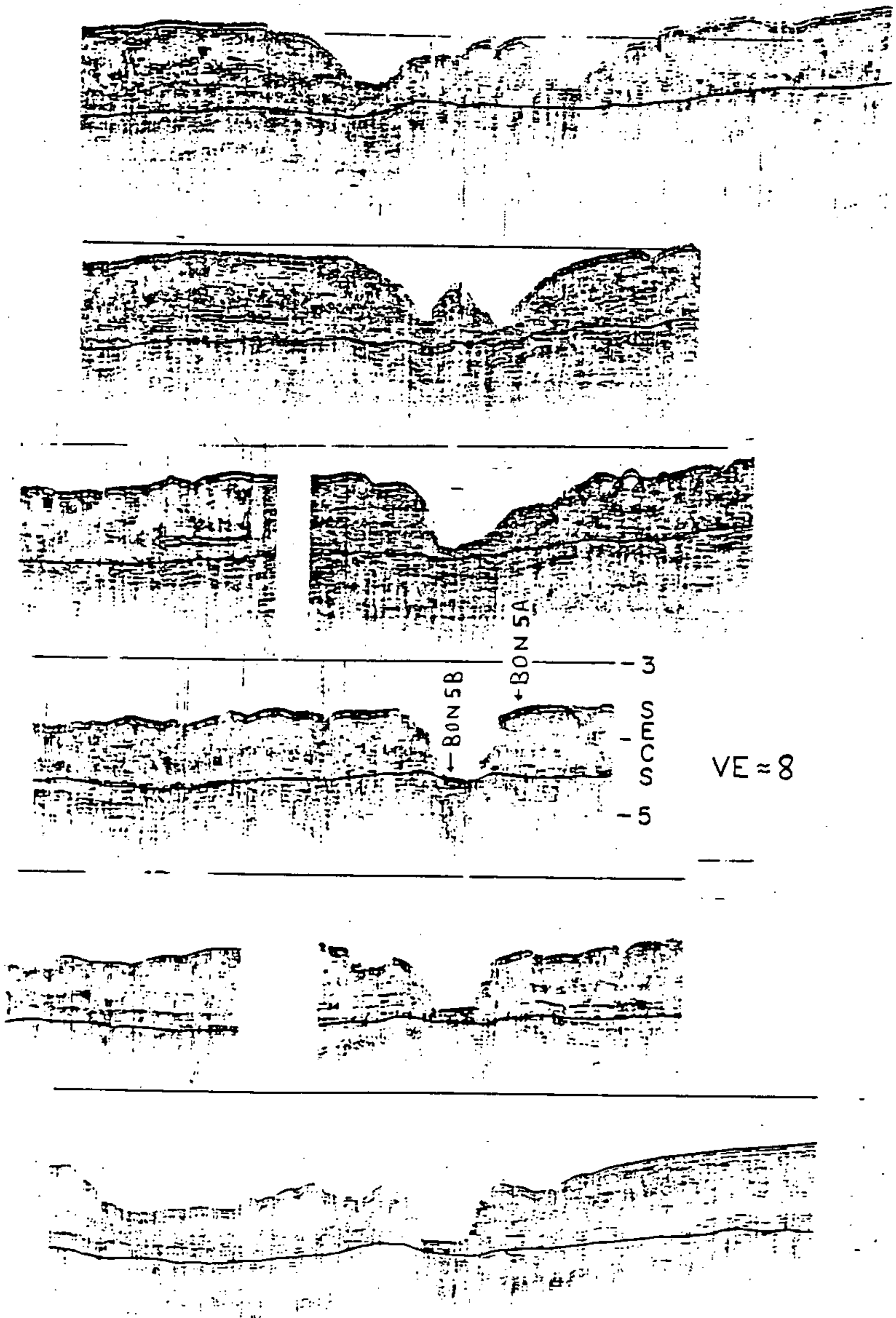


Figure 10. Sites BON 5A and 5B on HIG small volume, single channel seismic profiles (see Figure 5 for location). JNOC MCS line 78-A crosses these sites.

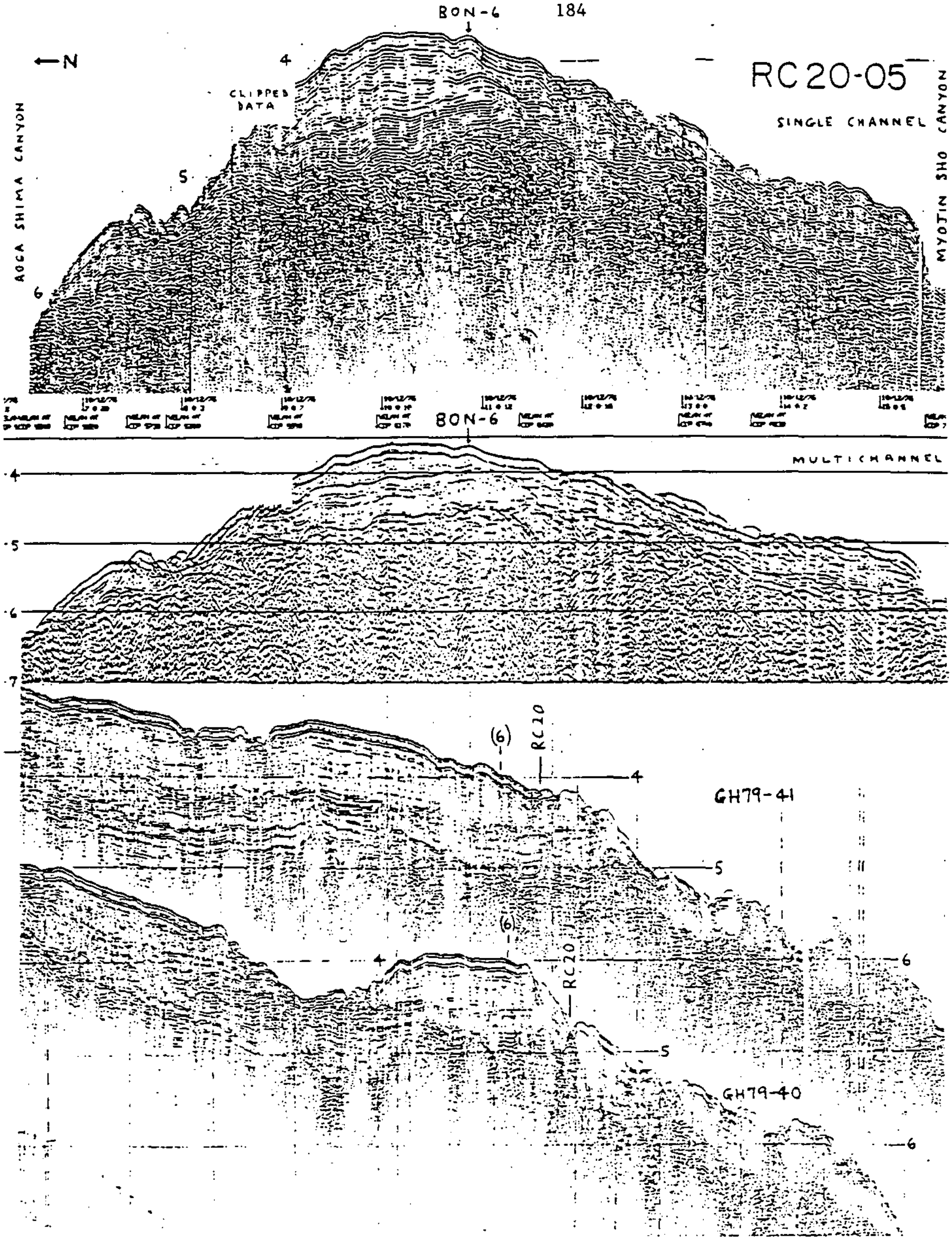


Figure 11. Site BON 6 on LDGO single and multichannel seismic profile RC20-05, and between GSJ single channel seismic profiles GH79-40 and 41.

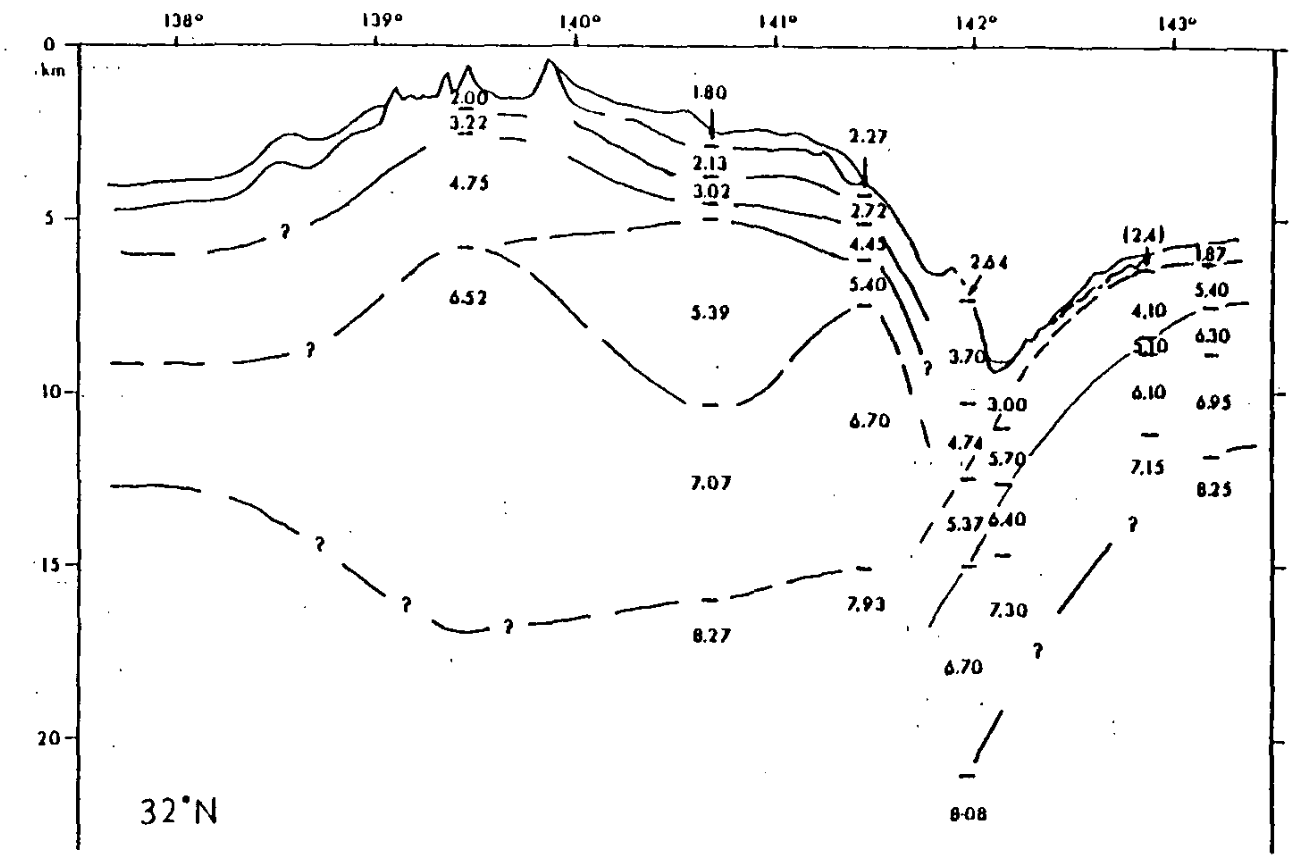


Figure 12. Crustal section across the Izu Arc-Bonin Trench along latitude 32°N from two-ship seismic refraction data summarized by Honza and Tamaki (1985).

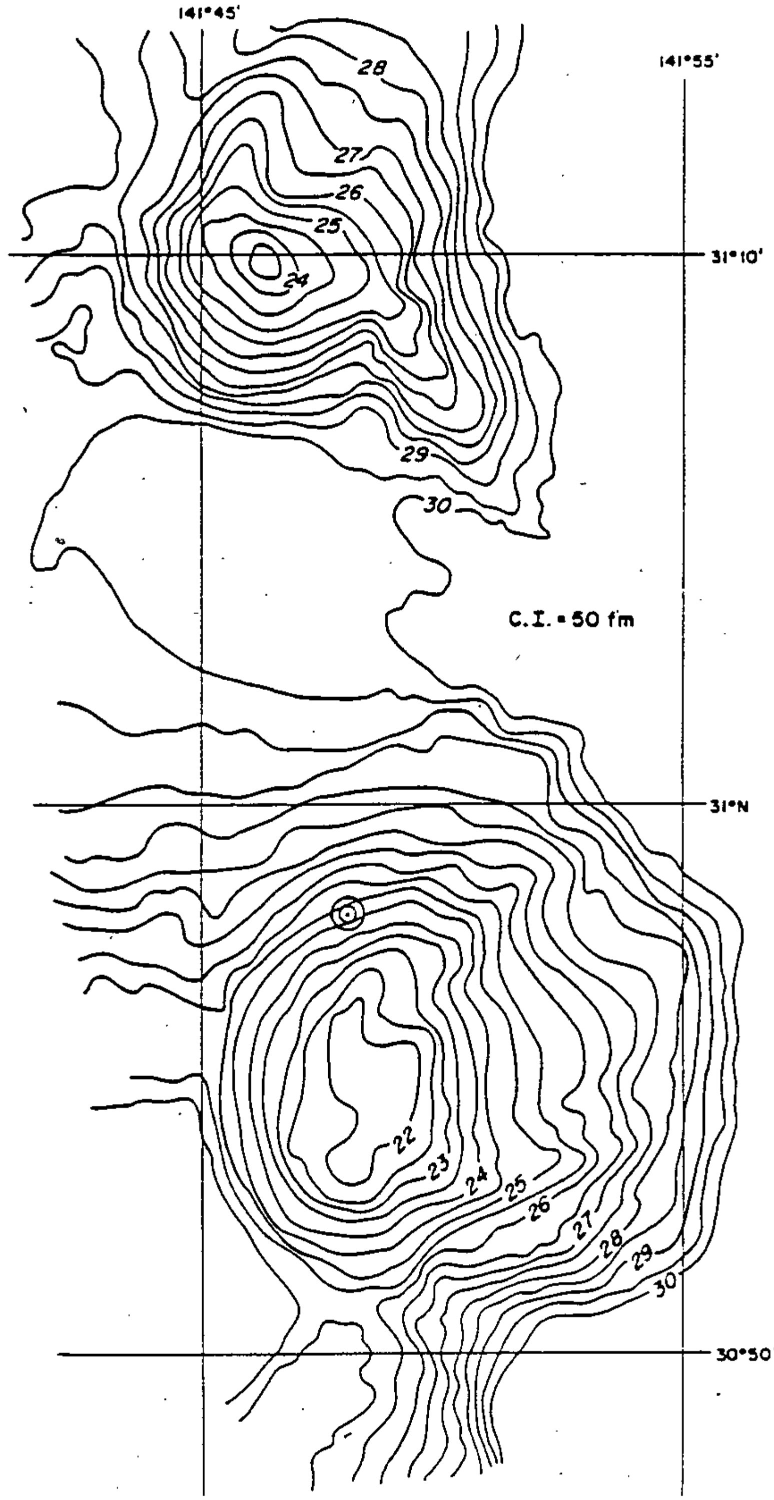


Figure 13. SASS bathymetry (in 100's of fathoms) of two domes along the lower slope terrace of the Bonin Trench inner wall. Site BON 7 is located by the double circle.

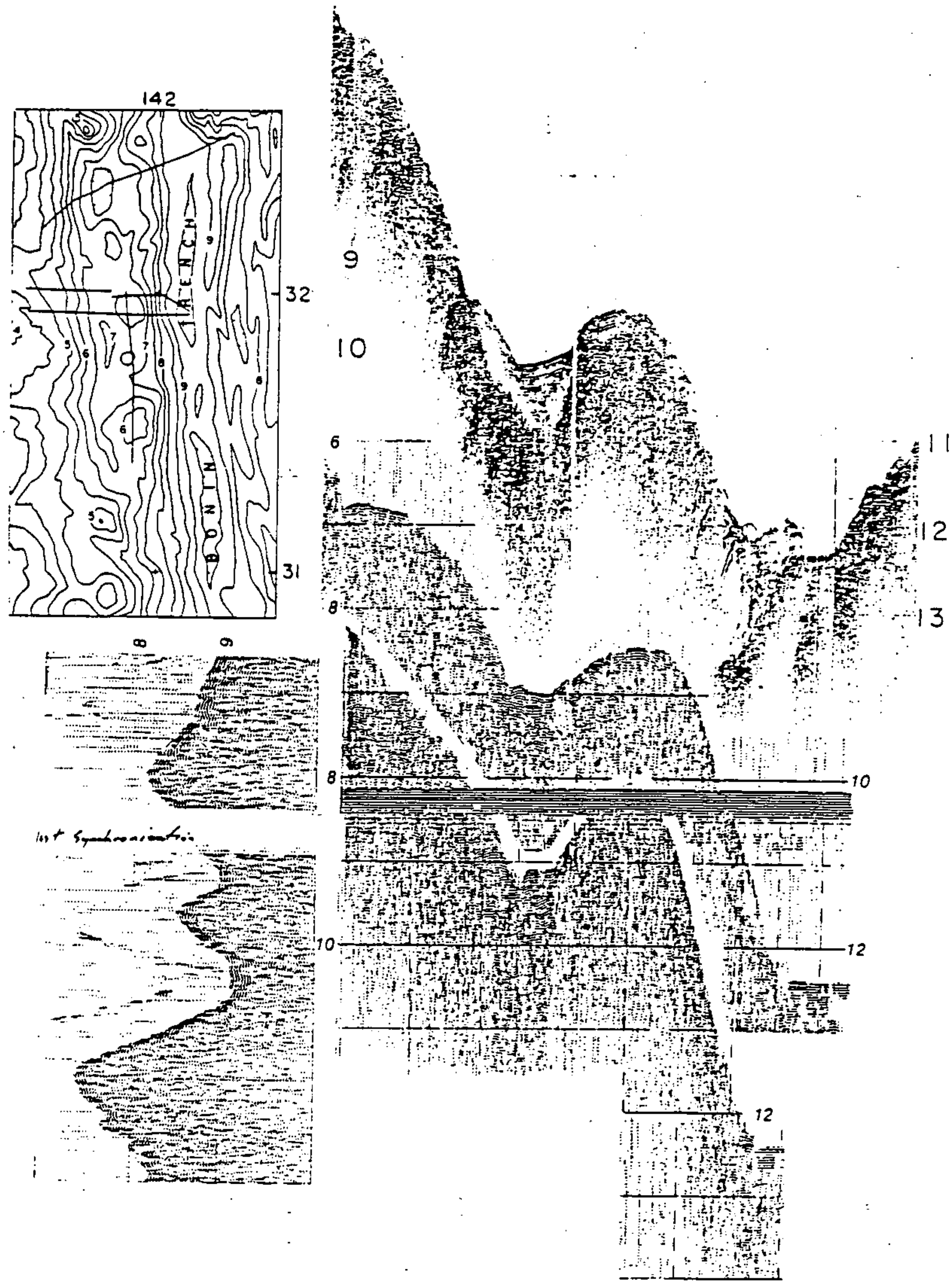


Figure 14. Single channel seismic profiles along and across the "domes" on the lower slope terrace of the Bonin Trench inner wall.

# SUMMARY OF DRILLING PROBLEMS IN THE SUNDA ARC REGION

By: Eli Silver, Joe Curray, Dan Karig, Greg Moore, and Don Reed

The Sunda arc shows nearly continuous variation from accretion of thick sediments in the western part off northern Sumatra, associated with oblique convergence, to normal convergence and accretion of thin sediment in the central part, south of Java to Sumba. This variation offers great potential for examining the changes in structural fabric as a function of changes in material input. South of Sumba Island we find a radical transition from subduction of oceanic crust with thin sediment to collision of Australian continental crust with thick sediment. Eastward from the point of initial collision the material input changes, from hemipelagic sediments in the western part to thick turbidites farther to the east (south of Timor Island).

A drilling program in the Sunda arc region would focus on several specific problems of the structural and mechanical development in subduction and collision zones. These problems are:

1) What is the role of recycling at the toe of the accretionary wedge and its affects on the structural fabric and conposition of the accreted masses?

2) What are the contact relationships of slope basins and accreted thrust plates, and the facies distributions across these basins?

Both of these problems can be addressed in the well-studied region offshore of Nias Island, where thick turbidites from the Bengal fan are accreted to the toe of the slope, and slump deposits have been identified at the toe. A series of basins on the inner trench slope typify the characteristic morphology recognized in many trench settings. The problem of facies distributions at the toe can be studied with a set of closely space HPC's. Excellent seismic reflection coverage exists here, but site surveys involving SeaBeam or SeaMARC would be necessary. The slope basins could be studied with two sites no deeper than one km apiece.

3) What is the origin of landward-dipping reflectors in the toe regions of accretionary wedges, especially where incoming sediment is thin?

These features were first recognized by Beck and Lehner, but the origin of the reflectors has remained an enigma ever since. Are they are bedding planes, as found off Mexico, the expression of thrust faults, or are they zones of elevated fluid pressures along dewatering conduits?

Excellent seismic data exist for the region south of Java, but further processing of the data are required. Bathymetric swath mapping is lacking for this region, and needs to be done for accurate interpretation.

4) What is the structure of the toe region of the wedge where non-accretion appears to be the characteristic process?

Southwest of the island of Sumba little sediment is entering the trench and an accretionary wedge is either absent or very poorly developed. We can compare the structure here both with that off southern Java and with the voluminous accretionary wedge formed in the zone of collision with the Australian continent, a short distance to the east.

5) What is the structure of the toe region of the initial collision zone, immediately adjacent to the region of non-accretion? Here we have a rare opportunity to examine very different structural effects in an area where convergence parameters are constant. We have good side scan and bathymetric coverage of this transition zone, but we require better quality seismic reflection. The main problem will be to image the upper 1-2 km of the lower slope region, so that a grid of high quality digital single channel seismic reflection profiles together with several multichannel seismic profiles should be sufficient.

6) What is the deformation rate south of Timor, and how does the structure of the deformed turbidite section compare with that of the zone of initial collision south of Sumba? Specific objectives involve dating the uplifted strata in small slope basins between thrust sheets. Here we have good sidescan and bathymetric coverage, but need additional high quality seismic reflection data.

7) In addition to the studies in the toe region, we also propose several sites in the Savu zone of backthrusting on the landward edge of the accretionary wedge, to examine structural and timing questions of the thrust and to determine facies relations in a sediment drift deposit formed against the thrust. Backthrusting has been proposed in other large accretionary wedges: Barbados, Nias, the Mediterranean ridge, and the eastern Sunda arc (Savu thrust). Of these the Savu thrust is the best developed.

# Proposed ODP Work in the New Hebrides Arc Region, Southwest Pacific

by

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This document suggests a number of ODP drilling and HPC sites in the New Hebrides (Vanuatu) Arc (see figure 1 for general location). We propose these sites because we believe that unusual geologic features in the New Hebrides may offer better opportunities than do other arc systems to solve certain scientific problems. Our suggested sites have been influenced by the June 1985 ODP Workshop at Scripps. We also seek to support, as best we can, the suggestions from the ORSTOM-Noumea document circulated at the Workshop entitled "Deep Sea Drilling Proposal on the New Hebrides". We have also had extensive discussions with J. Recy (October 1984, visit to the Institute for Geophysics, Austin) concerning drilling needs in the New Hebrides region. ORSTOM did not propose specific sites, but suggested sites that would address the effects of subduction of the d'Entrecasteaux Ridge on tectonic development and magmatism in the central New Hebrides. We suggest in addition, and ORSTOM would support this, that sites of incipient back-arc rifting, such as the Coriolis Trough east of the New Hebrides volcanic arc, are a second target due consideration by ODP. ORSTOM will probably prepare a far more elaborate drilling proposal in the near future.

In late 1985 the R/V Jean Charcot will arrive in New Hebrides' waters for seabeam studies of the Coriolis Trough and d'Entrecasteaux Ridge. The Charcot will return for further work in 1986. This work will provide necessary and important information for siting ODP holes. ORSTOM and the University of Texas plan to do OBS refraction experiments in the Coriolis Trough region which should help determine its suitability as an ODP target. It is probable that some of the R/V S. P. Lee multichannel data collected in 1983 and 1984 will also be of use in locating the ODP drill sites.

From the outcome of the Scripps workshop, it is clear that two or three major scientific problems can be better addressed in the New Hebrides region than elsewhere. These include:

(1) The consequences to an active island arc system when a linear bathymetric high (the d'Entrecaustex Ridge) is subducted.

(2) The extensional structures and magmas that result when a back-arc basin (the Coriolis Trough) begins initial rifting.

(3) The structure of the interplate thrust zone as revealed by drilling through a thin upper plate (non-accretionary wedge) (off Espiritu Santo Island).

The New Hebrides arc is particularly suitable for addressing these scientific problems because (1) the d'Entrecasteaux Ridge has obviously effected the central part of the arc (Santo-Malekula) (figure 2) and (2) the actively developing Coriolis Trough and related extensional features to the north of the Coriolis (figure 3) may indicate a new phase of back arc basin rifting that is interrupted in the area behind the d'Entrecasteaux Ridge subduction (Collot et al., 1975). Subduction of the d'Entrecasteaux Ridge has additional significance because it apparently causes an interruption in the trench morphology at the plate boundary immediately west of Santo. Nowhere else is it possible to drill in such shallow water depths (1 to 4 km) and be within striking distance of an interplate thrust zone.

D'Entrecasteaux Ridge

The d'Entrecasteaux Ridge may represent a strike-slip fault zone at the end of an Eocene island arc (Maillet et al., 1983) that is being subducted beneath the central part of the New Hebrides arc. It is actually two parallel ridges with a deeper region between the two ridges with a total width of about 100 km (Collot et al., 1985). Average relief is about 3 km above the adjacent sea floor, but some sea mounts rise more than 4 km above the sea floor and one comes to within 7 m of the sea surface. There is no physiographic trench west of Santo and Malekala Islands where the d'Entrecasteaux Ridge intersects the arc, although the trench is over 6 km deep immediately to the north of Santo and south of Malekula. The d'Entrecasteaux Ridge is being subducted N76$^{o}$E (Pascal et al., 1978) at a rate of roughly 10 cm/yr (Minster and Jordan, 1978; INDI/PACF Rate). Consequently, the zone of interaction between the arc and E-W oriented ridge may be migrating slowly northward.

Santo and Malekula Islands lie at the extreme western edge of the upper plate where the inner trench slope normally is located. However, neither island represents accreted sediments associated with the present subduction of the Indian Plate. Instead, they consist mainly of Miocene volcanoclastic sediments and igneous rocks deposited in an older New Hebrides arc which is believed to have faced east and subducted Pacific lithosphere until an arc reversal in late Miocene or early Pliocene time (Mitchell and Reading, 1971; Karig and Mammerickx, 1972; Carney and Macfarlane, 1977; Falvey, 1977).

Direct evidence of the late Quaternary effects of the d'Entrecasteaux Ridge subduction are well documented (Pascal et al., 1978; Taylor et al., 1980, 1981, in press; Collot et al., 1985). Though whether the unusual geography and bathymetry of the Santo and Malekula region are strictly due to subduction of the d'Entrecasteaux Ridge or are independent features that existed prior to the arrival of the d'Entrecasteaux Ridge at the New Hebrides arc is unknown. Karig and Mammerickx (1972) proposed that Santo and Malekula rotated westward to fill the trench. Others suggested that a high thick block of arc crust projected westward from the central New Hebrides arc prior to subduction of the d'Entrecasteaux Ridge (Robinson, 1969; Daniel and Katz, 1981; Isacks et al., 1981).

Effects of subduction of the d'Entrecasteaux Ridge in late Quaternary time include emerged reefs that indicate uplift rates exceeding 5 mm/yr in western Santo. This can be compared to the maximum rates of about 1 mm/yr on other uplifting parts of the New Hebrides arc (Taylor et al., 1980, in press; Jouannic et al., 1980, 1982). Boundaries between four frontal arc segments identified from reef terrace tilts and other data appear to be controlled by the d'Entrecasteaux Ridge topography. Recent seismic rupture zones and co-seismic uplift patterns are likewise controlled by these arc segment boundaries (Taylor et al., 1980, 1981, in prep.)

Chung and Kanamori (1978a, 1978b) proposed that uplift of Santo and Malekula caused elastic downwarping of the Aoba Basin. Collot et al. (1985) proposed that fractures controlling the orientation of Aoba, Ambrym and Epi volcanoes and other features are related to d'Entrecasteaux Ridge subductions. They suggest that the uplift of the back arc islands of Pentecost and Maewo is due to compression by the d'Entrecasteaux Ridge impinging on Santo and Malekula. Recent coral studies demonstrate on-going subsidence of Aoba Basin and uplift of Maewo and Pentecost at a rate of 0.5 mm/yr (Taylor, in prep.). Recent emergence events on Pentecost and Maewo occurred near the time of co-seismic uplifts of about one meter of Malekula in 1965 and Santo in 1973. These observations lead us to suspect that subduction of the d'Entrecasteaux Ridge has radically altered the structure of the central New Hebrides arc. Should this be true, then the effects of ridge subduction need to be understood because it is a common phenomenon that must be significant to arc development.

## Interplate Thrust Zone

Processes in the interplate thrust are another important problem that can be addressed at the d'Entrecasteaux Ridge subduction (figure 4). Subduction is occurring beneath a well-lithified, competent block of older rocks rather than beneath the usual accretionary prism. The drilling project has never drilled into such an interplate thrust. Questions to be considered are: the thickness of the zone, and the state of stress; how much sediment exists and what its condition is in the zone; and what is happening with fluids at the thrust zone.

Seismicity occurs near the surface along the Wadati-Benioff Zone which slopes down to the east beneath Santo indicating that the thrust zone is very close to the surface (Isacks et al., 1981; Chinn and Isacks, 1983). ORSTOM and Cornell have collected a long detailed record of the seismicity along the New Hebrides trench which may be the best data set of its kind in existence.

## Coriolis Trough and Related Extensional Features

ORSTOM-Noumea bathymetric data first revealed the existence of extensional features behind the New Hebrides arc which led Karig and Mammerickx (1972) to propose incipient opening of a back arc basin. Additional information on the troughs are revealed in Dubois et al. (1977). Though we do not know whether heat flow is associated with the rifts, the basin floors are sediment covered (figure 5) and tele-seismic data and recent uplift of Futuna Island (Carney and Macfarlane, 1979) suggest present-day activity. Additional site survey information will be obtained on the upcoming ORSTOM/UTIG cruise on the *R/V Jean Charcot* this winter.

## Suggested Drilling and Boring Sites

The seven proposed sites are shown on figures 2 and 3.

Site 1. In shallow water west of Santo. The goal is to penetrate the main interplate thrust zone at a reasonable depth. Collot et al. (1985) place the plate boundary immediately west of this site.

Site 2 would be a shallow hole to sample the d'Entrecasteaux Ridge in order that it can be identified if it is encountered at Site 1. Petrologic analysis of Site 2 basement rocks should give us important information concerning the origin of the d'Entrecasteaux Ridge. It is presently unknown if it is an abandoned island arc, fracture zone ridge or other anomalous high.

Sites 3, 4, and 5 are hydraulic piston core sites on bathymetric highs to sample sediments that should record decreasing paleodepths as the frontal arc rose. These sites should provide a much longer uplift history for the frontal arc than do the late Quaternary reefs on the islands. Paleodepths and ages might indicate whether the latest phase of uplift was superimposed on a pre-existing topographic high or whether all has occurred in the past million years or so and is thus related to subduction of the d'Entrecasteaux Ridge.

Coriolis Trough

The Coriolis Trough can be drilled if enough sediments are found in it. Site 6 in the trough would sample magmas that had been extruded onto the graben floor and may recover sediments that contain clues to the age and history of the rifting. Land studies on uplifted, reef-terraced Futuna Island on the east flank of the graben would reveal the vertical deformation history adjacent to the Coriolis Trough.

Site 7 was chosen on a small linear ridge to the east of the Coriolis Trough. This site was chosen for possible paleoceanographic interests as well for insight into the nature and possibly the origin of the ridge and should provide important information on uplift of the horst adjacent to the Coriolis Trough.

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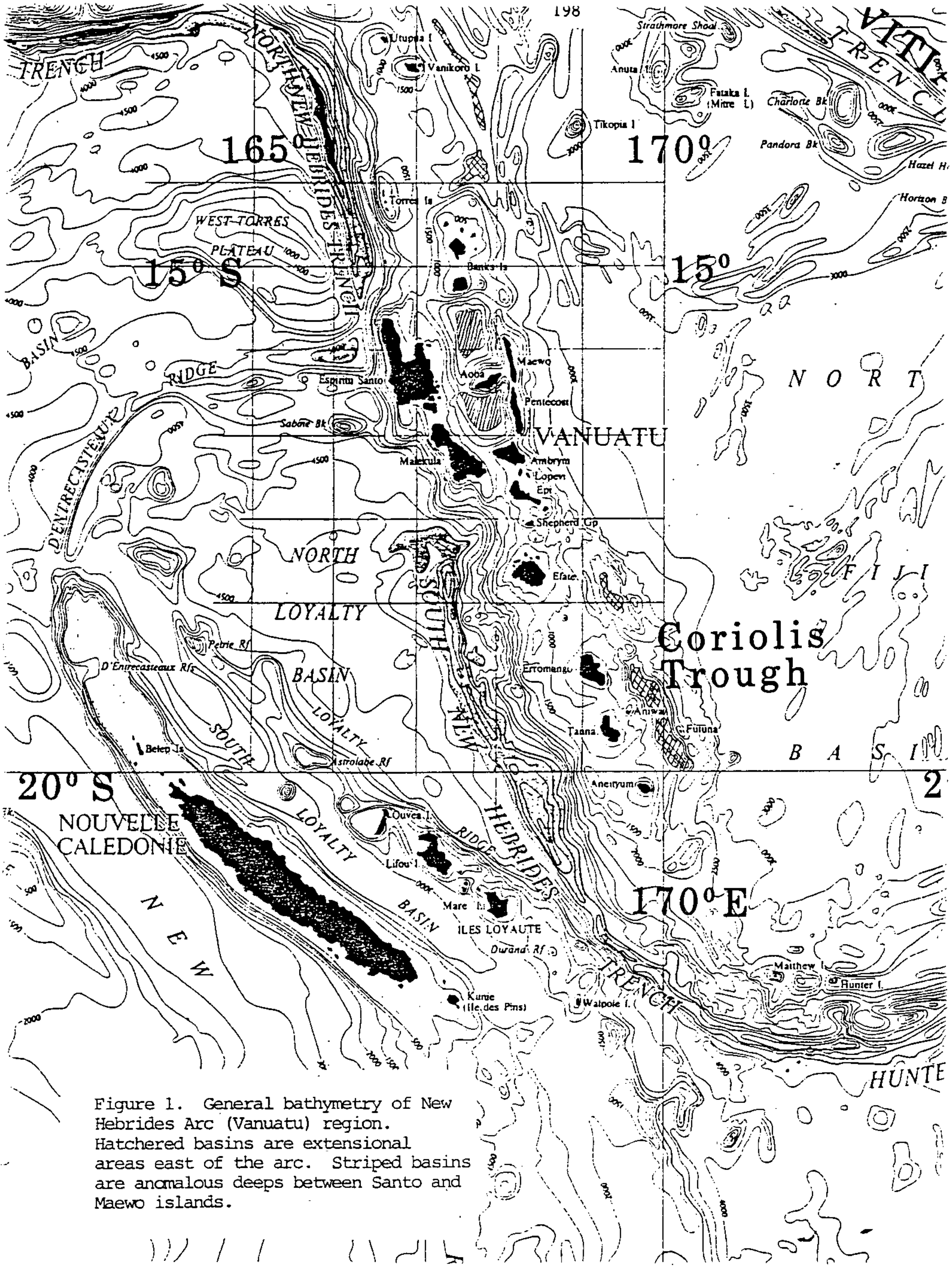


Figure 1. General bathymetry of New Hebrides Arc (Vanuatu) region. Hatchered basins are extensional areas east of the arc. Striped basins are anomalous deeps between Santo and Maewo islands.

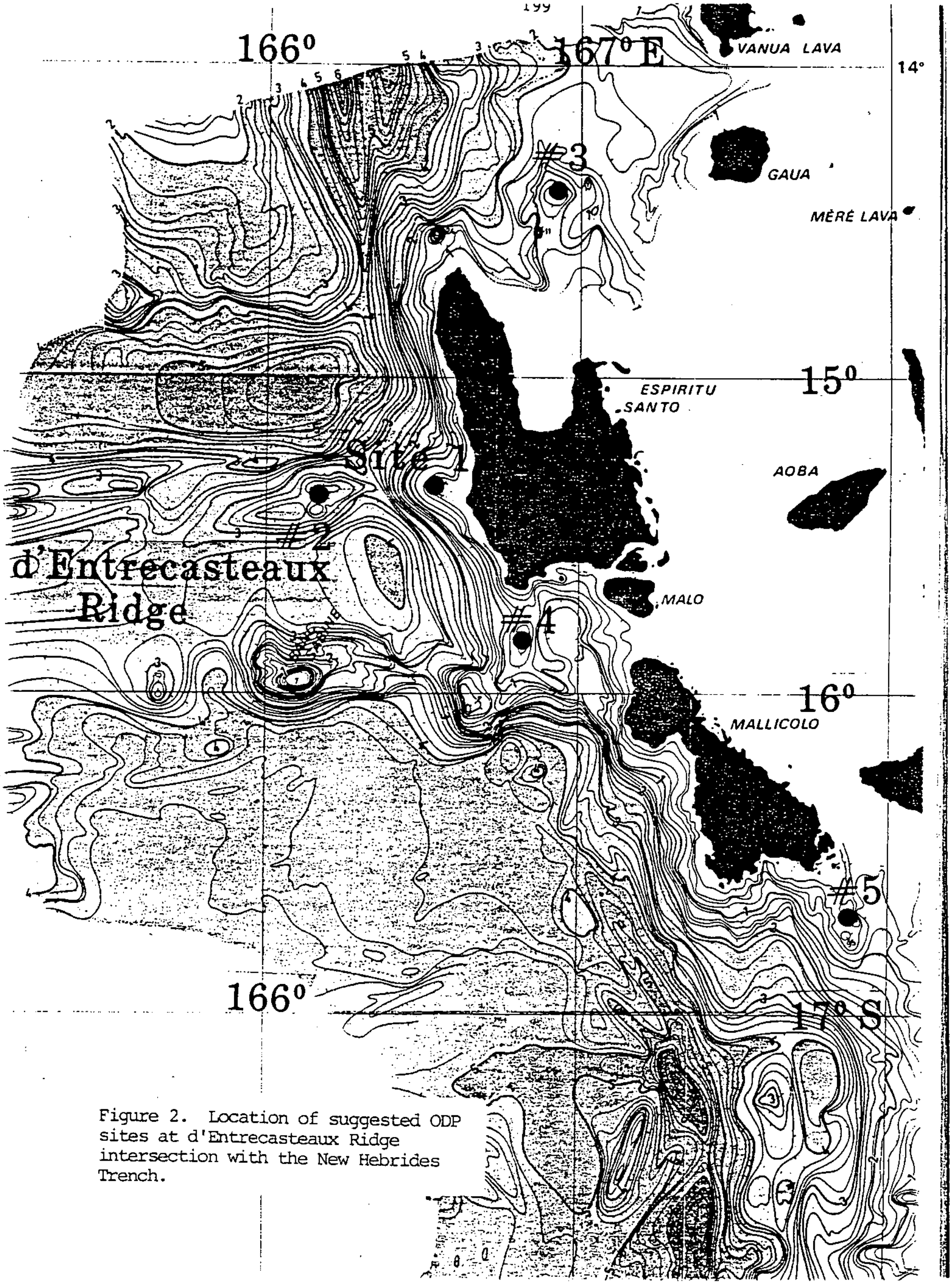


Figure 2. Location of suggested ODP sites at d'Entrecasteaux Ridge intersection with the New Hebrides Trench.

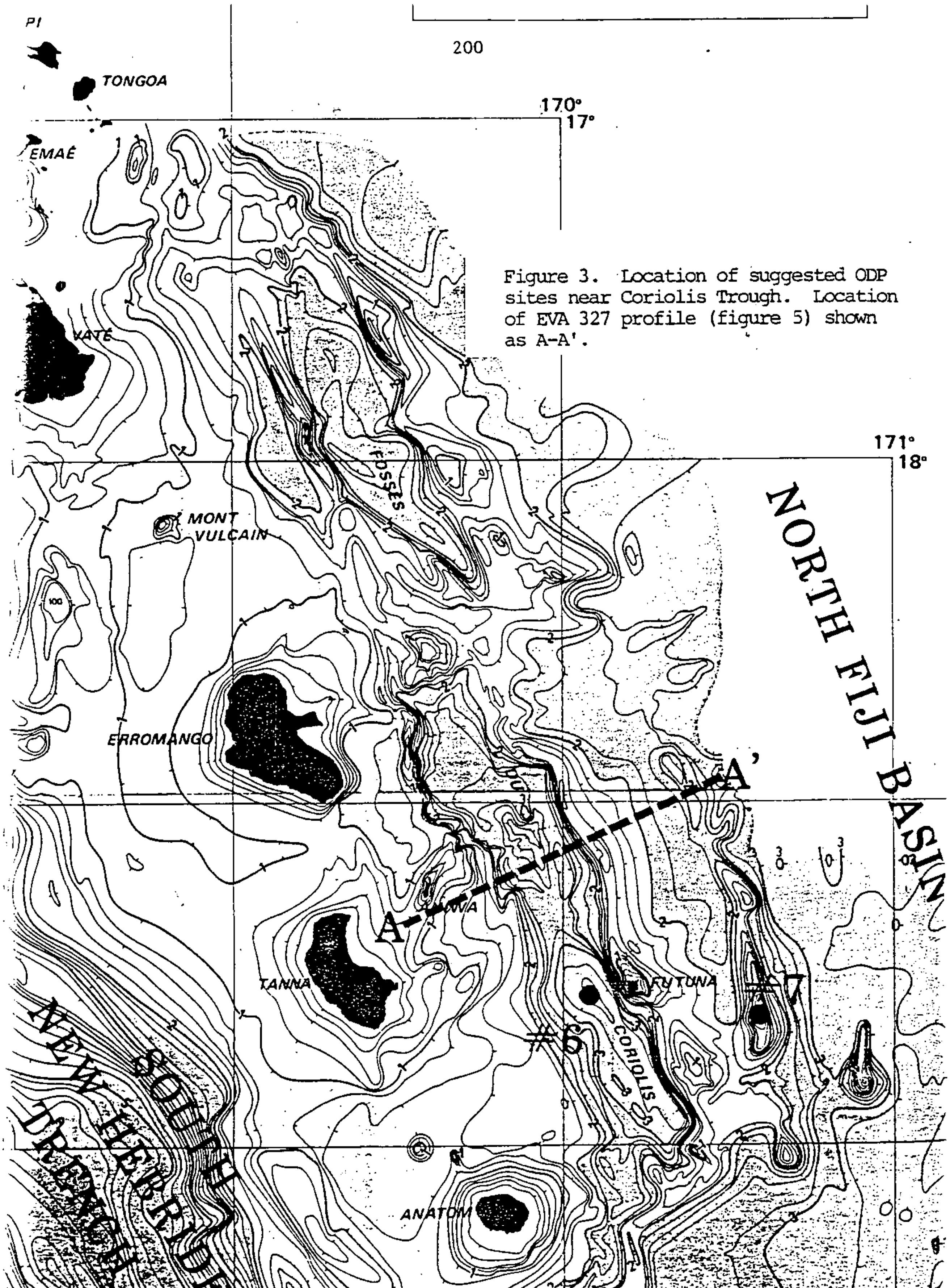


Figure 3. Location of suggested ODP sites near Coriolis Trough. Location of EVA 327 profile (figure 5) shown as A-A'.

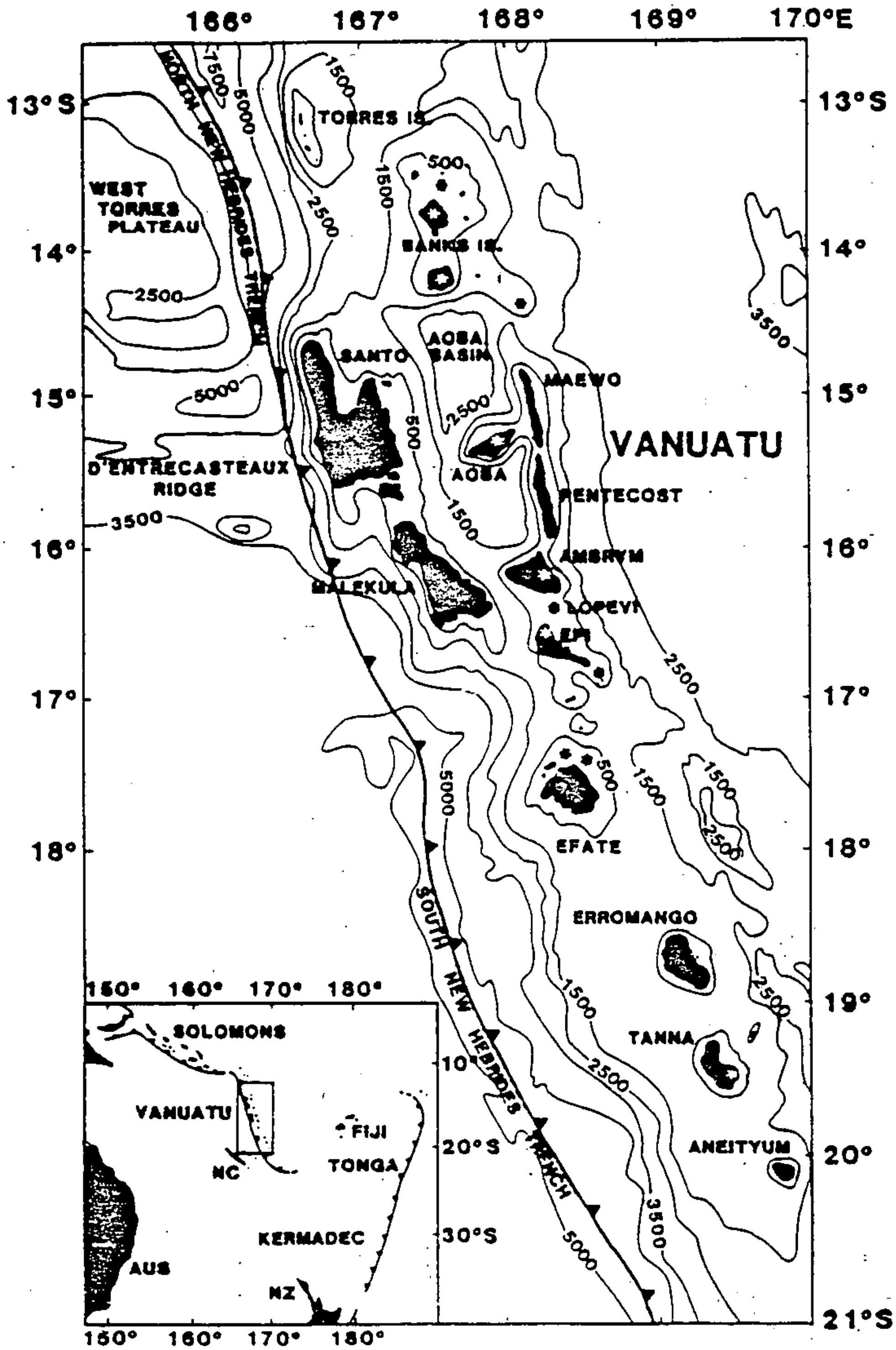


Figure 4. Map showing subduction zone with respect to New Hebrides Arc. * symbols indicate active volcanoes.

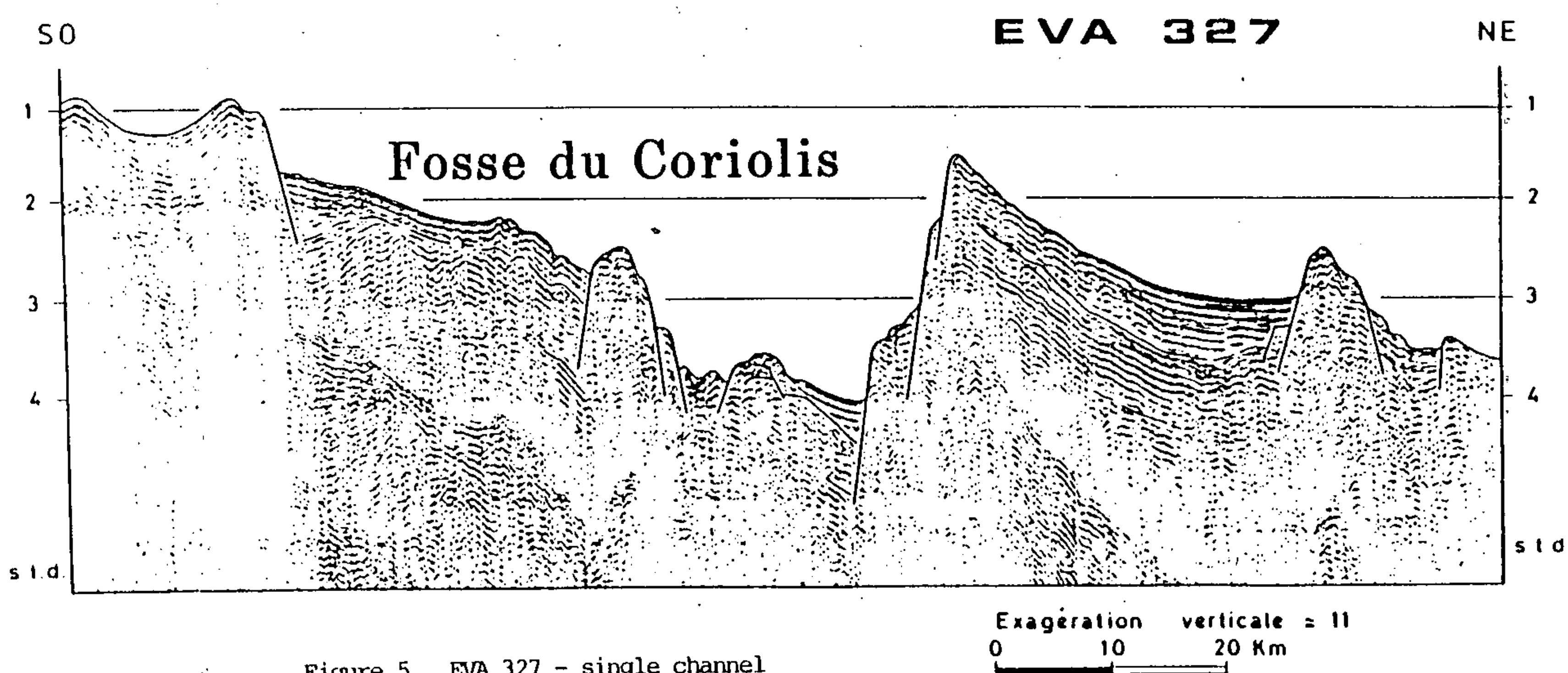


Figure 5. EVA 327 - single channel seismic reflection profile across Coriolis Trough taken from ORSTOM cruise plan (1985).

# OGASAWARA FOREARC "DIAPIR": A POSSIBLE SOURCE FOR THE ULTRAMAFIC ROCKS OF HIGH P/T METAMORPHIC TERRAIN

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Recent development on the geology of the ophiolite or dismembered ophiolite suggests that at least some of the ultramafic rocks of high P/T metamorphic terrains are sedimentary origin which might have accumulated at the trench (e.g. Cowan and Page, 1975; Platt, 1976). It is supposed that ultramafic rocks ascended along the thrust movement at the the trench slope are eroded tectonically and accumulated at the bottom of the trench axis.

Recent finding of the ultramafic rocks at the forearc (e.g. Bloomer, 1983, Bloomer and Hawkins, 1983), mostly at the trench slope break, apparently supports this idea. However, any distinctive thrust zones are not recognized near such forearc ultramafic rocks. They rather form independent dome-like high, which may indicate diapiric uprise of the ultramafic rocks rather than thrust-up mechanism. Detailed petrographical examination of the ultramafic rocks dredged from one of such topographical dome-like highs at the inner wall of the Ogasawara trench (Ogasawara Paleoland; Ishii, 1985; Fig.1 & 2) indicates that the high is mainly composed of serpentinized harzburgite associated with less amount of mafic rocks including gabbro, dolerite, amphibolite and basaltic volcanics. Serpentine sandstones are also recovered. Actually, these assemblages are similar to the ultramafic/mafic bodies which are often found in high P/T metamorphic terrains in orogenic belt.

Among these dome-shaped forearc highs, so-called serpentine diapirs, the topographic high at the junction of the Ogasawara Plateau and the Ogasawara Arc could be a suitable target of the ODP study, because it stands at relatively shallow water (the crest is 1050 m deep) and the access to the inner body could be easier than any other "serpentine diapirs" of the Ogasawara and the Mariana Arcs. Furthermore existence of detailed descriptions on many dredged samples is another advantage to the further examination. The following problems should be tested by the drilling of this site.

Are the total volume of the high occupied by serpentinized harzburgite ? Are any internal structures observed ? How is the stratigraphic relationship between ultramafic rocks and mafic rocks ? How intensive the degree of serpentinization within the body is ? How deep the ultramafic zone extends ? What kinds of sediments are observed beneath the ultramafic body if any ?

Are there any fragments or debris from the serpentinized harzburgite within the adjacent sediments ?

How was the up-down history of the high ?

Therefore, at least two holes are necessary; one hole into the diapir and another hole into the adjacent sediments to monitor the possible change of facies and contents of the sediments during its emplacement.

One of the peculiar thing related to this "serpentine diapir" is that the topographic high exist at the extension of the Ogasawara plateau where the plateau is believed to be colliding against the Ogasawara Arc. Therefore the nature of the topographical high could be different from that of other topographic highs in the main part of the Ogasawara forearc. Therefore, another "serpentine diapir" from the main portion of the Ogasawara forearc should be drilled for comparison.

The detailed descriptions of the expected sites can be found in the following proposal:

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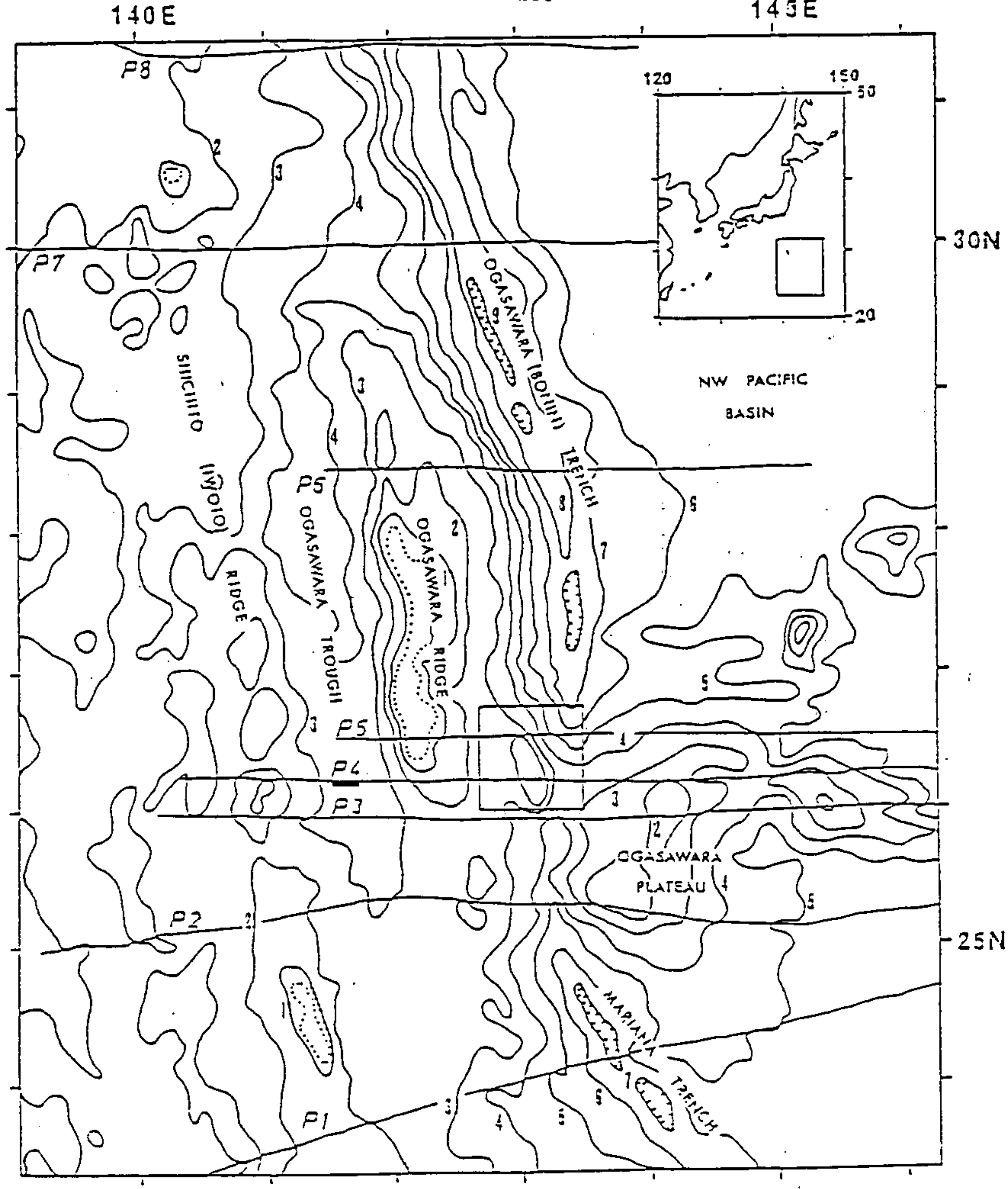
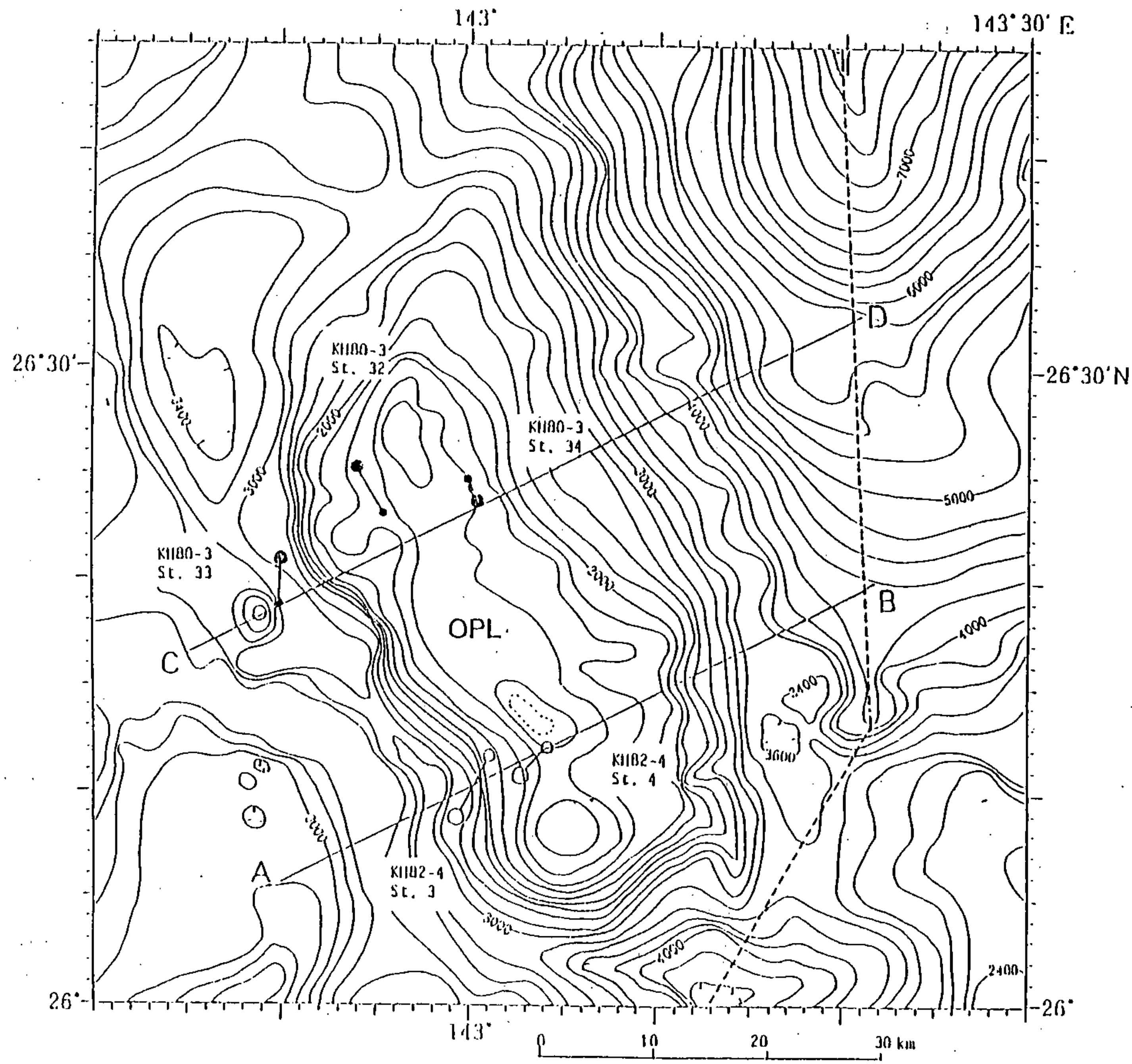



FIG. 1.
(from Ishii, 1985)


143°
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OPL
KH80-3
St. 32
KH80-3
St. 34
KH80-3
St. 33
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St. 4
KH82-4
St. 3
0
10
20
30 km

Fig. 2.(Ishii, 1

# The Kermadec Volcanic Arc System: some observations and suggestions for future work

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The Tonga/Kermadec Volcanic Arc System is unusual for its apparent linearity. Most arcs are arcuate, hence their name, but the Tonga/Kermadec system maintains an essentially straight, non arcuate shape from Samoa at 15 S to New Zealand at 38 S, a distance of more than 2500 km. However there are several distinct changes in the Tonga-Kermadec system that occur along strike. The two most significant of these occur at latitudes: (1) 24-26 S, and (2) 32-35 S (Fig. 1).

1. The northern change (at 24-26 S) is marked by:

   (a) offset trenches and forearc platforms;

   (b) narrowing of back-arc basins to the south;

   (c) shallowing of back-arc basins at these latitudes;

   (d) change in strike of Lau Ridge.

The Louisville Ridge collides with the Tonga-Kermadec subduction system at these latitudes and subduction of the ridge is thought to account for these changes.

2. The southern change (at 32-35 S) is marked by:

   (a) a shallowing of the Kermadec Trench to the south;

   (b) a substantial widening of the forearc basin to the south forming the Raukumara Plain;

   (c) a change in strike of Kermadec and Colville Ridges and Havre Trough;

   (d) a narrowing and reduction in size of Kermadec and Lau/Colville Ridges to the south.

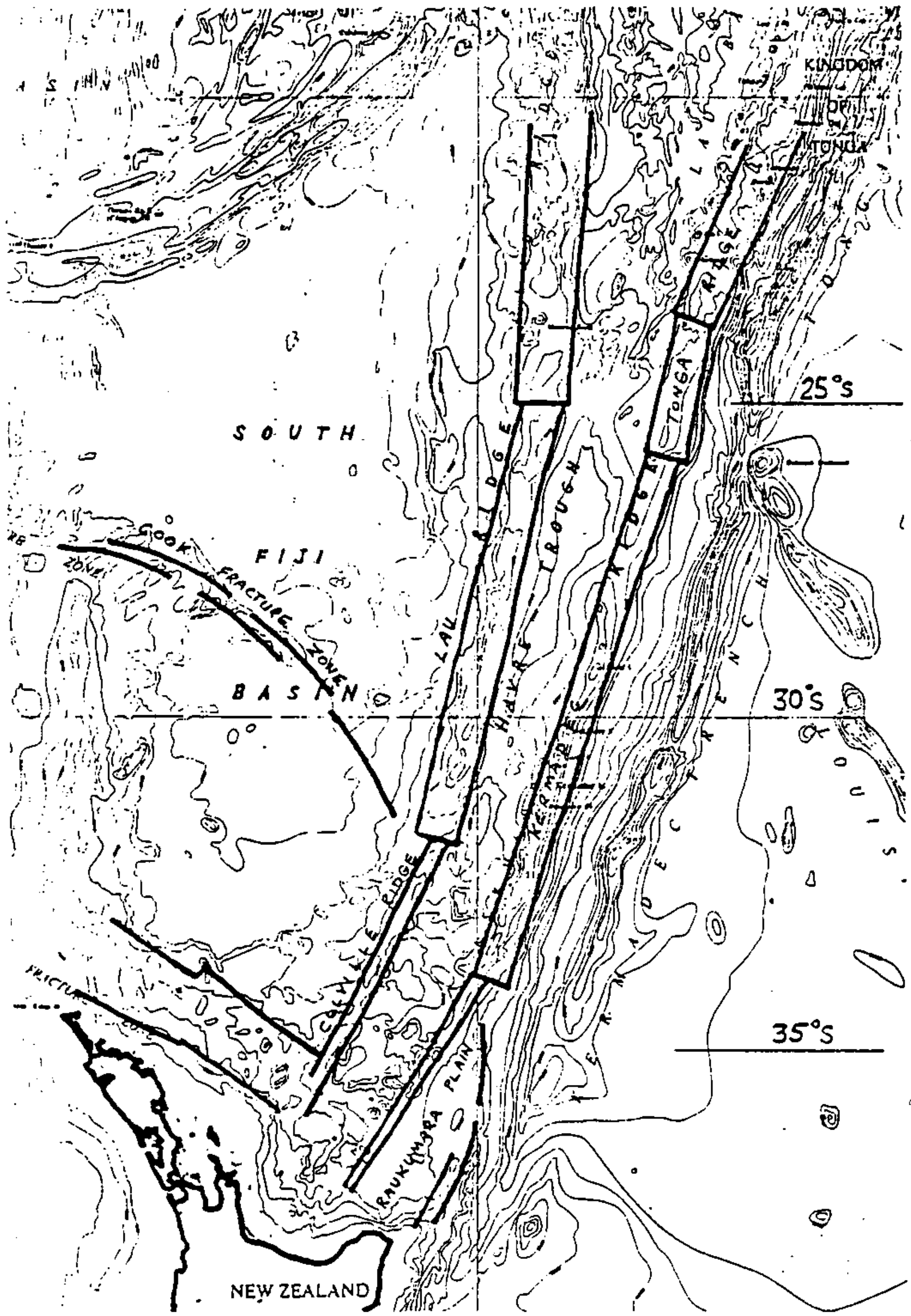
the south of particular note is the change in character of Kermadec d Lau/Colville Ridges. North of 32 S (Lau Ridge) and 34 S (Kermadec dge) both ridges are continuous sediment covered features presenting significant segments of arc crust. To the uth they are discontinuous and formed of lines of diment-free volcanic peaks. Arc crust appears to be absent uth of 32-34 S. The Cook Fracture Zone appears to et the Lau/Colville Ridge at 32 S where the ridge changes in aracter.

Some of the unusual features of the southern part of e Kermadec arc system, especially the wide Raukumara ain forearc, are thought to have formed in response to an :eanic plate boundary meeting a continent.

Another interpretation is that an older arc/back-arc ystem has been modified by movement on the Cook Fracture ne. It is possible that the southern part of the uth Fiji Basin and the original Kermadec arc forming its stern boundary were moved southeast along the Cook Fracture ne in the Miocene. Pliocene back-arc rifting separated c crust north of 32-34 S but to the south it appears to have fted the displaced oceanic crust of the South Fiji Basin. correct then Raukumara Plain is floored by Oligocene ceanic crust originally part of the South Fiji Basin and the avre Trough is bounded by oceanic crust. Volcanoes along e Havre Trough margins appear to be young and most may postate initial rifting of the trough.

The Havre Trough and its margins south of 32-34 S y be an excellent area to examine processes associated with initial fting of back-arc basins, especially volcanism. The presence both N-MORB and MTB-MORB crust in Lau Basin may be plained by assimulation of arc crust and magma mixing. study of the southern Havre Trough where arc crust ay be absent should have a more simple volcanic history with assimilation of arc crust and possibly minimal magma mixing.

The area is characterised by a lack of data. Initial rveys are needed to collect bathymetry, especially Seabeam, single annel seismic reflection, and rocks from Havre Trough, lville Ridge, Kermadec Ridge and East Cape Ridge. A eological and geophysical transect crossing Kermadec Trench, ast Cape Ridge, Raukumara Plain, Kermadec Ridge, Havre Trough, olville Ridge and South Fiji Basin is also recommended.


KINGDOM
OF
TONGA
25°S
30°S
35°S
SOUTH
FIJI
BASIN
COOK FRACTURE ZONE
LAU RIDGE
HAVRE TROUGH
TONGA RIDGE
KERMADEC RIDGE
KERMADEC TRENCH
TONGA TRENCH
COLVILLE RIDGE
RAUKUMARA PLAIN
NEW ZEALAND

# A CALL FOR THE DRILLING OF THE JAPAN SEA

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Understanding of the nature of the rifting and spreading of a continental margin is not sufficient compared with the backarc spreading of the oceanic crust. Scattered distribution of the continental fragments such as the Yamato Rise within the oceanic crust suggests that the Japan Sea was formed by the breakup of the continental margin by extension. The Japan Sea could be, therefore, a good target to study the backarc spreading tectonics in the continental margin. Furthermore, the recent accumulation of the various data including marine geophysics and land-based paleomagnetic and geochemical data suggests that the study of the Japan Sea is one of the most crucial problems to understand the tectonic evolution of the East Asia and the Japan Arc. Several holes were drilled during the former DSDP; however, the penetration into the basement was not obtained by several reasons (Karig and Ingle, 1975). Magnetic dating is not also successful because of the weakly developed magnetic lineation (Isezaki and Uyeda, 1973). The age and the geochemical nature of the oceanic crust of the Japan Sea are, therefore, still unknown.

It has been claimed that the Japan Sea was formed during late Cretaceous or Paleogene (e.g. Uyeda & Miyashiro, 1974). Kobayashi (1983) estimated the age of the Japan Sea based on the synthetic study of geophysical marine data as 45 Ma for the Japan Basin and 30 Ma for the Yamato Basin. Recently Tamaki(in press) suggested that the Japan Sea was formed 30 to 15 Ma based on the studies of the depth of the basement and heat flow data.

The recent results on the paleomagnetism of the Tertiary rocks of Japanese island (Otofuji and Matsuda, 1983, 1984; Otofuji et al., in press), however, lead to more drastic change of idea on the age of Japan

Sea. Otofuji and Matsuda (1984) concluded that the Southwestern Japan rotated clockwise 47 degrees at 15 Ma within a duration of 1 My. Tosha(1984) and Otofuji et al.(in press) suggested that the Northeast Japan rotated anticlockwise 20 degrees sometime during 22 to 15 Ma also based on the studies of the paleomagnetism. They claim that the Japan Sea might have opened 15 Ma and the event finished within a few My (Otofuji et al. prefer 1 My for the duration). If the suggestion from paleomagnetism is proved, the spreading rate of the Japan Sea is estimated to be 20-60 cm/year. The weakly developed irregular magnetic lineation within Japan Sea (e.g. Isezaki and Uyeda, 1973) could be due to the extraordinarily fast spreading rate.

Only the drilling penetrating the basement will give the solution to the above controversies on the age of the Japan Sea and present data on the geochemical nature of the oceanic crust because the thick sediments prevent sampling of the basement rocks by dredging. It is urgently necessary to determine the exact timing and the duration of the opening of the Japan Sea because the tectonic evolution of the Japan Arc and the East Asia is deeply related to the opening of the Japan Sea.

Wide distribution of 3.5 km/sec velocity layer (e.g. Ishiwada et al., 1984) with the thickness of 1 to 2 km is another unique characteristics of the Japan Sea. In the South China Sea Basin, such a 3.5 km/sec layer is not recognized. It could be related to the extraordinary feature of the back arc spreading of the Japan Sea. The materials constituting the peculiar layer should be identified by drilling.

Another feature to be addressed related to the Japan Sea is that a new subduction boundary is developing along the eastern margin of the Japan Sea (Seno and Eguchi, 1983; Kobayashi, 1983; Nakamura, 1983). Tamaki and Honza (in press) identified a thrust zone along the eastern margin of the Japan Sea and suggested that the oceanic crust of the Japan Sea is partly subducting beneath the Japan Arc but some parts are obducting onto the Japan Arc. The age of the initiation of the convergence is believed to be sometime after Pliocene based on the land-based geological data; however, the exact age is unknown. These suggestions should be testified by the drilling and the results will contribute to the understanding of the total history of back arc basins.

This paper is not a proper ODP site proposal but makes general remarks on the significance of the drilling of the Japan Sea. The detailed and the specific descriptions of the expected sites of the Japan Sea will be found in the proposals prepared by several people which are referred at the end of this paper. The locations of the drilling sites suggested in these proposals are plotted in Fig. 1. Those sites were carefully selected by Dr. Tamaki and his colleagues of the Geological Survey of Japan mainly based on MCS profiles to avoid the penetration of the possible ethene gas charged layers. The site number in Fig. 1 is based on the proposal prepared by Tamaki and others.

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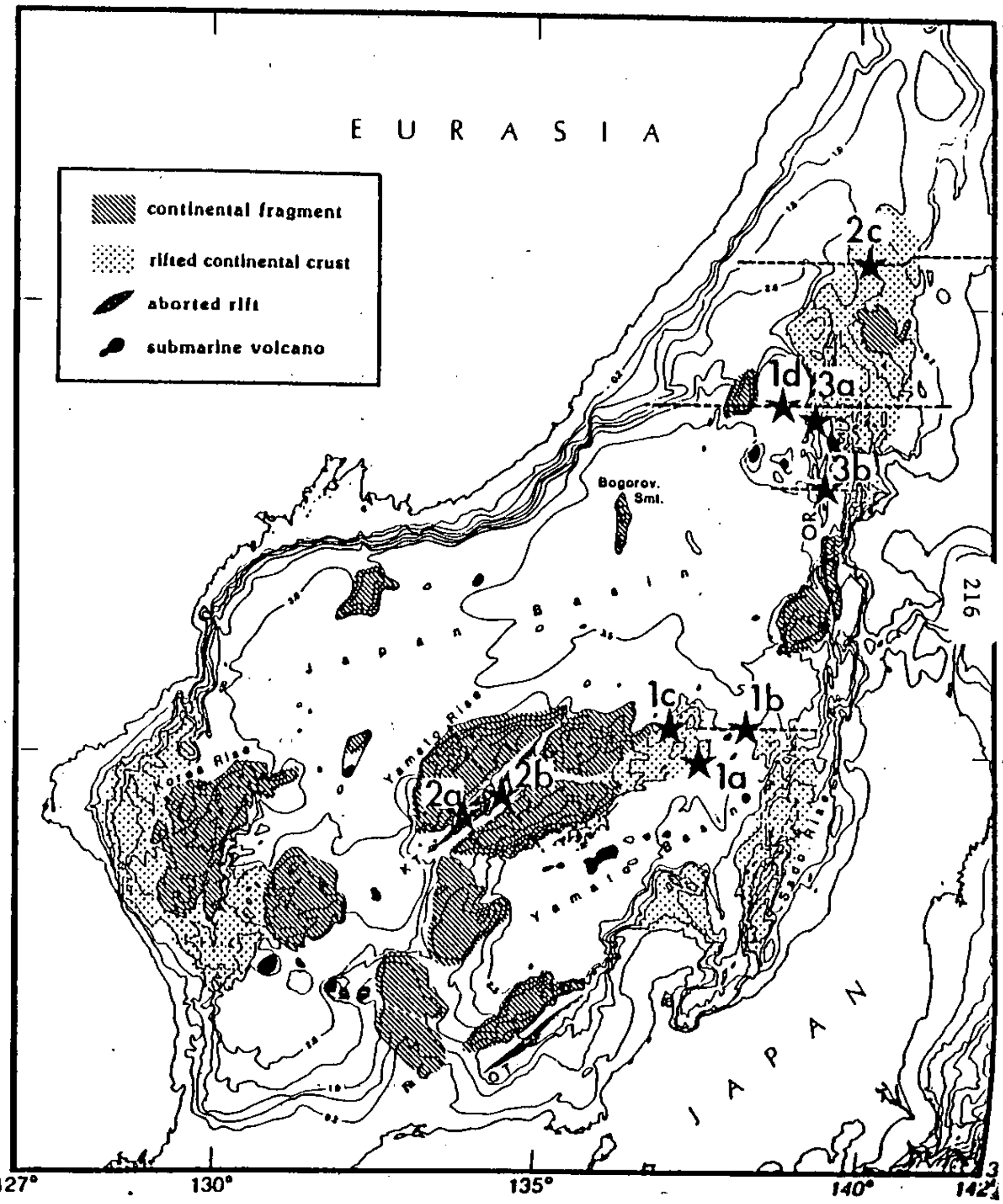


Fig. 1

Proposed sites of the Japan Sea with geological classification of the topographic highs (Tamaki, in press, a). Dashed lines show tracks of seismic profiles. KT:Kitayamato Trough, OR: Okushiri Ridge.

# DRILLING PROPOSAL TO BACK-ARC DRILLING CONFERENCE,

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## SUBMARINE FANS IN ARC-BACK ARC SYSTEMS; WHAT WE NEED TO LEARN:

The internal character, origin and variability of active margin submarine fans is poorly understood. Although morphology and both general facies patterns and processes are known from such fans (Normark,1978; Graham and Bachman,1983), Nash,1981; amongst many others), the degree of variability of sedimentation styles of active margin fans is only now beginning to be understood (Stow et al,1984; Normark and Barnes,1984).

In passive margins, more is known about sediment variability and causes of fan formation (Leg 96 Scientific Staff, 1984; Damuth and Flood,1984; Damuth et al,1983; Stow,1981). These workers, amongst others, demonstrated variability in size, sedimentation patterns, lobe occurrence and development, channel morphology and growth patterns. The degree of variability of sedimentation processes in passive margin submarine fans is large (Barnes and Normark, 1984), and appears to be as variable or more variable than deltas (Stow et al,1984; Normark et al,1984).

The timing and occurrence of submarine fans in response to extrinsic processes also is poorly understood. In passive margins, fan growth and active sedimentation appears to be favored during times when sea level is low (Leg 96 Scientific Staff,1984; Damuth et al,1983; amongst many others). In fact, recognition of submarine fans in seismic profiles recoverred from passive margins is a key baseline in identifying past times of low stands of sea level(Vail et al,1977). However, in active margins, tectonic uplift in island arc collision zones or other sources causes an increase in sediment yield to ocean basins (Yoshikawa,1984; Ohmori,1978). Thus, rates of sediment accumulation are large (Karig, Ingle et al,1975; Klein,1985) and periodicity of preserved turbidite events also is increased (Klein, 1984, 1985, In Press). This change in preserved turbidite periodicity is a direct function also of rate of tectonic uplift (Klein,1984) and masks the effects of sea level fluctuations (Klein, In Press). Thus, in active margins, sea level appears to be of lesser importance in controlling fan growth and evolution, but this interpretation requires testing which can be acheived only be careful drilling.

In the submarine fans of arc-back arc systems, the following problems need to be addressed and can be solved only by drilling.

1). What is the nature and origin of fan growth?

2). What is the vertical and lateral facies variation in such fans in response to shifting channels, levees, interchannel regions and fan lobes?

3) What is the periodicity of preserved turbidites in such fans and how do changes in periodicity record changes in uplift rate of known sources, as well as fluctuations in sea level?

4). Is the periodicity of turbidites a function of extrinsic processes such as sea level and uplift, or is it controlled locally by subenvironment? Does it differ between subenvironment. Or, does a uniform record of periodicity exist in all subenvironments of a fan because of processes of flow stripping (Piper and Normark,1983) which causes deposition of turbidites at the same time, but of different textural charachter, in all these subenvironments as a single event stratum?

5). How does the internal character of active margin fans differ from passive margin fans? How does the history of shifting fan lobes compare to passive margins and other fans? Do small or medium-sized lobes exist at the mouths of channels (Normark,1978) or does the fan represent a succession of partial or completely-stacked lobes such as in the Missisippi Fan (Leg 96 Scientific Staff,1984)?

The submarine fan recommended for intensive drilling in an arc-back arc system is the Toyama submarine fan in the eastern Japan Sea. The drilling rationale for selecting this fan is provided below. Drilling in Toiyama Fan also provides an opportunity to address other tectonic and lithospheric problems which are also discussed below

DRILLING RATIONALE AND LOCATION: Toyama Submarine Fan, eastern Japan Sea:

The Toyama Fan (figures 1 and 2) formed in response to major uplift in the Hida Range of Honshu Island, Japan (Sugi et al,1983; Matsuda et al,1967; Karig, Ingle et al,1975; Klein, 1984,1985, In Press). Uplift of Hida Range was in response to collision of the Eurasian and North American plates along the so-called magna fossa of Honshu (Nakamura,1983; Tamaki and Honza, In Press). That plate boundary extends into the Sea of Japan as the Toyama Trough which passes below the Toyama Fan (Figure 3). Thus drilling on the Toyama Fan provides dual opportunities not only to characterize, sediment-ologically, an active margin submarine fan system, but also to sample and obtain sedimentary, structural( fracture), tectonic and crustal data from a so-called "nascent trench" (Nakamura,1983). Moreover, it provides an opport-unity to determine to what extent, collisional uplift, sea level, or other factors, controlled fan sedimentation.

Drilling into Toyama fan is justified for other reasons as well. At the present time, models of fan growth are in a state of flux (Normark and Barnes,1984) with existing models considered premature. Recent studies emphasized that submarine fan deposition is extremely variable; perhaps more variable than deltaic sedimentation (Stow et al,1984; Normark et al,1984). Moreover, less is known about the sedimentology of active margin fans than those from passive margins. Drilling into the Toyama Fan will, therefore, be a major contribution to understanding the growth, evolution and variability of submarine fan systems.

Additionally, a great gap in data exists about the tectonics and lithospheric composition in the Japan Sea that awaits solution from drilling. The age of the sea floor underlying the Japan Sea requires direct confirmation of magnetic anomaly mapping by Kobayashi and Isezaki (1976). This confirmation only can be accomplished with drilling. Moreover, the nature and composition of the crust beneath Toyama Fan and the eastern Japan Sea is unknown also. Discovery of a major plate boundary along the eastern Japan Sea (Nakamura,1983; Tamaki and Honza, In Press) raises the question whether the crust east of the collision zone is continental or oceanic. Drilling will provide answers to this problem.

DRILLING OBJECTIVES:

Sedimentary Objectives: Drilling into the Toyama Fan should solve the following sedimentological and related problems:

(1) What are the basic sediment characteristics, variability and distribution in three-dimensions on an active margin submarine fan? How do these features differ from fans in passive margins or other active continental margins?

(2) What caused Toyama Fan to develop? Is it strictly uplift of the Hida Range as proposed by several workers, or did sea level changes play a role? What is the relative importance of each?

(3) What is the periodicity and frequency of preserved turbidite sedimentation events on this fan? Is the cause of systematic change in periodicity and frequency a function of uplift rate (Klein,1984, 1985, In Press) or is it sea

level fluctuations as in passive margin fans? Does change in periodicity and frequency of preserved turbidites indicate anything about a possible change in climate over Honshu while the Hida Range underwent uplift and change atmospheric circulation patterns?

(4) How do periodicities and frequencies of preserved turbidites differ in distinct subenvironmental components of Toyama Fan? Does each subenvironment record a different periodicity because of local environmental control, or is periodicity independent of local controls because processes of turbidity current flow stripping (Piper and Normark, 1983) separated a single turbidity current into several coeval turbidity currents, which accumulate in turn as separate turbidites in different subenvironments at the same time (Klein, In Press)?

(5) How does one characterize the sedimentary features of different fan subenvironments such as levees, channels and interchannel areas in active margin fans?

(6) What is the age of the fan?

(7) What is the nature of the sedimentary substrate below the fan? Or, does the fan rest directly on ocean or continental crust?

(8) How do different subenvironments of the fan shift through time?

(9) What was the growth and development of Toyama Fan, and can it serve as a reference for other submarine fans?

Tectonic and Crustal Drilling: Drilling is recommended in the eastern Japan Sea to solve the following structural, tectonic and petrological problems:

(1) What is the basement age of the eastern Japan Sea?

(2) How do fracture systems within recovered sediments and crustal rcoks change downhole? To what extent does change in fracture patterns indicate a change in stress field (cf. Moore and Lundberg,1983; Lundberg,1983). Can such inferred stress field changes be correlated to relatively recent collision of

the Eurasian and North American Plate? What is the age of the change in the inferred stress field? How does that age help date the collision events observed in the eastern Japan Sea?

(3) What is the composition of the crust below the Toyama Fan, and the sea floor of the eastern Japan Sea, east of Toyama Trough, which Nakamura (1983) and Tamaki and Honza (In Press) consider to represent part of the North American Plate?

## DRILLING PLAN SUMMARY

Eight drill sites (and seven alternate sites) are recommended to meet these objectives (figures 2 and 3). Figures 4 and 5 show bathymetric profiles through some of these sites, whereas Figure 6 shows 3.5 KHz seismic profiles through two of the proposed sites. Complete site proposal forms are attached.

## SITE SURVEY RECOMMENDATIONS

A complete site survey of both Toyama Fan and the eastern Japan Sea is recommended. A few Japanese seismic lines are available (Nash,1981; Honza, 1979) but of variable quality (See Figure 6 ). Detailed multi-channel seismic surveys are required over each proposed site as a minimum.

Bathymetry of the fan (Figures 1 through 5) is better known (Nash,1981; Honza,1979). However, for drill site selection, mapping of Toyama Fan with a SEAMARK or GLORIA system is mandatory.

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FIGURE CAPTIONS.

Figure 1. Bathymetry of Toyama Submarine Fan, showing also the location of DSDP Site 299 and piston cores obtained by University of Tokyo, ORI. (Redrawn from Nash,1981).

Figure 2. Recommended and Alternate Drill Site Locations, Toyama Submarine Fan and site bathymetries (Redrawn from Nash, 1981).

Figure 3. Map of eastern Sea of Japan showing plate boundary (dashed line; Toyama Trough) and proposed sites (and alternates) to test for differences in sediments, structure and crustal character (Redrawn from Nakamura, 1983) on either side of "nascent trench" zone.

Figure 4. Bathymetric profile Lines R and S, showing suggested Site TF-5, and profile index map (Redrawn from Nash,1981).

Figure 5. Bathymetric profiles, Toyama Submarine Fan for proposed sites and profile index map (Redrawn after Nash,1981)

Figure 6. 3.5 Khz Seismic Profiles N-7 and N-8 through proposed Sites TF-2 and TF-6, and profile index map, Toyama Submarine Fan (Redrawn from Nash, 1981).

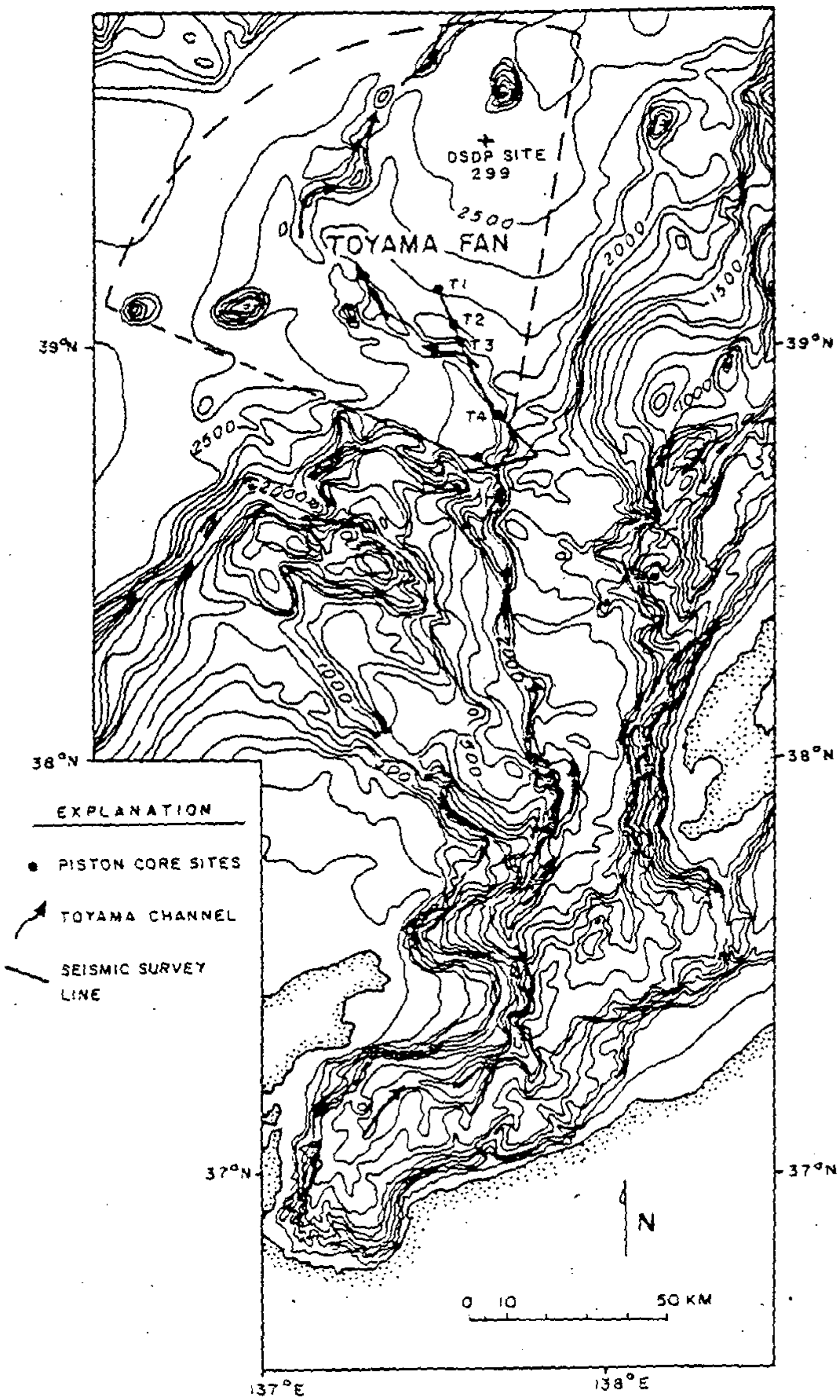

DSDP SITE
299
TOYAMA FAN
T1
T2
T3
T4
2500
2000
1500
1000
500
39°N
38°N
37°N
137°E
138°E
N
0 10 50 KM
EXPLANATION
PISTON CORE SITES
TOYAMA CHANNEL
SEISMIC SURVEY LINE

FIGURE 1

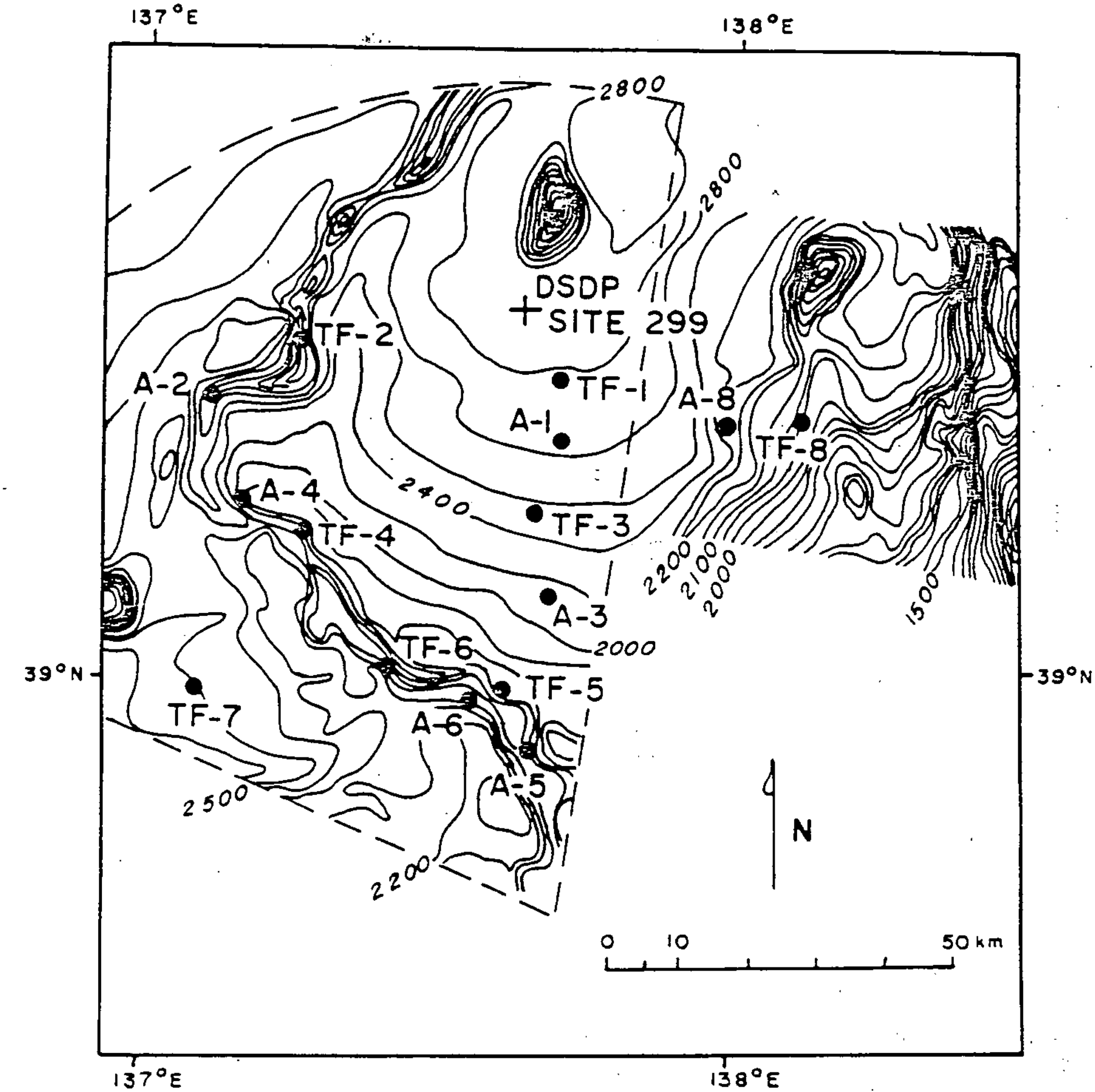
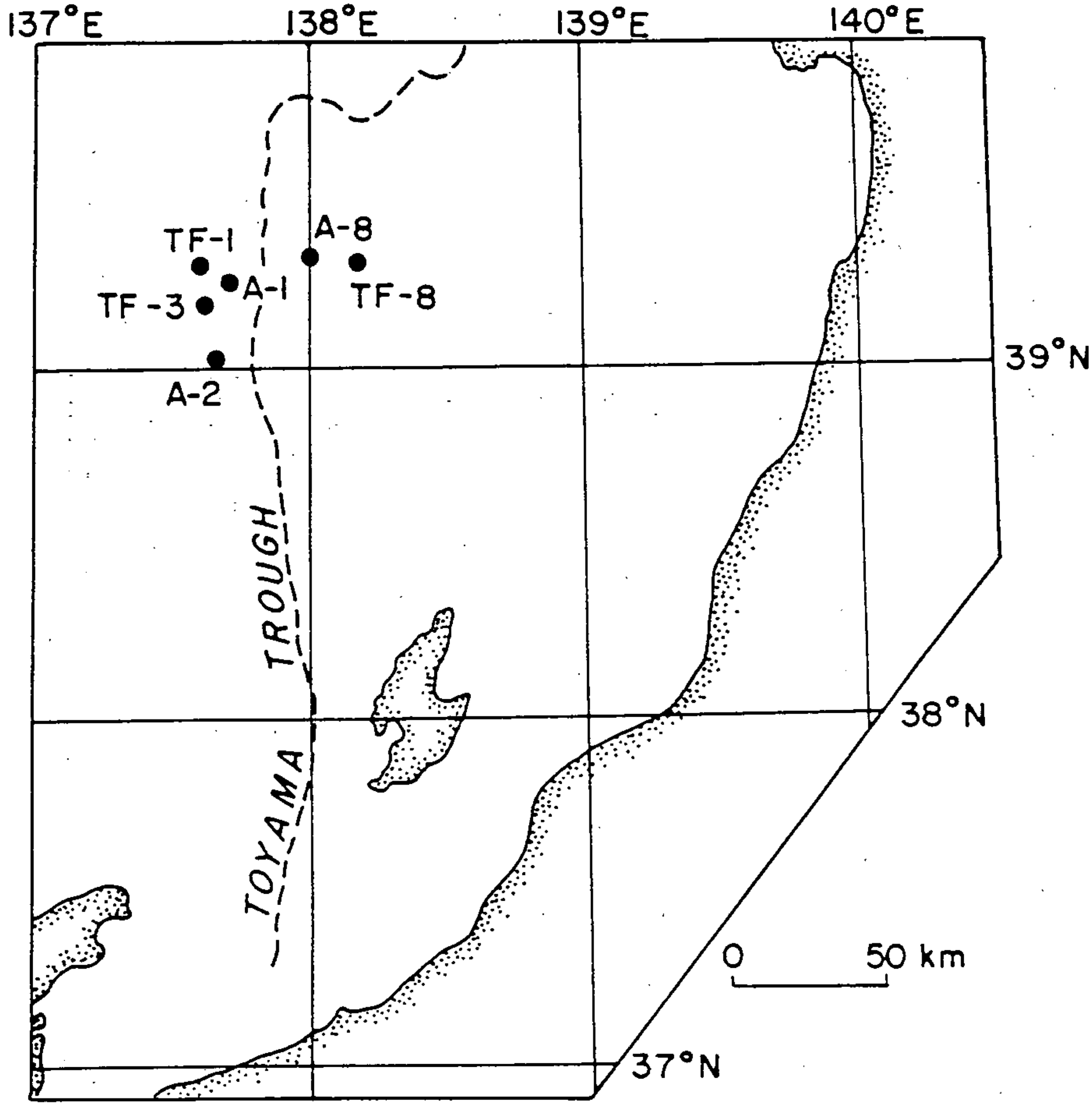

137°E
138°E
2800
2800
DSDP
SITE 299
TF-2
A-2
TF-1
A-8
A-1
TF-8
A-4
2400
TF-3
TF-4
2200
2100
2000
1500
A-3
2000
TF-6
39°N
39°N
TF-5
TF-7
A-6
A-5
2500
N
2200
0
10
50 km
137°E
138°E

FIGURE 2



137°E
138°E
139°E
140°E
39°N
38°N
37°N
TF-1
A-8
A-1
TF-3
TF-8
A-2
TROUGH
TOYAMA
0
50 km


FIGURE 3

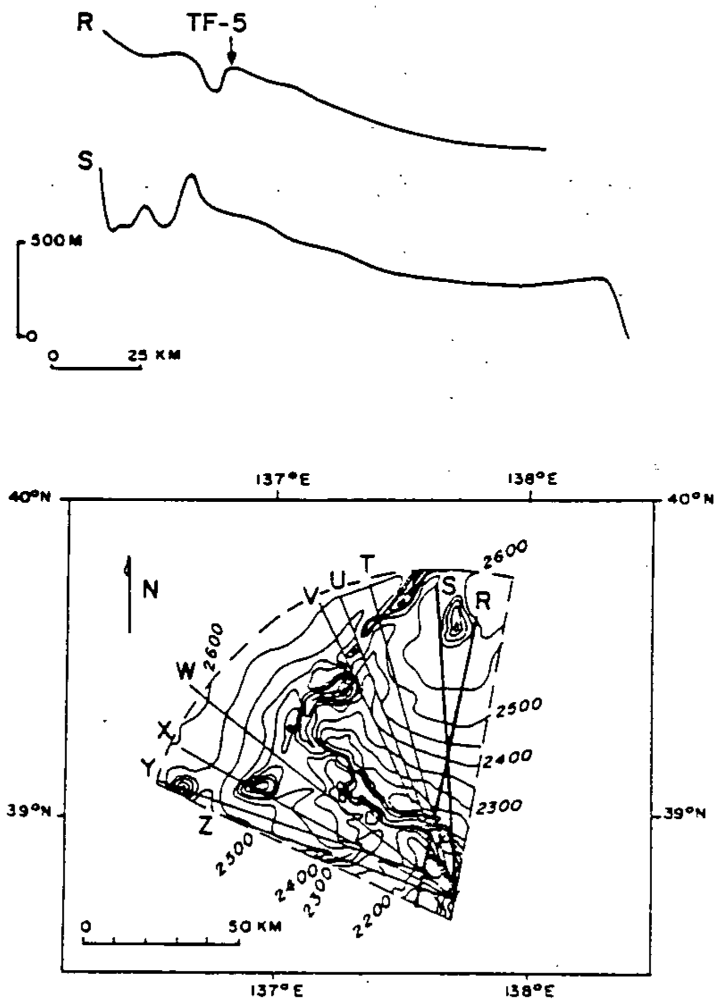

R
TF-5
S
500 M
0
0
25 KM
137°E
138°E
40°N
40°N
N
V
U
T
S
R
2600
W
2600
X
Y
2500
2400
2300
Z
2500
2400
2300
2200
39°N
39°N
0
50 KM
137°E
138°E

FIGURE 4.

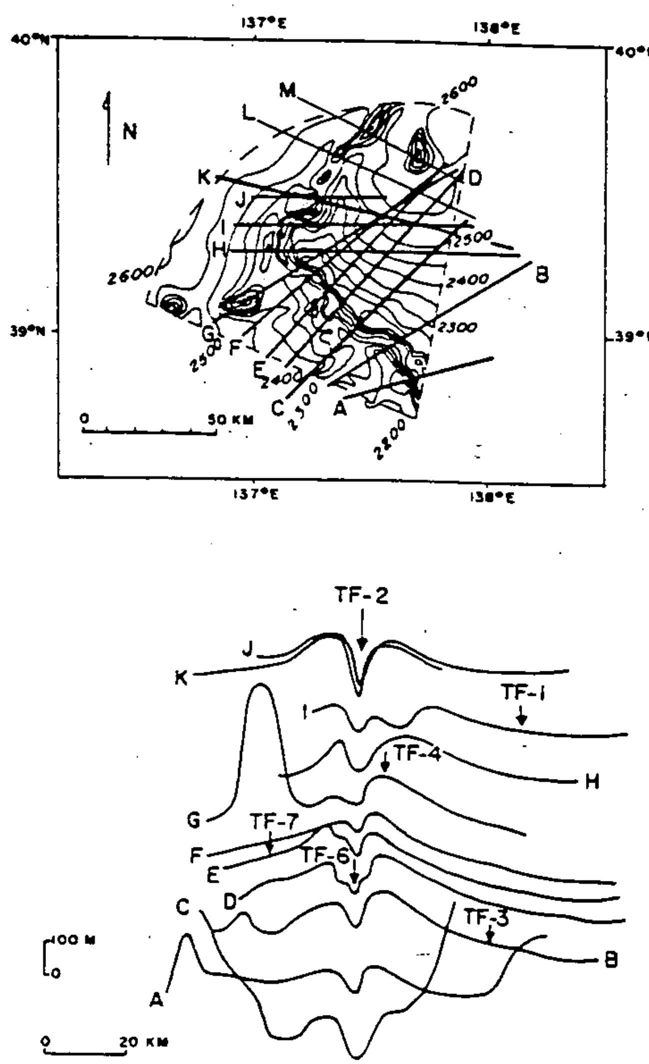

137°E
138°E
40°N
40°N
N
M
L
K
J
I
H
D
B
2600
2600
2500
2400
2300
2500
2400
2300
2300
2800
G
F
E
C
A
39°N
39°N
0
50 KM
137°E
138°E
TF-2
J
K
TF-1
I
TF-4
H
G
TF-7
F
E
TF-6
D
C
TF-3
B
A
100 M
0
0
20 KM

FIGURE 5

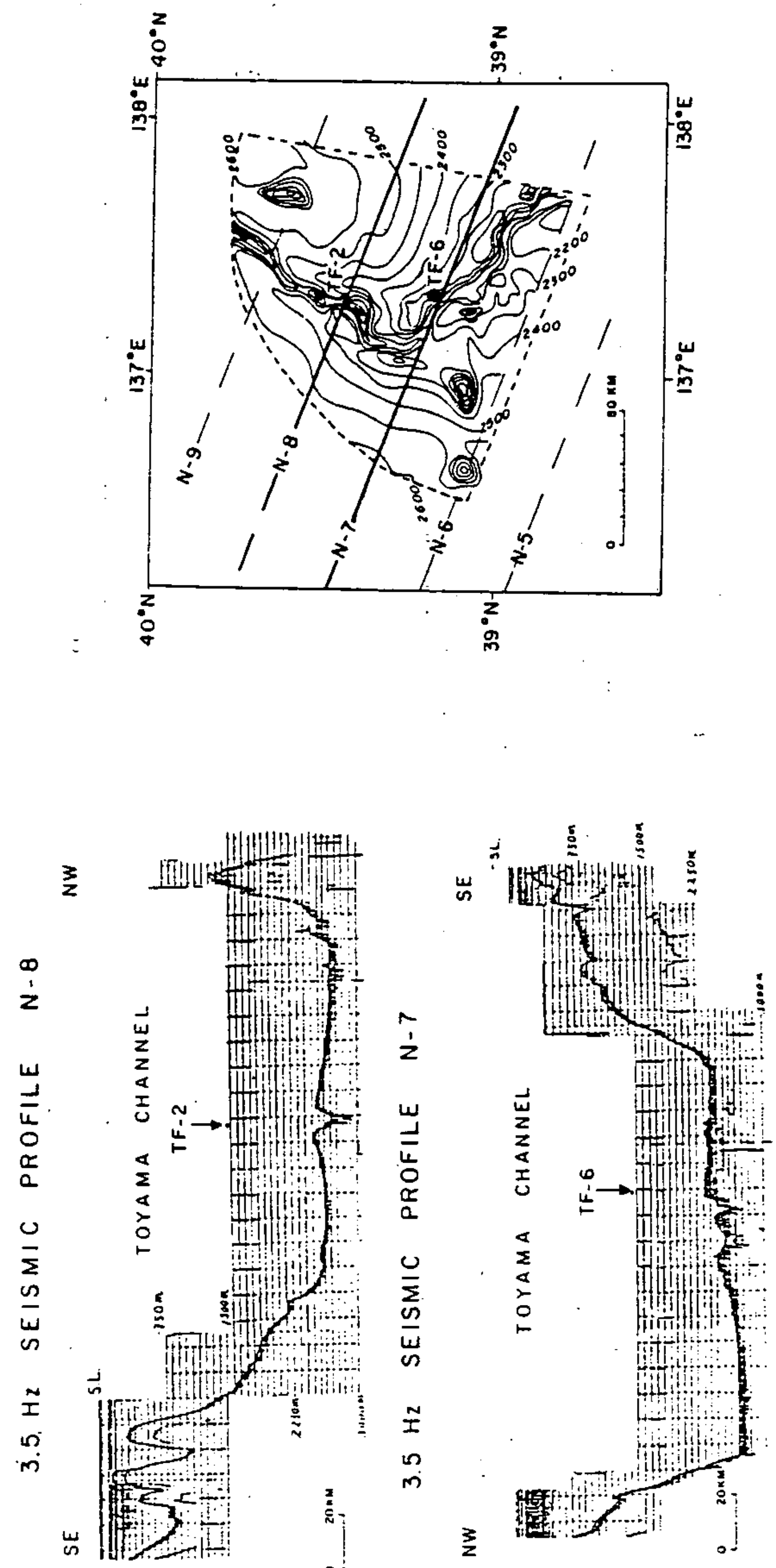

40°N
138°E
39°N
137°E
N-9
N-8
N-7
N-6
N-5
TF-2
TF-6
2200
2300
2400
2500
2600
80 KM
3.5 Hz SEISMIC PROFILE N-8
TOYAMA CHANNEL
TF-2
SE
NW
S.L.
20 KM
3.5 Hz SEISMIC PROFILE N-7
TOYAMA CHANNEL
TF-6
NW
SE
20 KM

FIGURE 6.

***ODP SITE PROPOSAL SUMMARY FORM***



osed Site: TF-1

yama SUbmarine Fan-Outer fan-
Interchannel fan region.

ral Area: eastern Sea of Japan
ion: 39°20 N, 137°41' E
nate Site: A-1

General Objective: (1) Character of fan subenvironment, (2) Turbidite periodicty and frequency, (3) change in fracture orientation, (4) age of basement, (5) nature of crust.

Thematic Panel interest: SOHP, TECP, LITHP
Regional Panel interest: WPAC

fic Objectives: (See Attached write-up). (1) Nature of Active margin fan, (2) sediment racteristics of interchannel fan area, (3) turbidite periodicity and frequency in response to ift history and sea level (4) Differences in turbidite periodicity and frequency in different subcomponents, (5) age of fan, (6) nature of sediments below fan, (7) changes in entation of fracture systems downhole in terms of collission history, (8) age of basement nature of crust, (10 History of shifting fan subcomponents and fan growth.

ground Information:
gional Data:
ismic profiles: Very few. ORI, Univ of Tokyo (Nash,1981) and Geol. SUrvey of Japan(Honza,1979) These are of fair to good.quality.
ther data: Piston cores (ORI; Geol. Survey of Japan), Bathymetry (ORI; Geol. Survey of Japan; thesis by Margaret Nash).
Survey Data - Conducted by:
ate: None
ain results:

ational Considerations

er Depth: (m) 2,670 m  Sed. Thickness: (m) 900m  Total penetration: (m) 1,100 m

++ ___  Double HPC ___  Rotary Drill ++ ___  Single Bit ___  Reentry +++ ___

re of sediments/rock anticipated: Sand, Silt, Clay, Basalt

ther conditions/window: April through July and Mid-September to mid-December is best time. Avoid typhoon season (Mid-July to Mid-September).
itorial jurisdiction: Japan

er:

ial requirements (Staffing, instrumentation, etc.)
ed to design core-catcher that will recover sand. Logging (Gamma Ray)
Bore-hole TV for fractures

onent: G.deV.Klein  Date submitted to JOIDES Office:

***ODP SITE PROPOSAL SUMMARY FORM***

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| | |
|---|---|
| ...posed Site: TF-2 Toyama Submarine Fan- outer fan - mid-channel.<br>...eral Area: eastern Sea of Japan<br>...ition: 39° 25'N, 137°17' E<br>...ernate Site: A-2 | General Objective: (1) character of outer fan channel sediments, turbidite periodicity and frequency (2) origin of fan (3) turbidite periodicity and frequency (in terms of tectonics/sea level) (4) Fan age.<br>Thematic Panel interest: SOHP<br>Regional Panel interest: WPAC |

...cific Objectives: (see attached write-up) (1) nature of active margin fan, (2) sediment ...racteristics of outer-fan channel system, (3) turbidite periodicity-frequency in response to ...ift history and sea level and (4) differences in periodicity-frequency between different ... subenvironments, (5) age of fan, (6) nature of sediments below fan (7) History of ...fting fan subenvironments and fan growth

...kground Information:

...gional Data:

...eismic profiles: Seismic Line N-8 from Geol. Survey of Japan (See figure 6 in attached write-up)

...ther data: Bathymetry (See Nash, 1981- also figure 1 and 2 in write-wup)

...te Survey Data - Conducted by: NONE

...ate:

...ain results:

...rational Considerations

...ter Depth: (m) 2,900 m  Sed. Thickness: (m) 1,000 m  Total penetration: (m) 600

... + Double HPC _____ Rotary Drill __+__ Single Bit + ____ Reentry _____

...ure of sediments/rock anticipated: Sand, silt and clay and lithified equivalents

...ther conditions/window: April through mid-July and Mid-September to mid-December are best times Avoid typhoon seas (Mid-July to Mid-September)

...itorial jurisdiction: Japan

...er:

...cial requirements (Staffing, instrumentation, etc.)

... a newly-designed core-catcher that will improve recovery of sand. Logging (Gamma Ray)

...ponent: G.deV.Klein  Date submitted to JOIDES Office:

Rev. 0281

* * *ODP SITE PROPOSAL SUMMARY FORM * * *



posed Site: TF-2
Toyama Submarine Fan- outer fan - mid-channel.

ieral Area: eastern Sea of Japan
ition: 39° 25'N, 137°17' E
ernate Site: A-2

General Objective: (1) character of outer fan channel sediments, turbidite periodicity and frequency (2) origin of fan (3) turbidite periodicity and frequency (in terms of tectonics/sea level) (4) Fan age.
Thematic Panel interest: SOHP
Regional Panel interest: WPAC

cific Objectives: (see attached write-up) (1) nature of active margin fan, (2) sediment racteristics of outer-fan channel system, (3) turbidite periodicity-frequency in response to ift history and sea level and (4) differences in periodicity-frequency between different subenvironments, (5) age of fan, (6) nature of sediments below fan (7) History of ifting fan subenvironments and fan growth

kground Information:
egional Data:
Seismic profiles: Seismic Line N-8 from Geol. Survey of Japan (See figure 6 in attached write-up)
Other data: Bathymetry (See Nash, 1981- also figure 1 and 2 in write-wup)

te Survey Data - Conducted by: NONE
Date:
Main results:

erational Considerations

ter Depth: (m) 2,900 m Sed. Thickness: (m) 1,000 m Total penetration: (m) 600

C + Double HPC ____ Rotary Drill + Single Bit + Reentry ____

ture of sediments/rock anticipated: Sand, silt and clay and lithified equivalents

ather conditions/window: April through mid-July and Mid-September to mid-December are best times Avoid typhoon seas (Mid-July to Mid-September)
ritorial jurisdiction: Japan
her:

cial requirements (Staffing, instrumentation, etc.)
a newly-designed core-catcher that will improve recovery of sand. Logging (Gamma Ray)

ponent: G.deV.Klein Date submitted to JOIDES Office:

Rev. 0281

# ***ODP SITE PROPOSAL SUMMARY FORM***



**Proposed Site:** A-2

ALTERNATE for TF-2

**General Area:** eastern Sea of Japan
**Position:** 39°22'N, 137° 9E
**Alternate Site:** (TF-2)

**General Objective:**

See TF-2

**Thematic Panel interest:**
**Regional Panel interest:**

**Specific Objectives:**

See TF-2

**Background Information:**
Regional Data:
Seismic profiles: SEE TF-2

Other data:

Site Survey Data - Conducted by: None
Date:
Main results:

**Operational Considerations**

Water Depth: (m) 2,600 Sed. Thickness: (m) 1,300 Total penetration: (m) 600

HPC ___±___ Double HPC _____ Rotary Drill _____ Single Bit ___+___ Reentry _____

Nature of sediments/rock anticipated: See TF-2

Weather conditions/window: See TF-2

Territorial jurisdiction: Japan

Other:

**Special requirements** (Staffing, instrumentation, etc.)

See TF-2

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

Rev.

***ODP SITE PROPOSAL SUMMARY FORM***



Proposed Site: TF-3
Toyama Submarine Fan - Middle fan-
Interchannel fan region

General Area:
Position:
Alternate Site: A-3

General Objective: (1) Character of interchannel-fan (mid-fan) sub-environment (2) turbidite periodicity and frequency, (3) origin of fan, fan age (4) chang in fracture orientation, (5) basement age (6) nature of crust.

Thematic Panel interest: SOPH, TECP, LITHP,
Regional Panel interest: WPAC

Specific Objectives: (See attached write-up) (1) Nature of active margin fan, (2) sediment characteristics of mid-fan, interchannel subenvironment, (3) turbidite periodicity and frequency (in terms of uplift and sea level) and (4) in terms of changing subenvironments on fan (5) age of fan, (6) nature of sediments below fan, (7) changing orientation of fracture systems downhole in terms of collision history, (8) basement age, (9) nature of curst (10) History of shifting fan subcomponents and fan growth

Background Information:
Regional Data: - Very little (See Nash, 1981)
Seismic profiles: ORI, Univ of Tokyo, and Geol. Survey of Japan (Honza, 1979).
These are of rair to goo quality.
Other data: Bathymetry - ORI (Nash, 1981)

Site Survey Data - Conducted by: None
Date:
Main results:

Operational Considerations

Water Depth: (m) 2450 Sed. Thickness: (m) 900 m Total penetration: (m) 1,050 m

HPC +++ Double HPC ____ Rotary Drill ++ Single Bit ++ Reentry Possible

Nature of sediments/rock anticipated: Sand, silt and clay (and lithified equivalents), Basalt

Weather conditions/window: April through Huly and Mid-September to Mid-December is best time.
Avoid typhoon season (mid-July to Mid-September)
Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)
Need to design core-catcher that will recover sand. Logging (Gamma Ray).
Bore-hole TV for fractures

Proponent: Date submitted to JOIDES Office:

Rev. 02-

# ***ODP SITE PROPOSAL SUMMARY FORM***



**Proposed Site:** A-3

ALTERNATE for TF-3

**General Area:** See TF-3
**Position:** 39°05'N, 137°42'E
**Alternate Site:** (TF-3)

**General Objective:**

See TF-3

**Thematic Panel interest:**
**Regional Panel interest:**

**Specific Objectives:** See TF-3

**Background Information:** SEE TF-3
Regional Data:
Seismic profiles:

Other data:

Site Survey Data - Conducted by:
Date:
Main results:

**Operational Considerations**

Water Depth: (m) 2120 Sed. Thickness: (m) 1,200 Total penetration: (m) 1,350 m

HPC +++ Double HPC ____ Rotary Drill +++ Single Bit +++ Reentry Possibly

Nature of sediments/rock anticipated: See TF-3

Weather conditions/window: See TF-3

Territorial jurisdiction: Japan

Other:

**Special requirements** (Staffing, instrumentation, etc.)

See TF-3

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

Rev.

***ODP SITE PROPOSAL SUMMARY FORM***



| | |
|---|---|
| osed Site: TF-4 | General Objective: (1 Character of fan sub-environment (levee), (2) turbidite periodicity and frequency, (=3) origin of fan (4) fan age |
| oyama Submarine Fan - Mid fan-Levee | |
| eral Area: eastern Sea of Japan | |
| tion: 39°12'N, 137°17'E | Thematic Panel interest: SOHP |
| rnate Site: A-4 | Regional Panel interest: WPAC |

ific Objectives: (See attached write-up). Nature of active margin fan (2)sedimentary characteristics of mid-fan channel system, (3) turbidite frequency-periodicity in response to uplift history and sea level, (4) differences in periodicity-frequency in different fan subenvironments, (5) age of fan, (6) nature of sediments below fan, (7) history of shifting fan components, and fan growth.

kground Information:

gional Data:

eismic profiles: Perhaps available from ORI, Univ of Tokyo and Geol. Survey.of Japan. None are published or available to me.

ther data: Bathymetry (ORI) - See also Figure 2

e Survey Data - Conducted by: None

ate:

ain results:

rational Considerations

er Depth: (m) 2,200 Sed. Thickness: (m) 1,150 Total penetration: (m) 500 m

__+__ Double HPC ____ Rotary Drill __+__ Single Bit __+__ Reentry ____

ure of sediments/rock anticipated: sand, silt and clay (and lithified equivalents)

ather conditions/window: Best time is April through Mid-July and Mid-September to Mid-December to avoid summr typhoon season and winter conditions.

ritorial jurisdiction: Japan

er:

cial requirements (Staffing, instrumentation, etc.)

Need special core-catcher to recover adequate volume of sand; gamma ray logging

ponent: G.deV.Klein

Date submitted to JOIDES Office:

Rev. 025-

***ODP SITE PROPOSAL SUMMARY FORM***



Proposed Site: A-4

General Area: See TF-4
Position: 39° 14'N, 137° 11'E
Alternate Site: (TF-4)

General Objective: SEE TF-4

Thematic Panel interest:
Regional Panel interest:

Specific Objectives: SEE TF-4

Background Information:
Regional Data: SEE TF-4
Seismic profiles:

Other data:

Site Survey Data - Conducted by: See TF-4
Date:
Main results:

Operational Considerations

Water Depth: (m) 2,300 Sed. Thickness: (m) 1,150 Total penetration: (m) 500

HPC ++-- Double HPC _____ Rotary Drill ___+ Single Bit + ____ Reentry _____

Nature of sediments/rock anticipated: SEE TF-4

Weather conditions/window: See TF-4

Territorial jurisdiction: See TF-4

Other:

Special requirements (Staffing, instrumentation, etc.)

See TF-4

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

Rev.

Proposed Site: TF-5

Toyama Fan - Upper fan - Levee

General Area: eastern Sea of Japan

Position: 38°59'N, 137°37'E

Alternate Site: A-5

General Objective: (1)Character of fan and levee sub-component, (2) fan origin, (3) periodicity and frequency (in terms of sea level and uplift, (4) periodicity-frequency variation between fan subenvironments. (5) fan age

Thematic Panel interest: SOHP

Regional Panel interest: WPAC

Specific Objectives: (See attached write-up) (1) Nature of active margin submarine fan and upper fan levee sediments (2) turbidite periodicity and frequency in response to uplift history and sea level, (3) differences in periodicity-frequency in different fan subenvironments, (4) age of fan, (5) nature of sediments below fan, (6) history of shifting fan components, and fan growth.

Background Information:

Regional Data:

Seismic profiles: Perhaps available from ORI (Univ of Tokyo) and Geol. Survey of Japan. None available to me

Other data: Bathymetry (See figure 2)

Site Survey Data - Conducted by: None

Date:

Main results:

Operational Considerations

Water Depth: (m) 1,900 Sed. Thickness: (m) 1,400 Total penetration: (m) 500

HPC + Double HPC ____ Rotary Drill + Single Bit + Reentry ____

Nature of sediments/rock anticipated: Sand, silt and clay (and lithified equivalents).

Weather conditions/window: April through mid-July and Mid-September to Mid-December is best time. Avoids typhoon season and winter cold-air outbreaks off Si-eria.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Core catcher change to improve recovery of sand. Gamma Ray logging.

Proponent: G.deV.Klein Date submitted to JOIDES Office:

**ODP SITE PROPOSAL SUMMARY FORM**



Proposed Site: A-5

General Area: See TF-5
Position: 38°53'N, 137°40' E
Alternate Site: (TF-5)

General Objective: SEE TF-5

Thematic Panel interest:
Regional Panel interest:

Specific Objectives: See TF-5

Background Information: SEE TF-5
Regional Data:
Seismic profiles:

Other data:

Site Survey Data - Conducted by:
Date:
Main results:

Operational Considerations

Water Depth: (m) 2,200 Sed. Thickness: (m) 1,700 Total penetration: (m) 500

HPC ++ Double HPC ____ Rotary Drill ++ Single Bit ++ Reentry ____

Nature of sediments/rock anticipated: See TF-5

Weather conditions/window: See TF-5

Territorial jurisdiction: See TF-5

Other:

Special requirements (Staffing, instrumentation, etc.)

See TF-5

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

JOIDES SITE PROPOSAL SUMMARY FORM

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Proposed Site: TF-6
Toyama SUbmarine Fan - upper fan - channel

General Area: eastern Sea of Japan
Position: 39°01'N, 137°27'E
Alternate Site: A-6

General Objective: (1) character of fan subenvironment (upper fan channel), (2) fan origin, (3) periodicity and frequency (in terms of sea level, uplift) (4) periodicity-frequency variation between fan subenvironments, (5) fan age, (6) shifts of channel
Thematic Panel interest: SOHP
Regional Panel interest: WPAC

Specific Objectives: (See attached write-up). (1) nature of active continental margin fan and upper fan channel sediments (2) turbidite periodicity-frequency in response to uplift and sea level, (3) differences between subenvironments in turbidite periodicity and frequency, (4) age of fan, (5) nature of sediments below fan, (6) history of shifting fan subcomponents, and fan growth

Background Information:
Regional Data:
Seismic profiles: One proifile (Figure 6) from ORI at Univ of Tokyo (Nash, 1981). Perhaps also from Geological SUrvey of Japan (Honza, 1979).
Other data: Bathymetry - ORI (Nash, 1981)

Site Survey Data - Conducted by: None
Date:
Main results:

Operational Considerations

Water Depth: (m) 2,550 Sed. Thickness: (m) 1,500 Total penetration: (m) 500

HPC + Double HPC ____ Rotary Drill + Single Bit + Reentry ____

Nature of sediments/rock anticipated: Sand, silt and clay (and lithified equivalents).

Weather conditions/window: April through mid-July and Mid-September to Mid December to avoid typhoons and winter cold-air outbreaks.
Territorial jurisdiction: Japan

Special requirements (Staffing, instrumentation, etc.)

New core catcher to improve recovery of sand. Gamma Ray logging.

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

Rev. 0...

**Proposed Site:** A-6

**General Area:** See TF-6
**Position:** 38°58'N, 137°33'E
**Alternate Site:** (TF-6)

**General Objective:**
See TF-6

**Thematic Panel interest:**
**Regional Panel interest:**

**Specific Objectives:** See TF-6

**Background Information:**
Regional Data: SEE TF-6
Seismic profiles:

Other data:

Site Survey Data - Conducted by:
Date:
Main results:

**Operational Considerations**

Water Depth: (m) 2,450 Sed. Thickness: (m) 1,600 Total penetration: (m) 500

HPC ++ Double HPC ____ Rotary Drill ++ Single Bit ++ Reentry ____

Nature of sediments/rock anticipated: See TF-6

Weather conditions/window: See TF-6

Territorial jurisdiction: See TF-6

Other:

**Special requirements** (Staffing, instrumentation, etc.)
See TF-6

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

Re:

Proposed Site: TF-7

Toyama Submarine Fan - Mid-fan-Interchannel fan region

General Area: eastern Sea of Japan

Position: 38°58.5'N, 137°06'E

Alternate Site: TF-3

General Objective: (10 CHaracter of fan subenvironment (interchannel fan area) (2) fan origin, (3) periodicity/frequency (in terms of sea level, uplift) and fan subenvironments, (4) fan age, (5) shifts of subenvironmetns through time.

Thematic Panel interest: SOHP

Regional Panel interest: WPAC

Specific Objectives: (See attached write-up). (1) nature of active continental margin fan and middle fan interchannel fan setting, (2) turbidite periodicity-frequency in response to uplift and sea level, (3) differences between fan subenvironments in terms of periodicity and frequency of turbidites, (4) age of fan, (5) nature of sediments below fan, (6) history of shifting fan subcomponents.

Background Information:

Regional Data:

Seismic profiles: Perhaps available from ORI (Univ. of Toky) and Geol. Survey of Japan. None available to me.

Other data: Bathymetry (Figure 2)

Site Survey Data - Conducted by:

Date: NONE

Main results:

Operational Considerations

Water Depth: (m) 2,500   Sed. Thickness: (m) 1,100   Total penetration: (m) 500

HPC ++   Double HPC ____   Rotary Drill ++   Single Bit ++   Reentry ____

Nature of sediments/rock anticipated: Sand, silt and clay (and lithified equivalents)

Weather conditions/window: APril - July and Mid-september-mid-December are best times to avoid winter col-air outbreaks and summer typhoons.

Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

core catcher to improve sand recovery. Gamma Ray logging.

Proponent: G.deV. Klein

Date submitted to JOIDES Office:

Proposed Site: TF-8

General Area: East side of Toyama Trough
Position: 39°19'N, 138°8'E
Alternate Site:

General Objective: (1) Age of basement, (2) vert change in fractures in response to collision his (3) nature of crust.

Thematic Panel interest: TECP, LITHP, SOHP
Regional Panel interest: WPAC

Specific Objectives: (See attached write-up). (1) Age of basement, (2) vertical changes in fracture orientation as an indication of progressive stress in response to collision and development of new plate boundary between Eurasian Plate and North American (or Honshu) plate as per Nakamura (1983), (3) Composition of basement rocks (are they oceanic or continental)

Background Information:
Regional Data:
Seismic profiles: Possibly available from Geol. Survey of Japan. None available to me.

Other data: Bathymetry (Figure 3- Nakamura,1983)

Site Survey Data - Conducted by: None
Date:
Main results:

Operational Considerations

Water Depth: (m) 2,100 Sed. Thickness: (m) 600 m Total penetration: (m) 750 m

HPC ____ Double HPC ____ Rotary Drill _+_ Single Bit ____ Reentry _+_

Nature of sediments/rock anticipated: Sand, silt and clay, either oceanic basalt, or continental granites, metamorphics or sediments.
Weather conditions/window: April through mid-July and Mid-September to Mid-December are best ti to avoid both typhoons and winter cold-air outbreaks.
Territorial jurisdiction: Japan

Other:

Special requirements (Staffing, instrumentation, etc.)

Gamma Ray Logging, Video borehole system.

Proponent: G.deV.Klein

Date submitted to JOIDES Office:

| | |
|---|---|
| posed Site: A-8 | General Objective: See TF-8 |
| neral Area: See TF-8<br>sition: 39°N, 138°00'E<br>ernate Site: (TF-8) | Thematic Panel interest:<br>Regional Panel interest: |

cific Objectives: See TF-8

ckground Information:
egional Data: See TF-8
Seismic profiles:

Other data:

ite Survey Data - Conducted by:
Date:
Main results:

perational Considerations

ater Depth: (m) 2,450 Sed. Thickness: (m) 600 m Total penetration: (m) 750

PC ++ Double HPC ____ Rotary Drill + Single Bit ____ Reentry +

ature of sediments/rock anticipated: See TF-8

eather conditions/window: See TF-8

erritorial jurisdiction: See TF-8

ther:

pecial requirements (Staffing, instrumentation, etc.)

See TF-8

roponent: G.deV.Klein

Date submitted to JOIDES Office:

## APPENDIX
## LIST OF CONTRIBUTIONS BY PARTICIPANTS

S.H. Bloomer, Tectonic erosion, accretion and vertical motions in forearcs of intraoceanic subduction zones

L. Dorman and J. Hildebrand, Deep structure of back-arc basins from seismic tomography

M. Flower and L. Rodolfo, North-zouth transect of diachronous arc sundering

P. Fryer,E. Ambos,and D. Hussong, Origin and emplacement of Mariana forearc seamounts

J. Haggerty, Determination of the historu of vertical movements in forearcs

E. Ito,R. Schuit,G. Smith, Possible problems to be addressed by lithospheric drilling program in the western Pacific arc- backarc systems

J. Morris, Deep drilling project, Western Pacific arcs, backarcs, and trenches

J. Morton, An axial magma chamber on Valu Fa ridge,a back-arc spreading center in Lau Basin

R. Poreda, Helium - 3 and deuterium in backarc basalts: Lau Basin and Mariana Trough

M. Rideout and L. Guth, Ocean Drilling Project studies in active western Pacific trench- arc- backarc systems

D. Stakes, Drilling targets in back-arc basin crust: recommendations from the Lau Basin

R. Stern, The earliest stages of islnd arc and backarc basin development; a call for study

DRILLING TARGETS IN FORE-ARC to ARC to BACK-ARC REGIONS OF THE WESTERN PACIFIC

a brief statement of philosophy and possible targets

Richard J. Arculus, Dept. of Geol. Sciences, Univ. of Michigan

Our knowledge of the early growth stages of arcs is fairly rudimentary, and we lack detailed understanding of the evolutionary and constructive processes taking place in mature arcs. The enhanced technical capability of the latest ODP drilling platform offers some exciting prospects for attacking some of the problems in these areas of uncertainty.

An important consideration for drilling arc-related targets seems to be the principle that the general pursuit of processes rather than specific parochial problem solving should guide the choice of drilling sites. However, a number of unusual tectonic locations are attractive despite the strong possibility that generalization of recovered rock information and stratigraphic detail may not be appropriate for many other locations. Furthermore, we know a good deal more about some locations than others, so it would seem inevitable that given a choice, the knowledge base should be a strong weighting factor.

Some of the general features that I would like to see tackled in a "deep" drilling program follow:

a) forearc — nature of fluids in overpressurd and dewatering sediments (latest developments in the oil business allow collection of unsullied formation fluids); stacking sequences over greater vertical intervals than heretofore sampled; serpentinite diapirs-structure, petrology, roots; possible penetration to slab-prism interface(s); boninite and other unusual forearc magmatism.

b) arc-forearc basins — volcanic-explosive activity records; nature of possible subaerial-submarine pyroclast flow deposits and chemistry; subsidence records.

c) arc — nature of basement over extended sampling depth (petrology, explosive and flow constructive elements, vertical compositional changes, sedimentary component, significance of dikes and sills in relation to the tectonic stress).

d) intrarc basins — nature of sediment fill; basement character; subsidence history.

e) back-arc — character of magmas in the transition zone with the arc and the local tectonic history; compositional evolution of magmas during subsequent spreading following initial rifting; nature of graben and leaky transform magmatism; volcanic history of arc determined from ash/pyrolclast cover; nature of continental fragments remnant from basin formation.

In terms of specific drilling targets, there is of course almost an embarassment of choice and many attractive sites come to mind. I would however, emphasize that my current knowledge of the activities of the various "international agreements for cooperative marine geologic studies" is not extensive, and I would urge collaboration wherever possible with these groups (eg Japan-France; Australia-New Zealand-USA etc.)

Specific Sites and Problems

forearcs Marianas-"pacman" eruptive and other hard rock outcrops observed in the Hawaiian group (Hussong, Fryer et al.) surveys

Solomon Is.-penetration through the prism to the shallowly subducted Solomon Sea Plate. A beautiful site explored with dredging and incorporating an astonishing variety of tectonic locations such as a subducting ridge overlain within a few kilometers by an active arc volcano.

The Nankai trough and Japan trench forearc--an extension of previous drilling programs in these regions capitalizing on the knowledge gained as well as being guided (hopefully) by the Japan-France submersible operations.

forearc basins New Zealand-northeast coast of the North Island; pyroclast flow and ash fall stratigraphy, volumetric relationships and physical volcanology.

arcs South of the Izu Peninsula (Honshu) for basement exploration (believed to be granitic); northeast of Hokkaido in transition to the Kuriles; Bonin Islands basement; near the submarine volcanoes of the northern Marianas; south end of Vanuatu near the recently constructed volcanoes of Mathew or Hunter; White Island off the North Island of New Zealand -interesting hydrothermal activity guaranteed.

intrarc basins Solomons and New Hebrides slots-beware of gas!

backarcs Marianas trough-northern area surveyed by the Hawaiian group; Bismarck Sea close to a ridge/transform junction and the Manus Basin close to the Willaumez-Manus Rise; Fiji Plateau at the possible triple junction; the Japan Sea microcontinental fragments and similarly the South China Sea continental remnants; the Three Kins Rise between Australia and New Zealand; the overdeeps along the Macquarie Ridge south of New Zealand.

# TECTONIC EROSION, ACCRETION AND VERTICAL MOTIONS IN FOREARCS OF INTRAOCEANIC SUBDUCTION ZONES

Notes for planning conference on ocean drilling studies in active trench-arc-backarc systems of the western Pacific

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One of the most exciting findings of the Deep Sea Drilling Project was that the forearcs and landward trench slopes of many active margins are shaped by episodes of sediment subduction and subduction erosion, as well as accretion. This recognition has changed many of our perceptions about subduction zone processes.

The Middle America Trench off Guatemala has undergone a long period of non-accretion, despite a relatively continuous supply of sediment to the trench (von Huene et al., 1980; Aubouin et al., 1982; Aubouin et al., 1984). Subsidence and subduction erosion have been postulated as the dominant, though not the only, processes in the Japan Trench (von Huene et al., 1980; Nasu et al., 1980; Murauchi and Ludwig, 1980), portions of the Peru-Chile Trench (Hussong et al., 1976; Kulm et al., 1977) and the Mariana Trench between 16°N and 18°N (Hussong and Uyeda, 1981; Bloomer, 1983).

The case for subduction erosion has perhaps been best documented in the Japan Trench and the Mariana Trench. This interpretation rests both on evidence for subsidence of the forearcs and the petrographic and geochemical identification of island-arc volcanic rocks as the principal constituent of the forearc basement. The Mariana Trench has been one of the most extensively studied of these non-accretionary margins (e.g., Beccaluva et al., 1980; Dietrich et al., 1978; Hussong and Uyeda, 1981; Meijer, 1980; Bloomer, 1983) and it is clear that most of the forearc basement and inner trench slope are of arc origin. These are among the oldest volcanic rocks associated with subduction in the Marianas (Meijer et al., 1983), they are also among the least enriched in incompatible elements and most depleted in high-field-strength elements. These extensive exposures of immature arc basement, immediately adjacent to the trench, have been interpreted to indicate an episode of subduction erosion early in the development of this margin (Beccaluva et al., 1980; Hussong and Uyeda, 1981; Bloomer, 1983). Arguments for tectonic erosion in the Japan Trench are based as well on the recovery of dacitic volcanics close to the axis of the trench, evidence for subsidence of much of the forearc and what has been termed the Oyashio landmass, and seismic evidence that the arc-like crust extends to within 30 km of the trench axis (von Huene et al., 1980; Nasu et al., 1980).

The concept of tectonic erosion has an important implication for the structure of island arcs. If erosion is a significant process during the development of the arc, much of the forearc basement will consist of island-arc volcanics and associated plutonics, presumably older than those of the associated active arc (Bloomer, 1983). As the erosion proceeds, the axis of volcanism must presumably shift inboard, resulting in a crudely layered type of forearc structure (Bloomer, 1983). Such a conclusion is important when one examines recent studies of some ophiolite complexes, such as Troodos and Vourinos, which show them to consist primarily of island-arc volcanics - in the case of Troodos arc volcanics with abundant boninites (Miyashiro, 1973; Robinson et al., 1983; Schminke et al., 1983; Noiret et al., 1981). One of the environments that has been postulated for the development of such an ophiolite is an immature island arc (Miyashiro, 1973; Cameron, 1980; Robinson et al., 1983; Dick and Bullen, 1984). It has been suggested that forearcs of some subduction zones may be locales where such crustal materials can be sampled today (Cameron, 1980; Robinson et al., 1983; Dick and Bullen, 1984; Natland, 1984). The volcanic and plutonic rocks exposed in the Mariana forearc bear a strong resemblance to rocks of the Troodos Ophiolite (Cameron, 1980; Bloomer and Hawkins, 1983; Natland, 1984).

The case for subduction erosion as an important process has really only been well-documented in the Mariana and Japan

Trenches; that of forearc exposure of an "island-arc" ophiolite has been shown only for the Marianas. It is also clear that subduction erosion is not the only process which has acted on the Mariana margin. There is evidence for extensive serpentinite diapirism throughout the inner trench slope, uplift of portions of the forearc at sometime in its history, and accretion of seamount fragments from the downgoing plate to the landward trench slope. One important question raised is whether subduction erosion is a fundamental process in the development of subduction zones to which there is a scant supply of sediment or is something peculiar to one or two trenches in the western Pacific. Even in the Marianas and Japan Trenches, it seems to be a process competing with accretion, or perhaps alternating with it. This would imply that in many cases one of the principal lines of evidence for erosion (exposures of arc basement in the landward trench slope) might be obscured by later, extensive accretion of sediment. Along continental margins distinguishing the case of non-accretion from that of subduction erosion, based simply on exposures of old continental basement, can be difficult. It is only in intraoceanic subduction zones, in which any arc materials present have probably been produced as a result of that subduction and at which there likely has never been significant sediment input, that the effects of subduction erosion may be easily identified. It is likely that the only way we can begin to understand this process is to identify and study as many areas in which it occurs as possible.

Below are outlined some of the pertinant data on the structure and composition of the Mariana forearc and a discussion of the characteristics of the Tonga forearc which lead us to believe it might resemble the Marianas.

## MARIANA FOREARC

### Erosion and subsidence

Arc tholeiites and boninites were recovered at DSDP sites 458 and 459 in the forearc (Natland and Tarney, 1981). These are probably late Eocene or Oligocene in age; the cessation of volcanism in the forearc appears to have been earlier than that in the frontal or remnant arcs (Meijer et al., 1983; Bloomer, 1983). The recovery of similar boninitic and tholeiitic series rocks in several dredges from the lower trench slopes (Beccaluva et al., 1980; Dietrich et al., 1978; Bloomer, 1983), similar exposures in the Bonin Islands and exposures of boninitic rocks on Guam (Reagan and Meijer, 1983) indicate that the drilled section may be characteristic of a large part of the forearc, at least between the Bonins and Guam. No ocean-ridge basalts of any type have been recovered from southeast of Guam northwards. The southern portion of the trench, south and southwest of Guam, is a complex shear zone and includes arc volcanics, ocean-ridge or back-arc basalts, serpentinites, gabbros and sediments. It is more likely a transform, rather than a convergent, boundary. There is some evidence in seismic refraction sections of a downbowing of crustal layers towards the trench axis (Latraille and Hussong, 1980). A carbonate section in cores from DSDP Site 460 have been interpreted as evidence for extensive subsidence of the forearc (Hussong and Uyeda, 1981). This data, in combination, is the basis for intepretations of a major episode of subduction erosion at some time in the development of the forearc. There has been a suggestion that this erosion was confined to the early stages of subduction (Bloomer, 1983).

Accretion/tectonic complications

There are several pieces of evidence which indicate that processes other than erosion have acted on the forearc. The interpretation of the Site 460 section is the subject of some debate; the section has alternatively been interpreted as a large slumped mass (Karig and Ranken, 1983). Seismic reflection data suggest a small accretionary wedge may exist at the toe of the landward slope (Mrzowski et al., 1981) and gravity modelling indicates a low density zone of sediments and/or fractured material beneath the lower slope (Sager, 1980). Interpretation of sediment sections in sites 458 and 459 indicate some net uplift of the forearc, or at least no significant amount of subsidence (Karig and Ranken, 1983); the morphology and blockage of a submarine canyon on the lower slope has also been interpreted as evidence of recent uplift of the trench slope (Karig, 1971; Karig and Ranken, 1983). Fragments of alkalic basalt, chert and hyaloclastite have been dredged from three sites on the lower slopes; Mesozoic fauna are found in one of these dredges and in Sites 460 and 461

(Hussong et al., 1981; Bloomer, 1983). These indicate the presence of some allochthonous materials in the lower trench slope, likely to be fragments of seamounts accreted to the slope from the downgoing plate. A set of ridges roughly parallel to the trench axis have been identified in the forearc southeast and east of Guam (Karig and Ranken, 1983). These have been suggested to be thrust slices, either of disrupted forearc basement or accreted oceanic crust (Karig and Ranken, 1983). This is also one of the only portions of the trench from which ocean-ridge basalts have been recovered (MARA D28, Mendeleev 1404). This southeastern portion of the forearc may be fundamentally different in structure than that to the north. Serpentinites are abundant throughout the trench slope, and there are seamount-like features on the trench-slope-break from which serpentinites and gabbros have been dredged. Serpentinite diapirsm has been postulated to be an important process in much of the slope (Bloomer, 1983).

## TONGA FOREARC

If erosion is a process fundamental to the development of intraoceanic subduction zones, the Tonga Trench should exhibit some evidence for this process. There are several reasons to believe that this is true:

1) The Tonga Trench bears a marked resemblance in setting and geometry to the Mariana Trench (Fig. 1, 2). The rates and angles of subduction are similar in both. Both bend to the west

at one end and become strike-slip margins. Both have a history of arc volcanism dating to the Eocene, have erupted principally basalts and basaltic andesites, have developed at least one back-arc basin and remnant arc, and have a forearc platform or frontal arc. The sediment supply to both trenches is slight.

2) There are few seamounts on the offshore flank now and, if the same has been true in the past 40 my, there is little chance that accretion of seamounts would have obscured the effects of tectonic erosion. In this regard the Tonga Trench provides as well an area in which to search for evidence of accretion of horst blocks from the downgoing slab. Most previous evidence for crustal accretion has been for addition of seamount fragments (Hawkins and Batiza, 1977; Bloomer, 1983).

3) If infilling of grabens is an important mechanism in erosion, the Tonga Trench should exhibit some effects of this process. It has abundant and well-developed grabens on the offshore flank, and few sediments or seamounts on the offshore slope to fill them in.

4) Existing dredge collections, and bottom photographs from nearly the same localities, confirm that hard rocks are exposed over much of the landward trench slope. Studies of those samples suggest that the mid- and upper- landward slopes are principally arc basement; the samples are few enough in number and small enough in size that an origin by transport cannot be totally discounted.

These facts do not establish that the Tonga Trench has experienced subduction erosion; they do mean that this is an ideal place to test for the effects of that erosion. Existing models incorporating observations to date would predict that it should have occurred. If the landward slope has been eroded we would expect that much of the exposure would be of island-arc volcanics, that those volcanics would be among the oldest in the subduction zone and perhaps among the least enriched (possibly including boninites), and that any accreted material would be confined principally to the lowermost slopes and be fragments of Oceanic Layer 2. If on the other hand the trench slope has developed principally by non-accretion or crustal accretion, the landward slope should expose the older oceanic crust upon which the Tonga arc was constructed and/or stacked, imbricate slices of oceanic basalt, possibly with sediments and seamount fragments.

## Geologic Setting and Previous Work

The Tonga Trench is the northern portion of the very linear Tonga-Kermadec system which marks the subduction of the Pacific Plate beneath the Indo-Australian plate (Fig. 2). It is characterized by a deep (to 600 km) Benioff zone which dips landward at about 45$^{\circ}$ and is very active seismically (Benioff, 1949; Isacks and others, 1969; Billington and Isacks, 1978; Billington, 1980). There are two linear chains of islands associated with the subduction zone separated one from the other by the deep (1800$^{+}$ m), sediment-filled (~2 km) Tofua Trough (Raitt and others, 1955). The easternmost islands - Tongatapu, Eua, Lifuka, Vava'u - are inactive coralline-capped edifices

(Lister, 1891). Volcanic basement is exposed only on the island of Eua, and includes basalt and basaltic andesite, probably of pre-late Eocene age; chemical data indicate these to be island-arc tholeiitic volcanic rocks (Ewart and Bryan, 1972). This eastern chain is analogous in some ways to the Guam-Saipan-Rota frontal arc of the Mariana region. The western island chain in Tonga is active, includes submarine and subaerial edifices, and is erupting basalts, basaltic andesite and minor amounts of dacite (Melson et al., 1970; Bryan et al., 1972; Ewart et al., 1973, Ewart and Bryan, 1973; Ewart, 1976; Ewart et al., 1977). There is an active back-arc basin, the Lau Basin, erupting tholeiitic basalts (Hawkins, 1976) and spreading, in an east-west direction, at a half-rate on the order of 1.0-1.5 cm/yr (Lawyer et al., 1976). Development of this basin has left one inactive remnant arc, the Lau Ridge (Gill, 1976).

Convergence between the Pacific plate and the microplate bounded by the Tonga Trench and the Lau Basin spreading axis is about 10.5 cm/yr at N82W, calculated from the poles of Minster and Jordan (1978) and assuming a 1.5 cm/yr east-west half-rate in the Lau Basin. Convergence is essentially normal to the trench axis for most of its length. To the north, southwest of Samoa, the trench shoals, trends to the west abruptly, and marks a zone of strike-slip motion. There are a few seamounts on the seafloor east of the trench (Figure 2). East of the Tonga Trench there is one huge seamount, Capricorn Guyot at 18°30'S, which is capped by Miocene reef limestones (Brodie, 1965) and is being tilted to the west as the Pacific plate descends into the trench (Raitt et al., 1955). To the south, at 26°N, the northwest end of the Louisville Ridge is entering the trench. The outer trench swell is subdued (Raitt et al., 1955) but as the crust enters the trench it is disrupted by numerous normal faults (throw about 700 m) producing a pronounced horst-and-graben topography (Raitt et al., 1955; Fisher and Engel, 1969; Burns, Andrews et al., 1973; Hilde and Fisher, 1979; Hilde, 1984). Sediment cover on the offshore plate is sparse. At DSDP Site 204, east of the trench at 24°57'S, 174°07'W, 147m of sediment were cored, with an estimated 100 m below that to basement. The sedimentary section included 103 m of Quaternary to Oligocene clays and ashes unconformably overlying 23 m of early Cretaceous tuffaceous sandstones and 21 m of vitric tuffs (Burns, Andrews et al., 1973). The onshore side rises from the trench floor at an overall angle of 8-15° with a distinct decrease of slope at about 5000 m (Fig. 3, 4). Where examined by seismic reflection profiling, the forearc basin is filled by eastward thinning sediments which pinch out against the slope break (Greene et al., 1983). A U.S.G.S. multichannel seismic line across the forearc at 22°10'S indicates that the frontal arc's Eocene basement, which is exposed on Eua, may extend out to the eastern margin of the platform (Greene et al., 1983).

Field studies of the morphology and compositions of the slopes of the Tonga Trench have been few in number. Raitt et al. (1955) described the morphology, crustal structure and magnetic characteristics of the trench. They noted that the 4-5 km/sec compressional wave velocities in the forearc and lower trench slope precluded any significant accumulation of sediment there, and that their attempts in 1952 to sample the deep inner cleft resulted only in battered, scored equipment. Fisher and Hess (1963), Karig (1970), Fisher (1974) and Dupont (1979) have discussed profiles of the Tonga Trench as compared to those of other trenches of the Pacific basin. Igneous samples from the inner slopes of the Tonga Trench were first described by Petelin (1964), who noted tuffs, agglomerates and basalts from 8500-7500 m at 20°20'S, 173°08.3'W. Fisher and Engel (1969) reported on igneous samples from four dredge hauls and one camera station taken on Scripps Institution of Oceanography's 1967 cruise to the Tonga Trench; they gave a description and bulk rock analysis of an utterly fresh harzburgite ($H_2O$+ less than 0.1%) from the deep inshore flank of the trench. Altered basalts, alkali olivine basalt, amphibolitized gabbro fragments and tuffaceous agglomerates were also described, though no analyses were given (Fig 3, Fisher and Engel, 1969). Here they interpreted the nearshore section as the exposed roots of the arc edifice. Andesitic and basaltic rock fragments and volcanoclastic sediments have been reported from 5700 m on the nearshore trench slope at 19°19'S, 173°09'W (Abdenko et al., 1972; Udintsev et al., 1974). Fisher (1974) presented some photographs of the deep slopes of the Tonga Trench and briefly described samples from 13 dredges collected on Scripps expedition SEVEN TOW in 1972 (Fig. 3). He pointed out an apparently sheared, slickensided, platy texture in photographs of the mid-and lower onshore slopes and interpreted the dredging results as reflecting a crude layering of the nearshore flank: siltstone, calcareous debris, pumice, intermediate volcanics, silicic volcanics and diabase shoaler than 5500 m; alkali olivine basalt and gabbro further downslope; harzburgites, dunites and serpentinized lherzolites above vesicular alkali basalts in the deepest onshore slope; finally, diabases, vesicular basalts and shale on the offshore flank (Fisher, 1974). Hawkins and others (1972) listed, in an abstract, a range of mineral compositions for some of the ultramafic samples described by Fisher (1974) and Fisher and Engel (1969), establishing that these had magnesium-rich, refractory compositions. Hawkins et al. (1972) interpreted the layering of the nearshore slope to be sediments at less than 5000 m; vesicular altered basalts and diabase between 5200 and 5400 m; greenstones, altered basalts and agglomerates from 6500–7000 m; gabbro between 7200 and 7700 m; dunite, pyroxenite, harzburgite, serpentinite and altered basalts from 9150 to 9400 m; and vesicular altered basalt and diabase between 9150 to 9750 m. From seismic reflection profiling on the 1967 NOVA Expedition, Hilde and Fisher (1979) speculated that at 20°00'S–20°20'S the lowest nearshore slope of the trench (below 9000 m) was the west wall of a graben in the subducting Pacific plate. They identified "oceanic-type basalts from the nearshore margin", presumably from petrographic characteristics, noted the absence of any accretionary prism of sediments and concluded "that the nearshore flank of the Tonga Trench below the trench slope break has remained barren of significant sediment emplacement becuase of mass wasting/slumping from the shoreward wall and offscraping of sediments from the horst blocks into the grabens and subduction within the oceanic plate". But they then stated "perhaps the nearshore flank between the terrace described above (i.e. at 9000 m) and the trench slope break is a section of lower oceanic crust that has remained exposed since the time of initial dislocation and subduction".

More recent surveying has included multichannel seismic profiles of the trench slope by the U.S.G.S (Maung et al., 1982; Scholl et al., 1982; Greene et al., 1983). This profiling confirmed the absence of sedimentary material on the lower trench slope. The USGS work included a dredge haul from 8650 to 7800 m on the trench slope at 22°10'S, 174°10'W, which recovered fragments of serpentinite, volcanic breccias, sandstone and siltstone (Greene et al., 1983). Vallier et al. (1984) have identified some of the volcanic clasts as arc-derived, and the serpentinites as altered refractory ultramafics similar to those of the Papuan ophiolite. The occurrence of carbonate sediments at these depths was attributed to either mass movement along the trench slope or erosion and subsidence of the slope since the deposition of those sediments (Vallier et al., 1984).

Soviet workers have reported on an extensive dredging program along the northern, strike-slip portion of the Tonga Trench which reinforces the suggestion that there are distinct similarities between the landward slopes of the Mariana and Tonga Trenches.

(Fig. 1, 2). Thirty dredges along the landward slope north of 15°20'N recovered boninites, arc volcanics, gabbros, serpentinites, diabases, plagiogranites and volcanoclastic sediments (Sharaskin et al., 1983a; 1983b). These hauls are very similar in composition to those from the southern, strike-slip portion of the Mariana Trench in the vicinity of the Challenger Deep. There is evidence of brecciation and cataclasis in both sets of samples. The Soviet work confirms that boninites occur in the Tonga region (though the Soviets, unlike essentially all other authors, consider the boninites to be unrelated to subduction), and that there is an "island-arc ophiolite" type rock assemblage exposed on at least a portion of the trench slope. These results are difficult to use in formulating erosion-accretion models for the structure of the trench slope to the south because of the very complex history of the northern margin. Rather than simple subduction there has been extensive rotation and transverse motion along this portion of the trench. Rock exposures here may reflect mixtures of material from several different structural portions of the arc and forearc. A similar detailed study is required along the "normal" sections of the trench before we can draw any reasonable conclusions about its development. If the analogy to the Marianas holds, allowing for inversion in plan view, less mixed section, lacking any intense brecciation or cataclasis.

Bloomer and Fisher (1985) undertook a detailed petrographic and geochemical study of the samples from 20°20'S collected by

Fisher in 1967 and 1970 to try to determine if there was any evidence of arc basement in the trench slope. An interpretive cross section of the trench at 20°20'S based on this work is shown in Figure 4. The lowermost onshore and offshore slopes comprise normal and transitional ocean-ridge basalts; based on rock composition, texture, bottom photographs, reflection profiles and the wide-beam survey they suggested that in this part of the trench the axis corresponds to a graben in the offshore plate and that the plate boundary is actually at about 8000 m on the landward slope. A single SEABEAM swath recently (1984) run down most of the length of the trench axis clearly identifies the grabens by their steep sides and slight angle to the trench, and confirms this interpretation (P. Lonsdale, pers. comm.). Above this zone of ocean-ridge basalts is a narrow band of peridotites. Unlike the case near 18°N in the Marianas few serpentinites were recovered - the ultramafic samples are true peridotites, primarily harzburgites. The mineral chemistry of the peridotites suggests that they are more refractory than is typical of peridotites or serpentinites from spreading ridges (Fig. 5). Shoaler than this the sample set is sparse and ncludes fragments of gabbro, volcanoclastic sediments and a few clasts and blocks of volcanic rock. These volcanic rocks are either arc-like in their geochemistry, or are of indeterminate compositions (Table 1, Fig. 6); none have compositions like those of samples from the lower slope or of typical ocean-ridge basalts. From these recent results, Bloomer and Fisher (1985) suggest that most of the landward slope exposes a crustal section which is something other than normal spreading ridge generated oceanic crust. If this crust is of arc origin, it presents a strong argument for tectonic erosion in the Tonga Trench. The difficulty with the existing sample set is that most of the dredge hauls and nearly all of the samples are from deeper than 8000 m. There were fewer hauls attemptied at shallow depths; two of these were empty and others recovered only a few very small samples. Most of these shallow volcanic samples are small enough in size and number that an origin by transport from the arc cannot be ruled out. The complete absence of any ocean-ridge basalt samples from these depths though argues that there may be a fundamental difference in crustal composition between the upper and lower slopes.

Samples from dredge hauls by other investigators on the landward slope at least hint that the slope may indeed expose arc-like materials. Fragments in USGS D9 at 22°S include arc-tholeiitic volcanics (Vallier et al., 1984) and samples from 5700 m at 19°19'S include arc-like andesitic compositions (Abdenko et al., 1972; Table 1). Both these hauls however yielded small fragments of only a few rocks and are subject to the same criticism that they were transported from the arc.

Definitively establishing that dredged samples from a trench represent nearby outcrops requires a careful sampling plan which recovers coherent assemblages, and which includes blocks of a size, kinship in composition and number which reduce the likelihood of transport. Dredged samples from 18°N in the Mariana Trench are quite similar to those drilled in-situ nearby in the forearc; the dredges in fact sampled several units (gabbros and serpentinites) which were missed in drilling because of the constraints on site selection. The size of talus blocks seen in most bottom photographs of trench slopes, the highly variable (from near vertical to near horizontal) slopes, and the broad forearc basins in both the Tonga and Mariana Trenchs make it unlikely that much of the igneous material on the trench slope has been transported the more than 100 km from the active arc. When an adequate sample population exists, as in the case of the Marianas samples, an origin from the arc can sometimes be ruled out based on chemical dissimilarities between the arc and forearc samples. The problem in the Tonga Trench doesn't stem from a lack of outcrop; bottom photographs clearly show abundant talus and outcrop from the trench axis to the trench slope break. Rather the ambiguity in interpretation is due to the scant number of dredges heretofore attempted at intermediate or shallow depths; the bulk of the sampling was concentrated in the deep onshore, and to lesser degree offshore, flanks, most of which appear to be structurally a part of the subducting plate.

The weight of the avaiable evidence suggests that the slopes of the Tonga Trench expose something other than spreading-ridge produced crust - that "something" may well be arc volcanic basement. The situation in Tonga is complicated by the fact that what is morphologically the trench axis locally is the axis of a graben in the offshore plate, and hence structurally part of the subducting plate. Lonsdale's SEABEAM swath down the trench axis clearly identifies the areas in which this is the case. A clear picture, ideed a reliable picture of any kind, of the structure of the trench slope is not now possible becuase of the paucity of samples from the mid- and upper ( < 8000 m) sections of the landward slope.

## DRILLING CONSIDERATIONS

There are two ways in which the data from the Mariana forearc might be viewed:

a) Subduction erosion and accretion are episodic processes whcih operate at different times in the development of a subduction zone, or which may alternate with each other. The Mariana forearc and trench slope have been shaped by multiple processes; understanding its structure and evolution can help guide interpretations in other intraoceanic subduction zones.

b) The Mariana Trench developed from an initially anomalous geometry or geologic conditions and its complex structure is a result of that anomalous origin. There is, from this viewpoint, no reason to consider its structure, or models for the origin of that structure, as typical of intraoceanic subduction zones in general.

Depending on whcih view one wishes to start from, there are two tacks to take with a forearc drilling program:

a) Examine another intraoceanic forearc to establish whether or not the processes and history inferred for the Marianas are in any way apllicable to other areas. Questions to be addressed include the nature and age of the forearc basement, the extent of arc-derived basement in the forearc, the relation of the forearc basement (in age and composition) to the frontal and active arcs, and the subsidence, uplift and sedimentologic histories of the forearc and landward trench slopes. The drilling program would have to be combined with dredging, narrow-beam surveys and seismic reflection adn refraction work. The Tonga Trench and forearc would be the most likely place to search for an analog to the Mariana forearc. The two are grossly similar in many of their characteristics and there is some scant evidence that the Tonga forearc exposes arc materials.

b) Examine the Mariana forearc in greater detail and try to resolve some of the conflicts about its structrue and origin. Problems to be addressed would include:

1. How representative is the Leg 60 transect of the forearc? How does the forearc basement vary in age and composition? Subduction erosion hypotheses suggest that there may be a younging of the forearc basement inboard from the trench.

2. What is the history of vertical motions in various parts of the forearc and lower trench slope? What does this tell us about the timing and possible alternation of erosion and accretion?

3. Is there any evidence for older pre-arc oceanic basement or accreted oceanic crust in the forearc?

It should be noted that while an important objective of either program is basement penetration and recovery, an understanding of vertical motions and sedimentologic processes are equally important in unravelling the history of the forearc. A program of forearc drilling can easily be tailored to address both the problems discussed here and those raised by Haggerty, Moore and Natland.

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FIGURE CAPTIONS

1. Geometry and dredge sample sites in the Mariana Trench. a=arc volcanic, b=boninite, s=serpentinite, v=volcanoclastic sediment, g=gabbro, i=alkalic basalt, o=ocean-ridge basalt, m=metamorphis (principally cataclastic), p=peridotite. A ? indicates that the samples are so small or few that an origin by transport cannot be ruled out.

2. Geometry and dredge sample sites in the Tonga Trench. Symbols as in figure 1.

3. Distribution of rock types in dredge hauls from the 20°20'S region of the TOnga Trench.

4. Hypothetical cross-section of the landward trench slope at 20°20'S.

5. Mineral compositions of pyroxenes and spinels from peridotites dredged from the landward slopes of the TOnga Trench (D88 and D57). Hachured field in right hand pyroxene quadrilateral indicate compositional range for harzburgitic samples.

6. Ti vs. Zr for volcanic rocks dredged from the landward slope of the Tonga Trench. D55, D70, D60, D88 from mid- to upper slopes. Field a Type I ocean ridge basalts, DSDP sites 410-412; field b Type II ocean ridge basalts from DSDP Sites 407-409; Dotted filed for volcanics from Tonga active arc and Lau Ridge, dahed-dotted filed for dacites from the Tonga-Kermedec arcs (Gill, 1976, Bryan, 1979, Bryan et al., 1972).

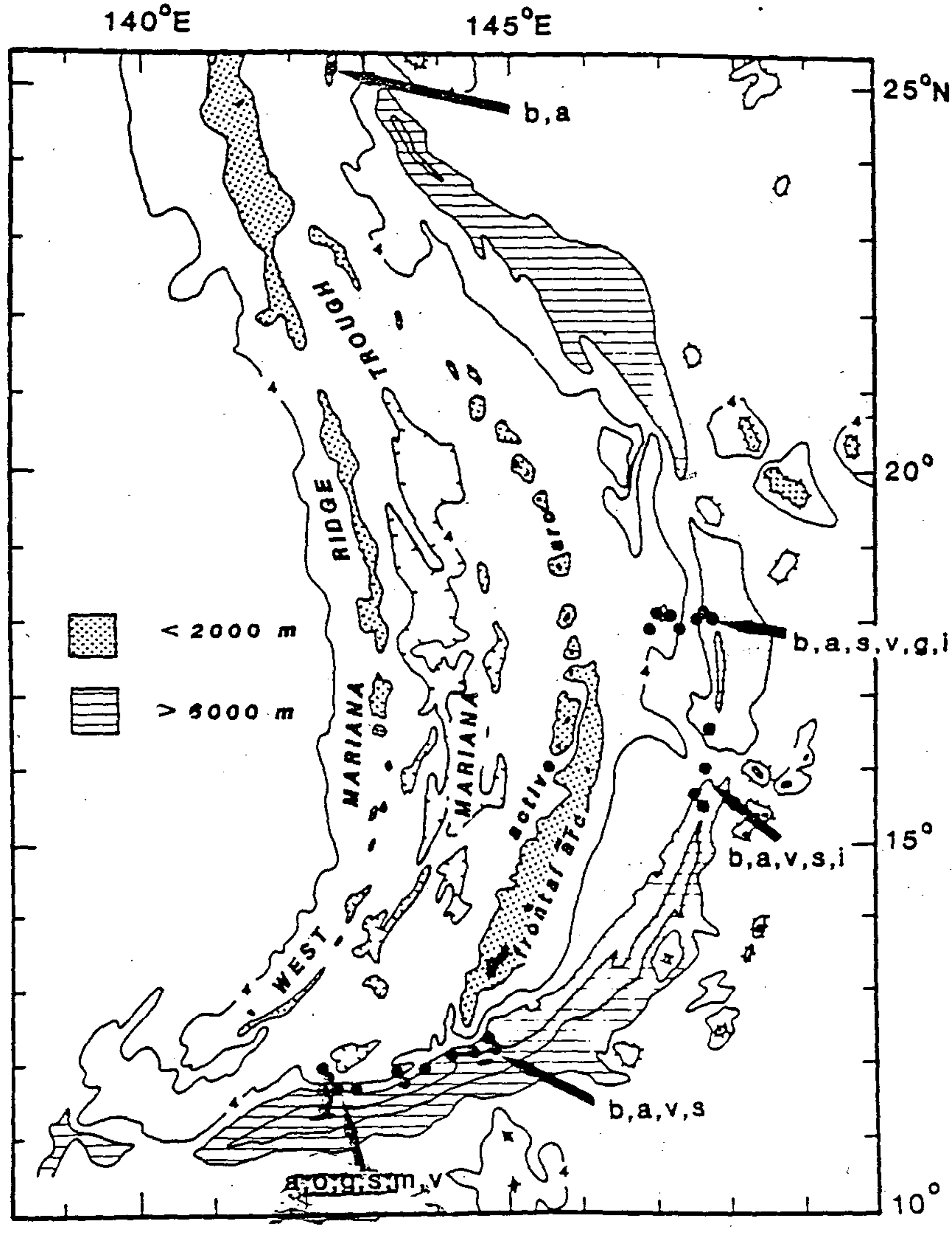

140°E
145°E
25°N
20°
15°
10°
b,a
b,a,s,v,g,i
b,a,v,s,i
b,a,v,s
< 2000 m
> 5000 m
WEST MARIANA RIDGE
MARIANA TROUGH
active frontal arc

Figure 1

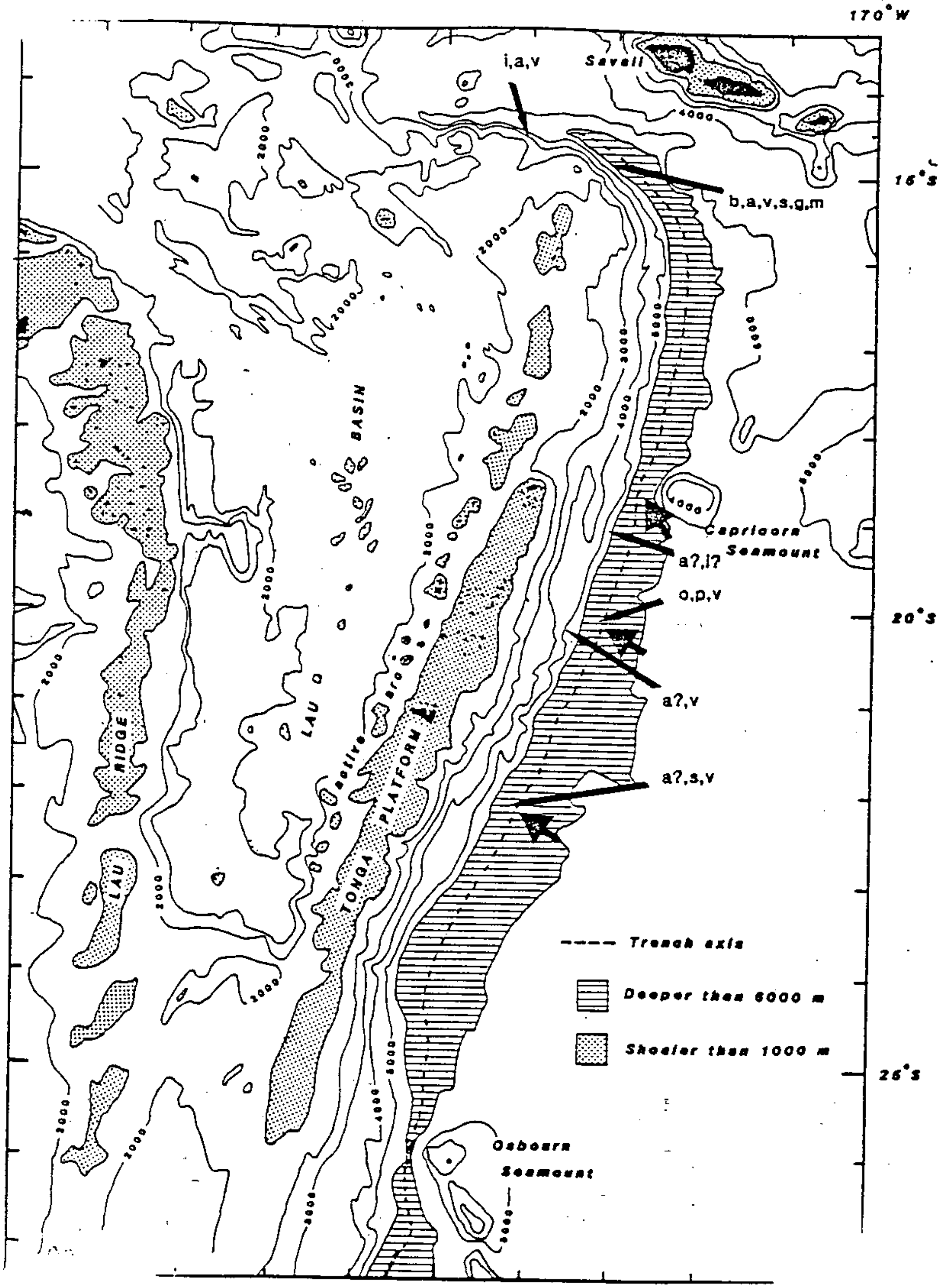

170°W
16°S
20°S
25°S
i,a,v
Savaii
b,a,v,s,g,m
Capricorn Seamount
a?,l?
o,p,v
a?,v
a?,s,v
LAU BASIN
LAU RIDGE
active arc
TONGA PLATFORM
Osbourn Seamount
Trench axis
Deeper than 6000 m
Shoaler than 1000 m

Figure 2

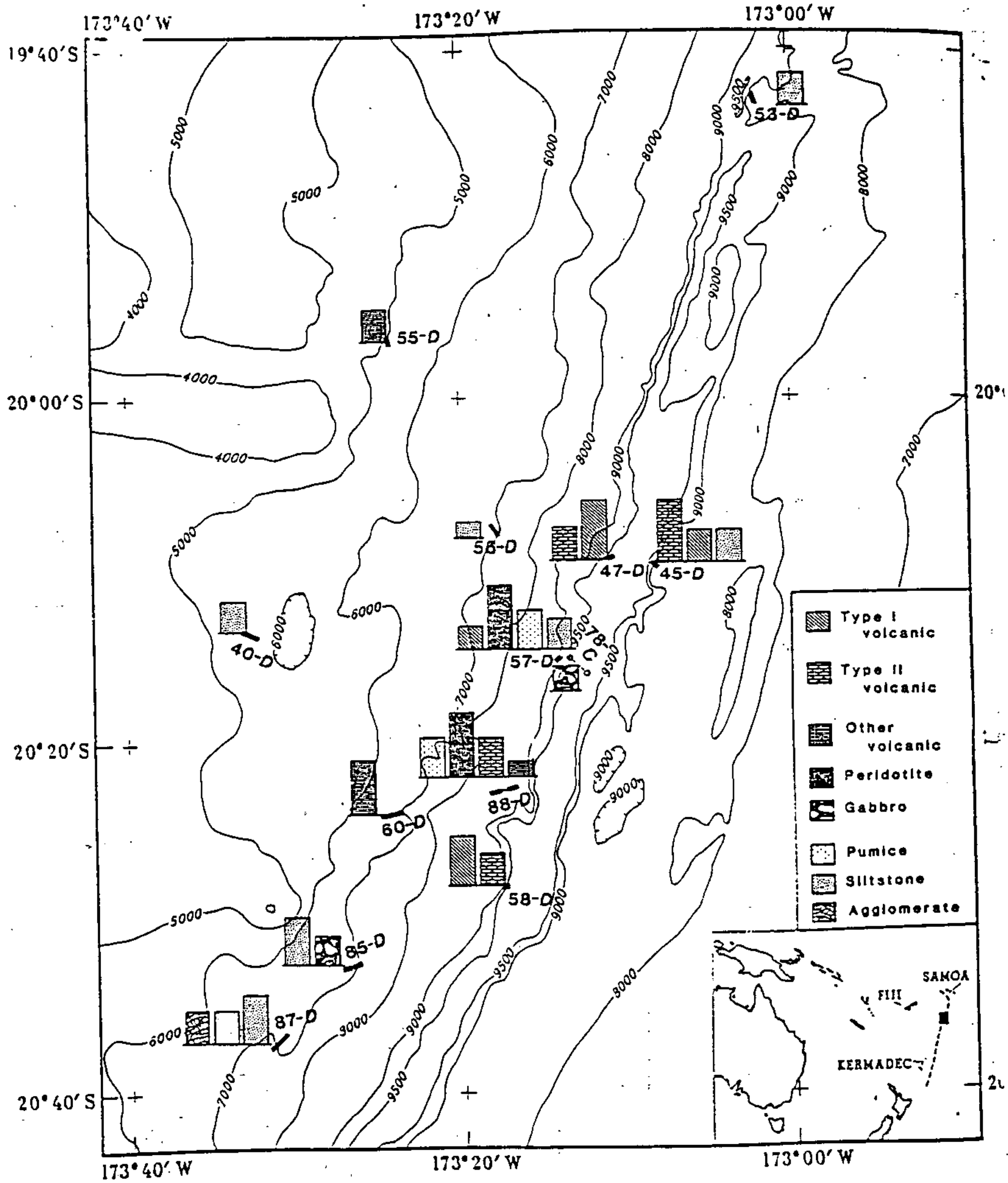

173°40′ W
173°20′ W
173°00′ W
19°40′S
20°00′S
20°20′S
20°40′S
53-D
55-D
56-D
47-D
45-D
40-D
57-D
78-C
88-D
60-D
58-D
85-D
87-D
Type I volcanic
Type II volcanic
Other volcanic
Peridotite
Gabbro
Pumice
Siltstone
Agglomerate
SAMOA
FIJI
KERMADEC

Figure 3

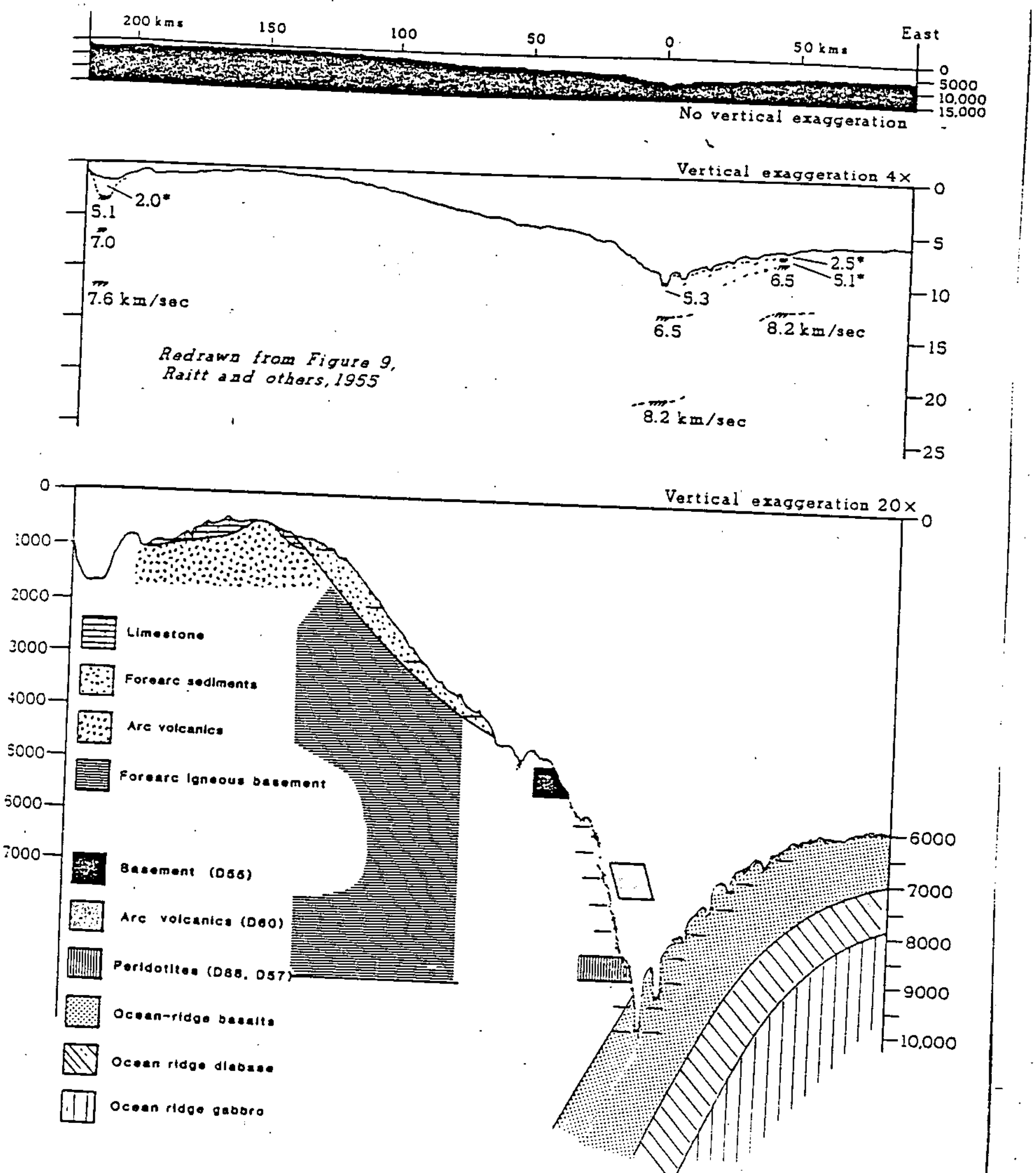

200 kms
150
100
50
0
50 kms
East
0
5000
10,000
15,000
No vertical exaggeration
Vertical exaggeration 4×
2.0*
5.1
7.0
7.6 km/sec
2.5*
6.5
5.1*
5.3
6.5
8.2 km/sec
Redrawn from Figure 9, Raitt and others, 1955
8.2 km/sec
0
5
10
15
20
25
Vertical exaggeration 20×
0
1000
2000
3000
4000
5000
6000
7000
Limestone
Forearc sediments
Arc volcanics
Forearc igneous basement
Basement (D66)
Arc volcanics (D60)
Peridotites (D88, D57)
Ocean-ridge basalts
Ocean ridge diabase
Ocean ridge gabbro
6000
7000
8000
9000
10,000

Figure 4

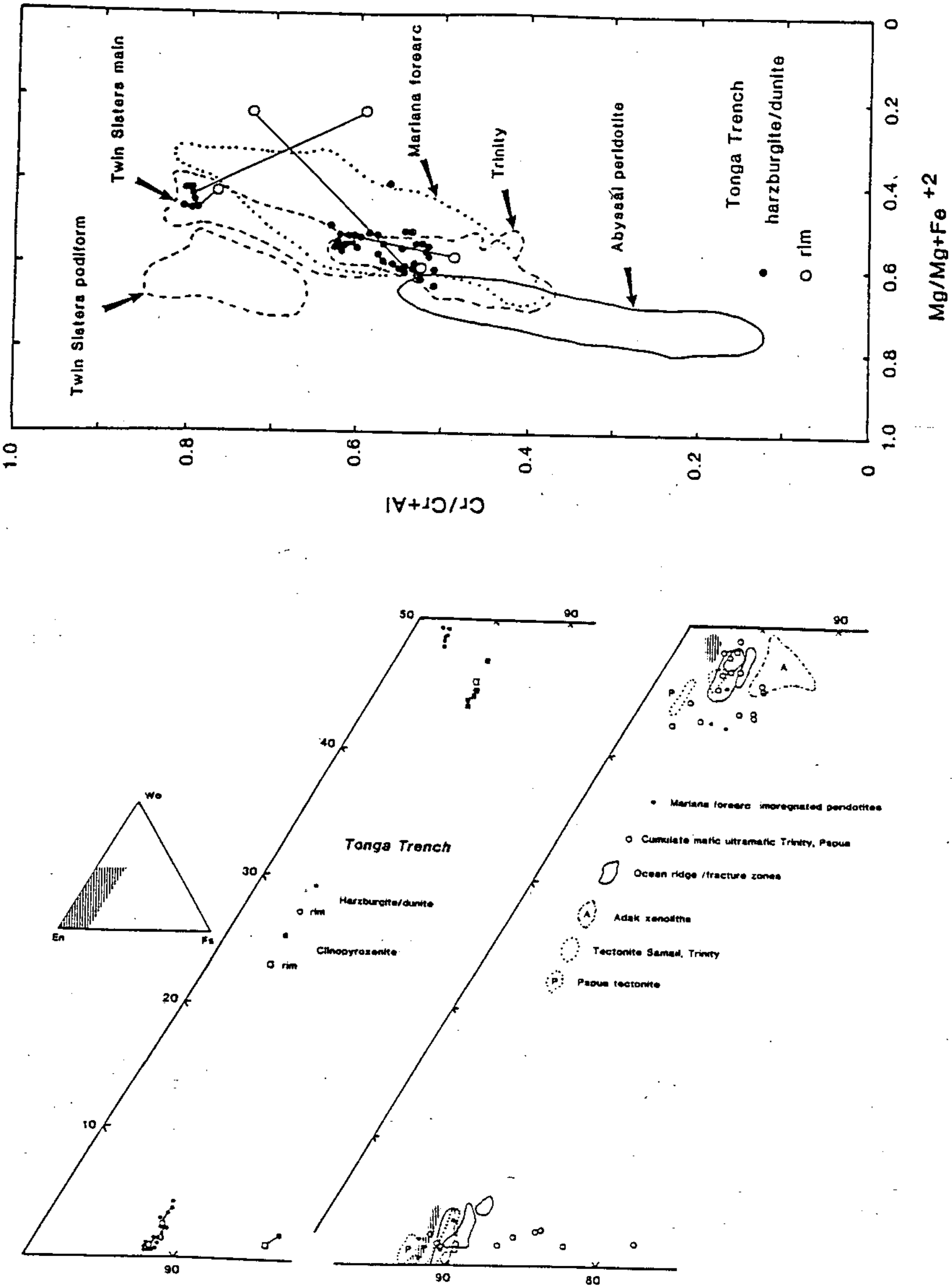
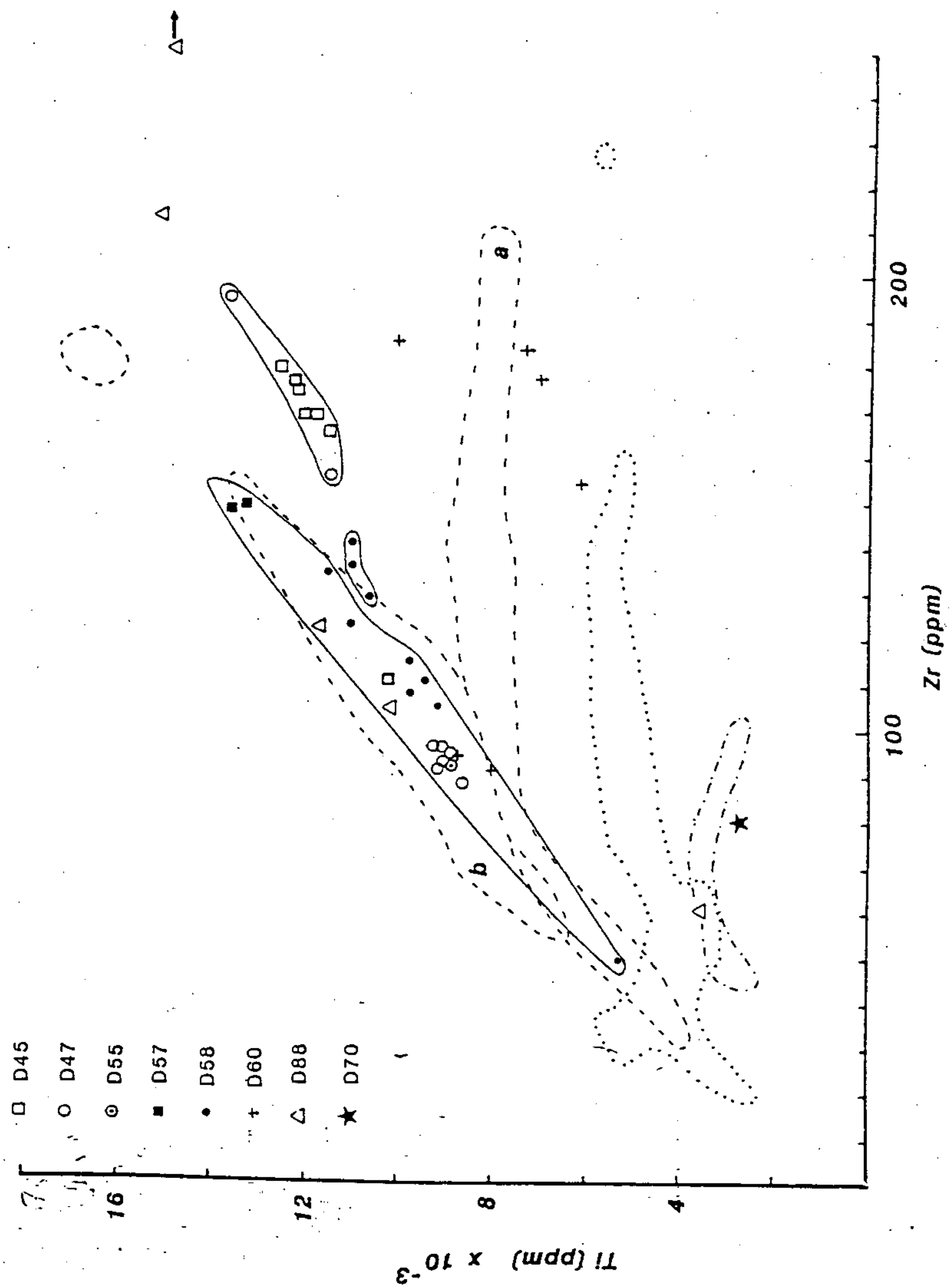

Twin Sisters main
Twin Sisters podiform
Mariana forearc
Trinity
Abyssal peridotite
Tonga Trench
harzburgite/dunite
rim
Mg/Mg+Fe +2
Cr/Cr+Al
Tonga Trench
Harzburgite/dunite
rim
Clinopyroxenite
rim
Wo
En
Fs
Mariana forearc impregnated peridotites
Cumulate mafic ultramafic Trinity, Papua
Ocean ridge /fracture zones
Adak xenoliths
Tectonite Samail, Trinity
Papua tectonite

Figure 5



D45
D47
D55
D57
D58
D60
D88
D70
Ti (ppm) x 10^-3
16
12
8
4
Zr (ppm)
100
200
a
b


Figure 6

Deep Structure of Back-Arc Basins from Seismic Tomography

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Summary

A seismic tomography experiment can add significantly to our understanding of the deep structure of island arcs and the processes which form them.

Current arc-basin seismic models are derived from island-based seismic observations and therefore are limited in the range of raypaths collected. Use of ocean bottom seismographs allows for optimal placement of seismic stations and for collection of seismic raypaths crossing beneath a Back-Arc basin. The choice of the subject area influences the effectiveness (and hence value gained) from such an experiment. These considerations favor a region where the Benioff zone extends beneath the Back-Arc basin, slopes moderately (45° for example), and has a high and reasonably uniformly distributed seismicity.

We assert that the proposed experiment would help distinguish between models of basin opening such as those shown in Figure 3. From these models one can generate diagnostic fields such as temperature (Figure 4) which can be compared to the observed seismic velocity and absorption distributions. A plan view of our proposed work in the Lau Basin is shown in Figure 5. The relationship of the instrument locations to the seismicity and Benioff zone depth are given in Figure 6.

Applicability to other Back-Arc or Behind-Trench Areas - Geometric and Activity Considerations.

This class of experiment can be carried out in other areas with some qualifications, primarily due to the geometry of the Benioff zone and the level of seismic activity on it. The dip of the Benioff zone (45° under the Lau Basin) allows many raypaths to cross at substantial angles. The accuracy or sensitivity of the tomographic method is highest (for simple geometries) when many raypaths cross at nearly right angles and is worst when raypaths are sub-parallel.

The level of seismic activity controls the time necessary to obtain an adequate data set. The current generations of OBSs (ours and others) are useful for 1 to 2 month deployments, being limited by clock drift and the consequent degradation of timing accuracy. We estimate that a useful data set would consist of at least twenty events recorded by twelve or more OBSs. The chosen site should therefore have a level of seismic activity sufficient to yield twenty events (magnitude three or above) within a two-month period. It is, of course, impossible to know what earthquakes one can obtain in a month or so except on a statistical basis.

Tomography is a term used to describe an integrated method of generating a seismic model which fits some set of seismic data. Each seismic arrival can be characterized simply by its time, energy, and spectral shape. These parameters are controlled by the slowness (reciprocal velocity), geometric focusing and attenuation encountered by a ray along the entire raypath. The goal of seismic analysis is the partitioning or allocation of these influences to the various parts of the raypath. Refraction profiles are initially analyzed by assuming a laterally homogeneous earth and this assumption permits the decomposition. In tomographic analyses, the decomposition is made possible by utilizing multiple raypaths through a common model. The stability of the analysis depends on multiple raypaths passing through each element of the model and the resolution obtained varies according to the number and angle of intersection of the raypath. (Sub-parallel rays, like sub-parallel lines of position in navigation, add little information.)

## General Comments on Anticipated Resolution

For tomographic experiments with a subduction zone geometry (sources on a dipping plane with receivers on a horizontal plane above), as in Figure 7, some general comments based on geometry can be made about the resolution expected. The poorest resolution will be encountered just above the lower part of the Benioff zone since no rays cross there. We can thus expect little resolution in depth there. Near the surface the vertical resolution will be comparable to that obtainable from refraction profiles using earthquake sources while the horizontal resolution will be limited by the interval between receivers. The aspect ratio of resolvable blocks might be 5 or 10 to 1 in the near-surface region.

The central part of the model should contain the best combination of ray angles and ray density, and thus yield, from geometric consideration, aspect ratios of order unity for resolvable blocks. The seismicity distribution with depth (Figure 8) is uniform enough to provide a reasonable approximation to a uniform source distribution.

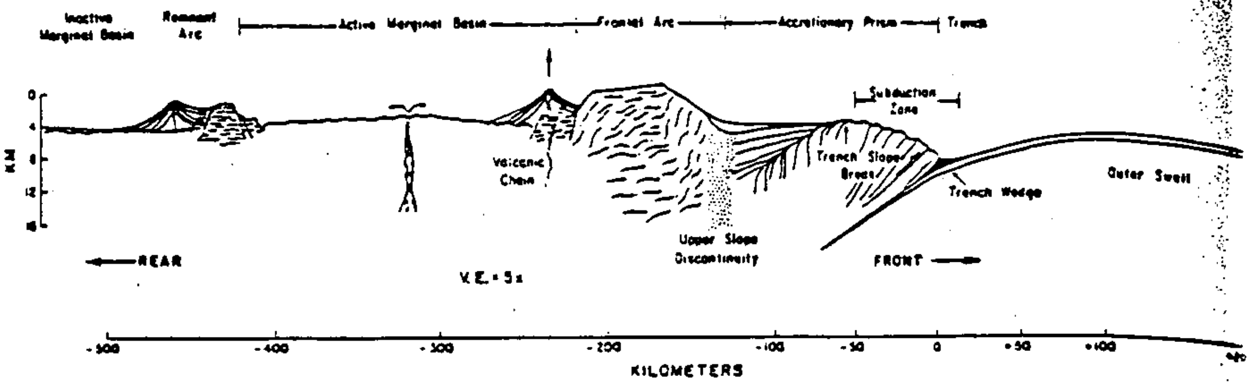



Fig. 1 - Cross section of a typical trench-arc system, showing tectoni
units and terminology (after Karig and Sharman, 1975).

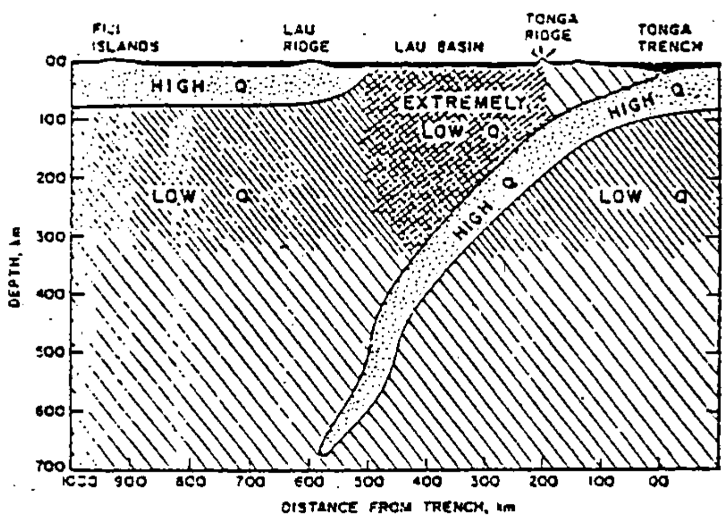



Fig. 2 - A schematic cross section perpendicular to the Tonga Trench-A
showing lithospheric plates (dotted) and the zones of high and low att
uation for seismic propagation as inferred by Barazangi and Isacks (1

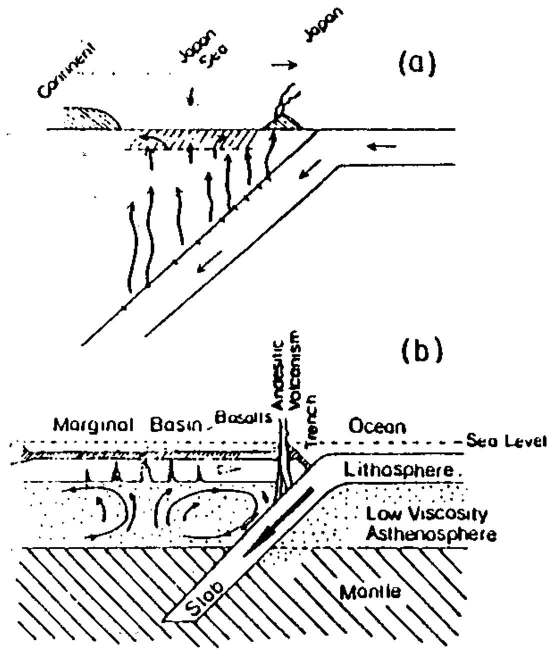



Fig. 3 - Two models for basin opening:
(a) frictional model
(Matsuda and Uyeda, 1971)
(b) secondary flow model
(Sleep and Toksoz, 1973).

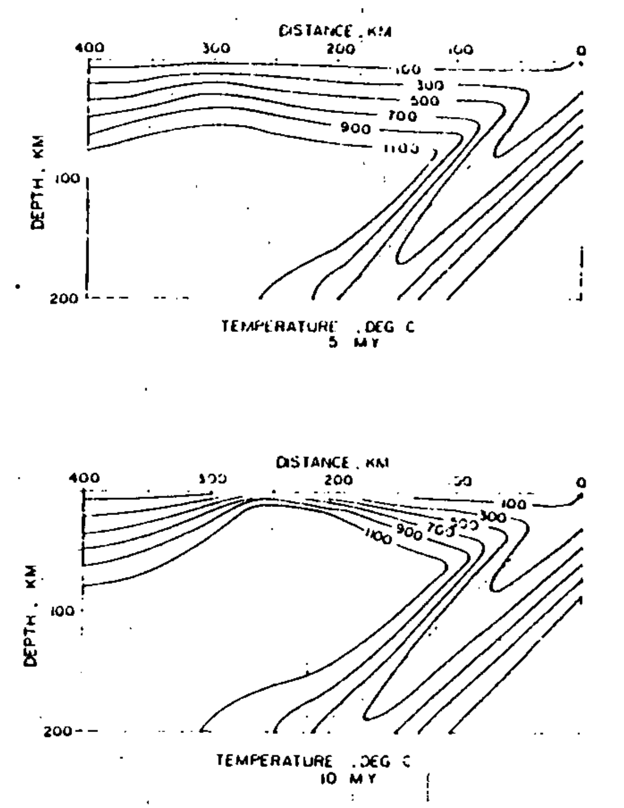



Fig. 4 - A Model of the temperature distribution produced by lithospheric subduction (Andrews and Sleep, 1973). Temperature shown at 5 and 10 m.y.

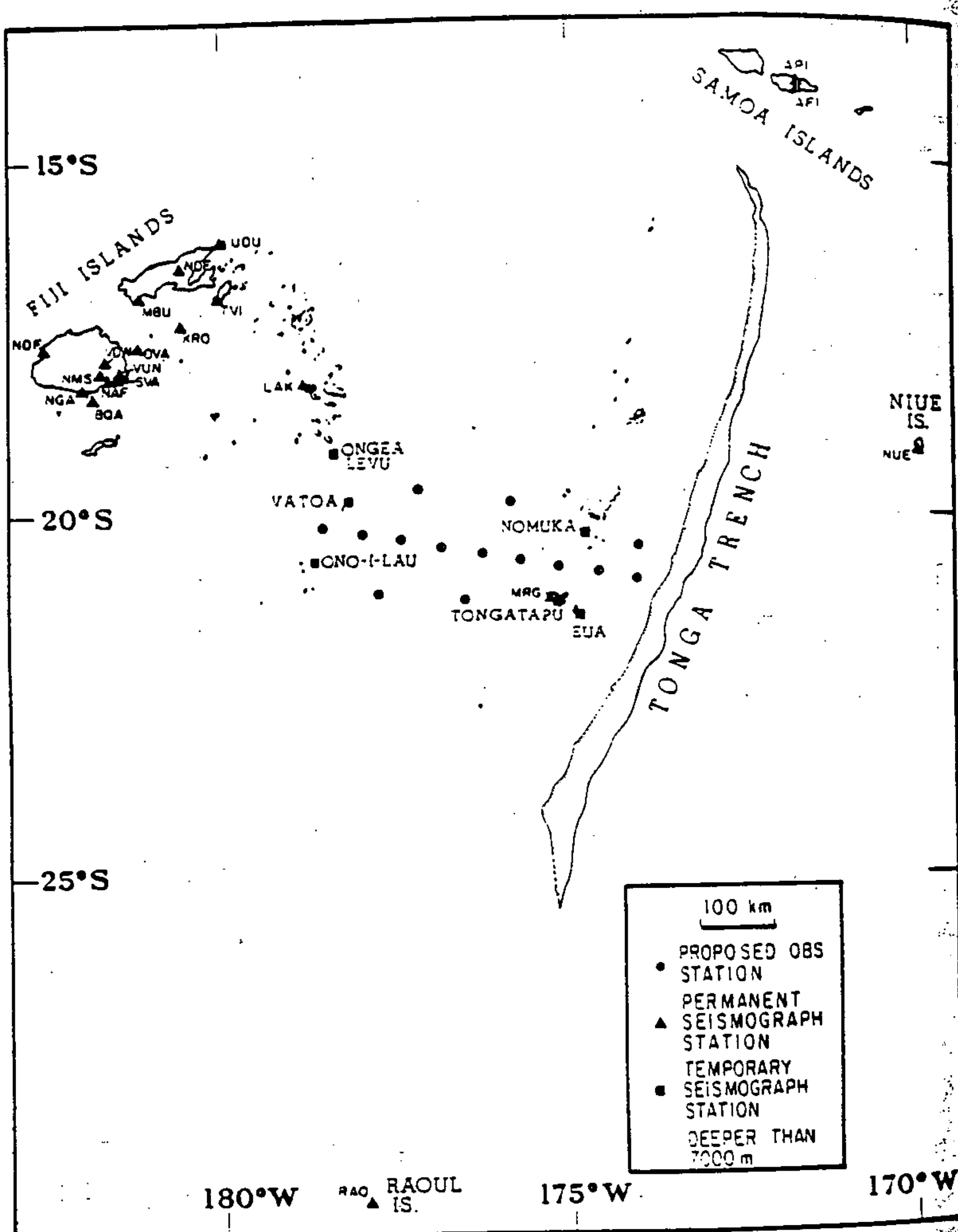
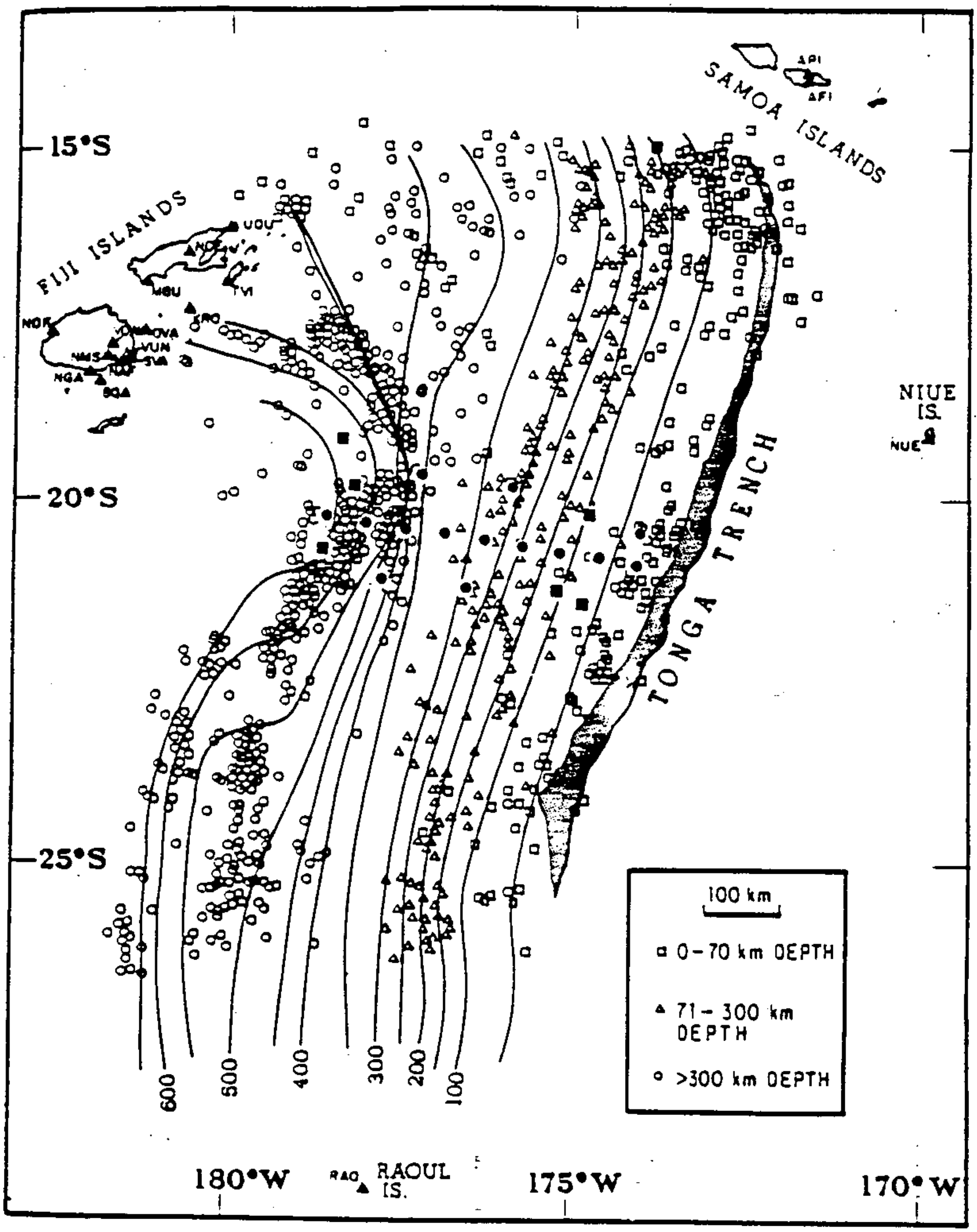



Fig. 5 - Proposed deployment locations for the ocean bottom seismographs and the temporary island seismographs, as well as the locations of permanent seismograph stations in the Tonga region.




3. 6 - Epicenter map for the Tonga-Fiji region (open symbols) with superimposed positions for the proposed seismic stations (solid symbols). Also shown is a map of contours of the depth in km to the top of the Benioff zone (after Billington, 1980).

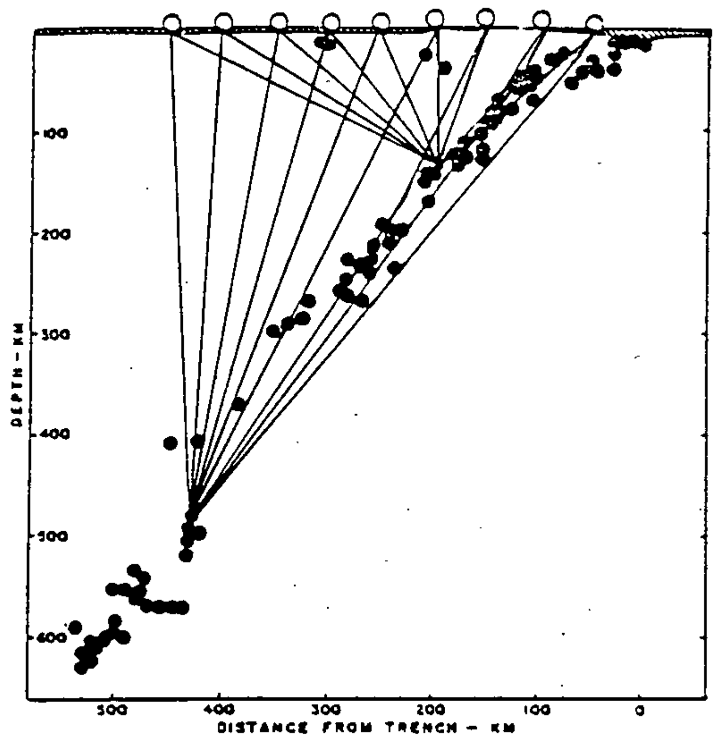



Fig. 7 - Cross section of Benioff zone perpendicular to the trench-arc ax in the vicinity of Tongatapu island with proposed seismograph stations indicated along top. The ray paths are drawn between two earthquake event and the seismographs (after Oliver et al. 1973).

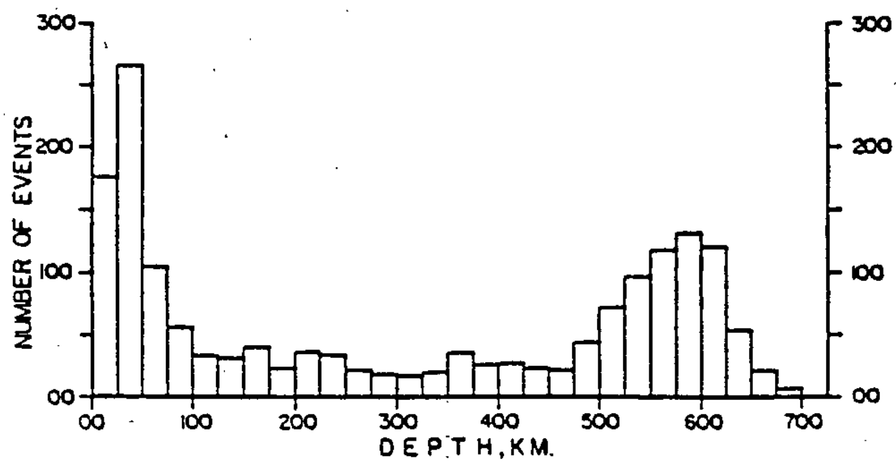



Fig. 8 - Distribution of the events shown in Fig. 6 plotted as a function of depth (after Billington, 1980).

# NORTH-SOUTH TRANSECT OF DIACHRONOUS ARC SUNDERING

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Volcanic arcs appear to be split, or sundered, into (inactive) remnant and (active) frontal segments, the latter comprising products of successive episodes of arc activity (1, 2). Arc sundering and back-arc spreading appear to be diachronous, and the magmatic expression of these processes at the present time may be partly analogous to that of propagating rifts at mid-ocean ridges (3). It is proposed that a longitudinal (north-south) transect of the Iwo Jima Ridge and Mariana Trough will monitor diachronous arc sundering and early stages of back-arc spreading (4). Other longitudinal transects could include parts of the older Shikoku and Parece Vela Basins, the Palau-Kyushu Ridge, West Mariana-Okinawa ridge complex, and the Bonin Ridge-Trough complex. We believe that results from such transects will help (a) document space/time relations between and within island arc tholeiite, back-arc basalt, and boninite magma series, during a single cycle of subduction and spreading, (b) ascribe these to changes in tectonic/thermal environments, and (c) resolve controversies about boninite. In contrast to the east-west IPOD transect (5, 6) north-south transects would sample the effects of a single diachronous process.

Magmas in the colliding plate environment can, in general, be characterized in terms of their mantle sources (fertile versus refractory) and relative extent of processing in fractionation systems (primitive versus evolved), all such variation being a direct or indirect expression of tectonic environment. Tectonic inferences from petrologic models depend as much on the chronologic association of magmas as on geochemical mass balances, isotope systematics, and phase equilibria. For instance, alternative roles for boninite suggest it to (a) represent the first-formed magma of a subduction episode (due to advent of slab-derived water), (7, 8), or (b) signal initial stages of sundering and back-arc spreading (due to tension-induced diapirism), (9, 10). In either case, boninite appears confined to brief intervals in the cycle of arc/back-arc activity, and reflects hydrous contamination of a refractory, basalt-depleted, source (11). Its ultramafic character, high liquidus temperatures, and apparent low pressure of origin (12), testify to unusual thermal conditions. Both tectonic and magmatic aspects of the arc/back-arc transition thus remain problematic. We need more data on arc stratigraphy, diachronism, and changes in tectonic expression along active arc systems. Frontal arc stratigraphy is best established through field mapping and land-based drilling. Longitudinal transects would complement the latter, and provide tests for diachronous arc sundering, arc/back-arc transitions, and the tectonic significance of boninite.

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PREPRINT

# Origin and emplacement of Mariana forearc seamounts

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ABSTRACT

Large seamounts occur on the outer half of the Mariana forearc. They represent a new class of seamounts consisting of horsts and diapirs of metamorphosed forearc material. The degree of metamorphism in this material depends on the amount of water available and the P-T regime of the forearc wedge. The major source for the water involved in the metamorphism is most likely the descending slab. Theoretical models for thermal regimes in convergent margins suggest the lower grade metamorphic facies will be restricted to the outermost portion of a forearc. Zeolite and chlorite facies rocks predominate in dredge hauls from horsts on the outer 50 km of the Mariana forearc. Thermal models indicate higher grade, greenschist facies should occur further from the trench. Seamounts which were probably formed in response to diapiric emplacement of serpentinite predominate from 50 to 120 km from the trench. Uplift of the horsts and emplacement of the serpentinite diapirs were probably facilitated by vertical tectonic movement in response to subduction of plate seamounts and by fracturing of the Mariana forearc.

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INTRODUCTION

Recent investigations of the Mariana forearc include study of bathymetry data from both academic and U. S. Navy sources (Fryer and Smoot, 1985), interpretations of SeaMARC II side-scan and bathymetry data (Fryer and Hussong, in press; Hussong and Fryer, in press), and analysis of seismic refraction data collected with ocean bottom seismometers (Ambos, 1984). From bathymetry and side-scan data we have determined the distribution of major forearc features of the Mariana system (Fig. 1). Seamounts, large grabens, and regions of hummocky terrain are restricted to the outer half of the forearc over its entire length. Chloritized mafic and serpentinized ultramafic plutonic rocks along with lithified to semi-lithified vitric siltstones were retrieved in most dredge sites on these seamounts (Bloomer, 1983; Hawkins et al., 1984; Fryer, unpub. data). Samples from seamounts within about 50 km of the trench axis show some serpentinization of ultramafic material, but contain more chloritized and lower grade metamorphosed material. There is little magnetic signature associated with these seamounts (Hussong and Fryer, 1981), indicating that they are probably not volcanic nor composed of highly magnetized material. One of these seamounts has a very subdued free air gravity expression (Hussong and Fryer, 1981), as would be expected from a small uplifted block of forearc material in deep water. Such seamounts are probably horsts formed as a result of vertical tectonic movement in the outer forearc. Seamounts composed primarily of serpentinized ultramafic material occur from about 50 to 120 km from the trench axis. These seamounts usually have a strong magnetic signature (Hussong and Fryer, 1981). The magnetic signature is probably related to the presence of picotite, chromite, and magnetite, which can form as a result of serpentinization. There is a small positive free air gravity anomaly associated with these seamounts (Hussong and Fryer, 1981), but it is much less than would be expected from a volcanic edifice in these depths. Diapiric rise of serpentinized ultramafics to shallow levels in the forearc crust has probably caused uplift which forms such forearc seamounts. Where the serpentinite reaches the surface it erupts onto the seafloor (Fig. 2). Dredge samples from such serpentinite flows are very similar to material exposed in serpentinite terrain on land (Carlson, 1984). The restriction of the seamounts to the outer half of the forearc is probably related to the geometry of the Mariana subduction zone, its thermal structure, and to the rheological properties of the forearc wedge.

HYDRATION OF THE FOREARC

The source for the water that is involved in the metamorphism of the Mariana forearc wedge is probably the subducted oceanic slab. The details of dehydration of a descending lithospheric slab in a subduction system are very complex. However, the general process is quite simple. As the oceanic plate subducts, sediments, their diagenetic and metamorphic products, upper crustal basalts and their secondary products, and any serpentine present in the oceanic lower crust and upper mantle will be dehydrated. Sediment dewatering occur by compaction and dessication of hydrated alteration products to a depth of about 6 km (Burst, 1976; Pittman, 1979). From 6 to about 15 km an increase in pressure and in temperature (to a few hundred degrees Celsius) will result in dehydration of zeolite facies minerals in the down-going slab. From about 15 km to about 30 km and at temperatures from a few hundred degrees to about 550°C greenschist facies minerals, including serpentine, will predominate. Deserpentinization and associated release of water can begin at temperatures as low as a few hundred degrees Celsius, and it will be complete before temperatures rise above about 550°C. Deserpentinization is not strongly controlled by pressure, but the stability field of greenschist minerals does not extend above about 10 kb (30 km). Although other hydrated minerals (talc, for instance) can persist to greater depths and temperatures, the volume of water available from dehydration of these minerals is far less than that available from the dehydration of zeolite facies minerals or the reaction of serpentine to olivine. Therefore, the greatest amount of dehydration of the down-going slab should be complete before the slab descends below about 30 km or warms much above 500°C. If serpentine in the descending slab is dehydrated above 30 km, the region of the forearc that would be most likely to experience influx of fluids from this reaction would be from about 70 km to 120 km from the trench axis (see Fig. 3). This roughly corresponds to the region in which the diapiric seamounts are most prevalent. The stability range of serpentine can be extended to higher pressures if excess water is present in the system. The maximum depth to which serpentine can persist in the descending slab will be controlled by the temperature in the descending slab. In order to determine the distribution of metamorphic facies in a forearc environment it is necessary first to determine the thermal structure of the forearc.

FOREARC THERMAL CONDITIONS

The most critical and least well-defined aspect of our discussion of metamorphism in the Mariana forearc is the assumed thermal structre. No thermal model has been proposed for the Mariana arc. Existing models for the thermal structure of subduction zones do not consider the thermal effects of reactions (e. g. deserpentinization is endothermic), the effects of varying degrees of fracturing of the forearc, or the effects of circulation of fluids in those fractures. All of these are probably important in the Mariana forearc. We have based our discussions on a thermal model calculated by Sydora et al. (1978, their Fig. 15). We have modified this model by decreasing the width of the forearc to 200 km and adjusting the geometry of the subducting slab. No adjustment was attempted for the higher convergence rate of the Mariana system (about 8 cm/yr), which is more than twice that given by the Sydora et al. (1978) model (3cm/yr). Note that a higher convergence rate would have its greatest effect on the deeper portions of the subducting slab, and we are concerned here with the conditions of the shallower portion (upper 30 km) of the forearc wedge.

Thermal models of convergence zones configure isotherms as vertical or overturned at the boundaries between the plates. In the simplest sense, the outer half of the forearc wedge, near the trench axis, experiences the cooling effect of contact with the down-going plate. Therefore lower grade metamorphic facies should predominate in the forearc wedge within a few tens of kilometers of the trench axis. The stability range for zeolite and chlorite facies metamorphism would occur in this region. Uplifted blocks of zeolite bearing, chloritized mafic material and some serpentinized ultramafic rocks occur within 50 km of the trench axis (Fig. 3). From about 70 to 150 km from the trench axis the deeper portions of the forearc wedge will be subjected to temperatures in the range of 250°to about 500°C. This is within the stability range for greenschist metamorphism, thus serpentinization could occur in this region. In the Mariana forearc, the diapiricly emplaced serpentine seamounts which we have identified are confined to a zone which lies about 50 to 120 km west of the trench axis. The western boundary of this region would be the vertical or overturned 500°C isotherm, a thermal wall, arcward of which serpentine cannot occur in the subducting slab or the overlying forearc wedge. The water driven off the subducting plate can cause metamorphism, including serpentinization, of deep-seated plutonic rocks in the overlying forearc wedge, if temperatures of the overlying material are below about 500°C.

A comparison of the Mariana forearc with suspected forearc terrains in California shows a number of similarities. Seismic refraction data collected from OBS studies near the trench-slope break in the Mariana fore-arc (Ambos, 1984) indicate the presence of a velocity inversion at mid-crustal (10-15 km) depths in the overlying plate (see Fig. 3). The velocities within this layer (5.9-6.3 km/sec) are within the range for serpentinite. G. S. Fuis and co-workers (pers. comm.) have studied the Trinity ultramafic body in northern California, part of an ancient forearc terrain. They have shown a correlation between a velocity reversal at the base of the ultramafic body and a region of higher magnetic suseptibility. They suggest the magnetic anomaly represents a serpentinized zone. Thus, they interpreted the inversions to represent serpentinized regions of the ultramafic body. If water is provided from below, the degree and grade of metamorphism of the overlying arc wedge should decrease upward as temperature as well as volume of fluid available decreases. Such a distribution of metamorphic effects is consistent with observations of decreasing serpentinization upwards that have been made in some ophiolite sequences (Nichols et al., 1980). These ophiolites may have been generated in an environment similar to that in the Mariana forearc. It should be noted however, that if the thermal model for the Mariana forearc shown in figure 3 is reasonable, then serpentine in this portion of the Mariana forearc would most likely be metastable. Studies of forearc sequences exposed elsewhere in California show a distribution of metamorphic facies similar to that proposed here for the Mariana forearc (Carlson, 1984), suggesting that the thermal history of these two regions may have been similar. Carlson (1984) has suggested that some of the serpentinite bodies of central California were emplaced by diapirism, similar to that which has occurred in the Mariana forearc.

EMPLACEMENT OF SEAMOUNTS

We know of no other forearc which has as well developed a forearc seamount province as the Mariana forearc. By comparison, the Izu arc, which is the northward continuation of the Mariana arc and which has a similar subduction rate, age of down-going lithosphere, and subduction geometry, lacks a wide zone of seamounts or large scale vertical tectonic features on its forearc (Taylor and Smoot, 1984). The Izu forearc differs in two regards from the Mariana forearc. It is overriding oceanic plate that is essentially devoid of seamounts. Also, the Izu arc is a linear feature with no obvious large scale fracture patterns identifiable on its forearc.

The floor of the Pacific plate east of the Mariana trench has a large number of seamounts. Fryer and Smoot (1985) suggested that these seamounts are being subducted at least partially intact, are not being scraped off the oceanic plate nor accreted to the forearc. Fryer and Hussong (in press) suggested that subduction of these seamounts causes uplift of the forearc. The effect of subduction of these seamounts is probably a function of the rheologic properties of the forearc. Theoretical models of the variation in rheology of the oceanic lithosphere (Watts et al., 1980) indicate an increase in thickness of the elastic layer as the lithosphere cools with age. We do not know the thermal structure of the forearc in detail, but the effect of the subducting slab would be to cool the outer forearc and facilitate fracturing in response to stress. The generation and emplacement of magmas in the arc would warm the inner forearc wedge and facilitate a plastic response to stress. It is likely the central portion of the Mariana forearc is far enough removed from the arc heat source and from the cooling effect of the subsiding slab to approach an adiabatic thermal gradient. Based on an age of the forearc of about 40 my (Hussong and Uyeda, 1981), we suggest this part of the forearc probably responds elastically to point loads to a depth of about 30 km. This depth is attained at a horizontal distance of about 120 km from the trench axis (see Fig. 3). Beyond this distance from the trench axis, seamounts on the surface of the down-going slab probably enter a plastic regime in the forearc lithosphere and are far less effective in causing vertical tectonic movement of the overlying material. Small degrees of partial melting may occur in the forearc, possibly at depths as shallow as 30 km (Jakes and Miyake, 1984). The occurrence of partial melts would increase the plastic response of the mantle below that depth. This argument suggest that most of the vertical tectonic movement in response to seamount subduction should occur within 120 km of the trench axis.

Distribution of forearc seamounts is probably also related to regional and local fracture patterns on the Mariana forearc. There are obvious fracture trends on the Mariana forearc (see Fig. 1). The origin of these fractures is not well understood, but is likely related to local adjustments to the increasing curvature, with time, of the active Mariana arc. The subduction of oceanic plate seamounts and adjustments to changes in curvature of the arc both cause fracturing of the Mariana forearc. These fractures provide planes of weakness along which vertical tectonic movement can take place, facilitating graben and horst formation, and along which diapirs of serpentinized ultramafics can rise.

The occurrence of numerous exposures of deep-seated forearc material in the Mariana region presents a rare opportunity to study in situ metamorphic processes in the forearc of a convergent margin. The distribution of metamorphic facies presented here for the Mariana forearc is likely also to occur in other convergent margins. Thus, the Mariana forearc seamounts provide windows through which we can see processes that may be common to most forearc environments, but that usually are not so accessible for study. Exploration of two of these seamounts with the deep submersible, ALVIN, has been scheduled for 1987.

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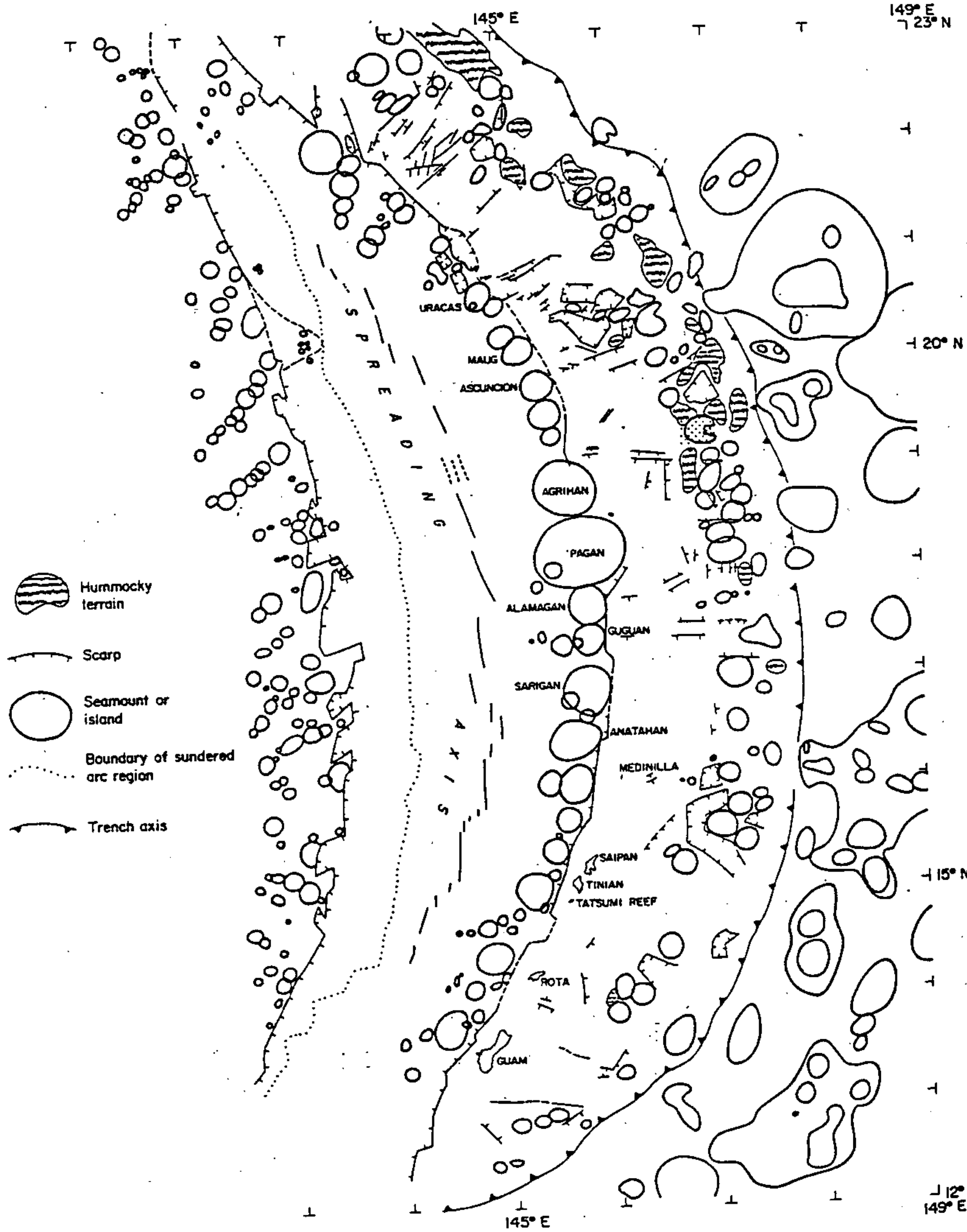
Figure captions:

Figure 1. Sketch of outer Mariana arc region showing distribution of major seafloor features. Scarp following strike of island arc marks position of eastern margin of Mariana back-arc basin. Distance from scarp to trench axis is about 200 km along most of arc. Positions of seamounts and fractures based on bathymetry and sidescan data from academic sources, SeaMARC II data, and U.S. Navy bathymetry data. Stipple indicates area of Figure 2.

Figure 2. SeaMARC II side-scan image and bathymetry of crescent-shaped seamount in outer Mariana forearc (see Fig. 1 for location). Dark ovoid shape in the center of side-scan image is thick (100 m) flow of serpentinized ultramafic material about 7 km in diameter emanating from near summit of seamount (outline shown by dashed line on bathymetry).

Figure 3. Cross section through Mariana arc at about lat 18°N (no vertical exaggeration). Position of top of the downgoing slab is chosen as top of seismic zone at this latitude. General form of isotherms modified after Sydora et al. (1978). Dashed line represents 30 km boundary between proposed elastic forearc lithosphere and underlying plastic lithosphere. Diagonal-line area represents velocity inversion zone in mid-crustal layers of forearc.



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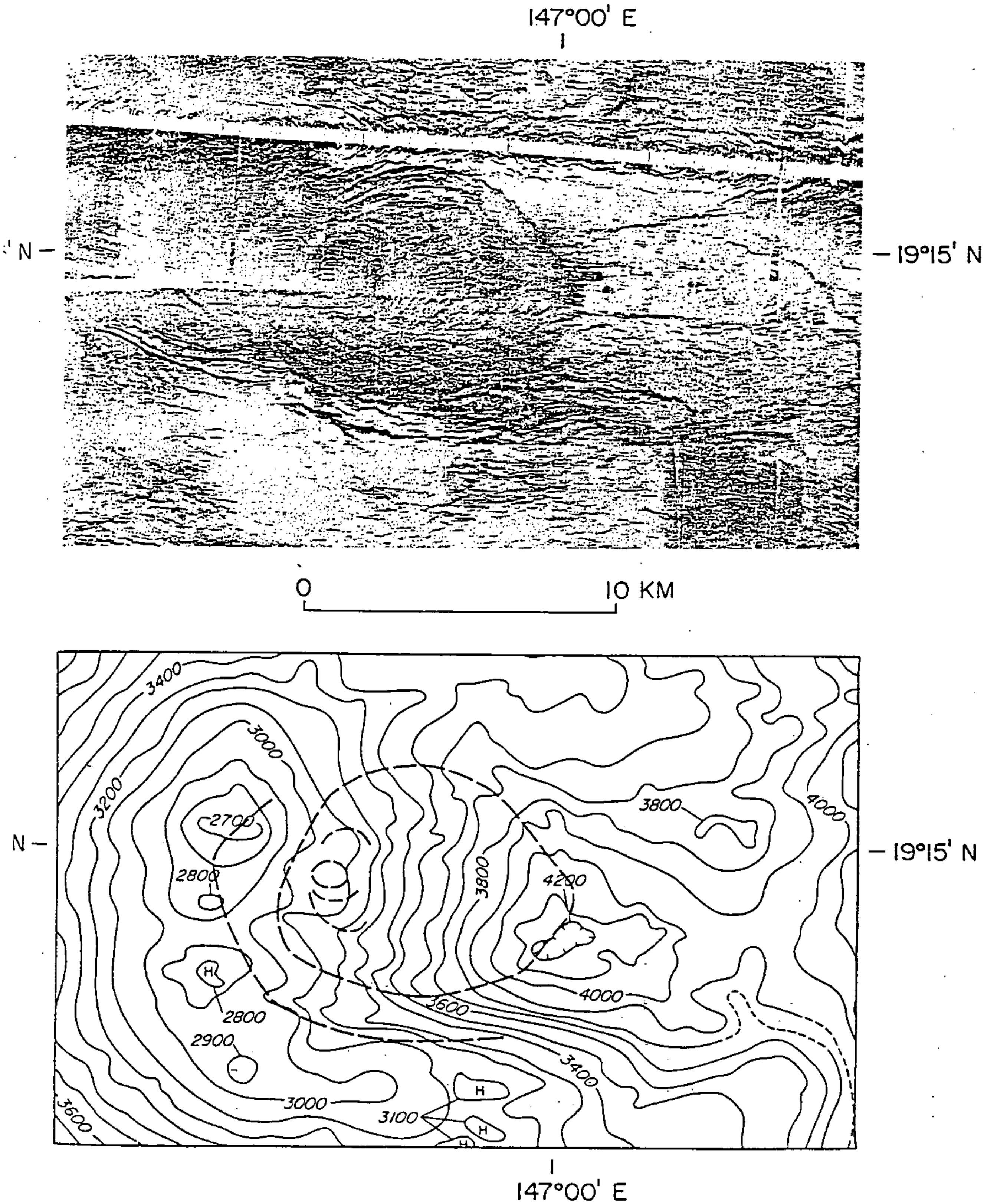
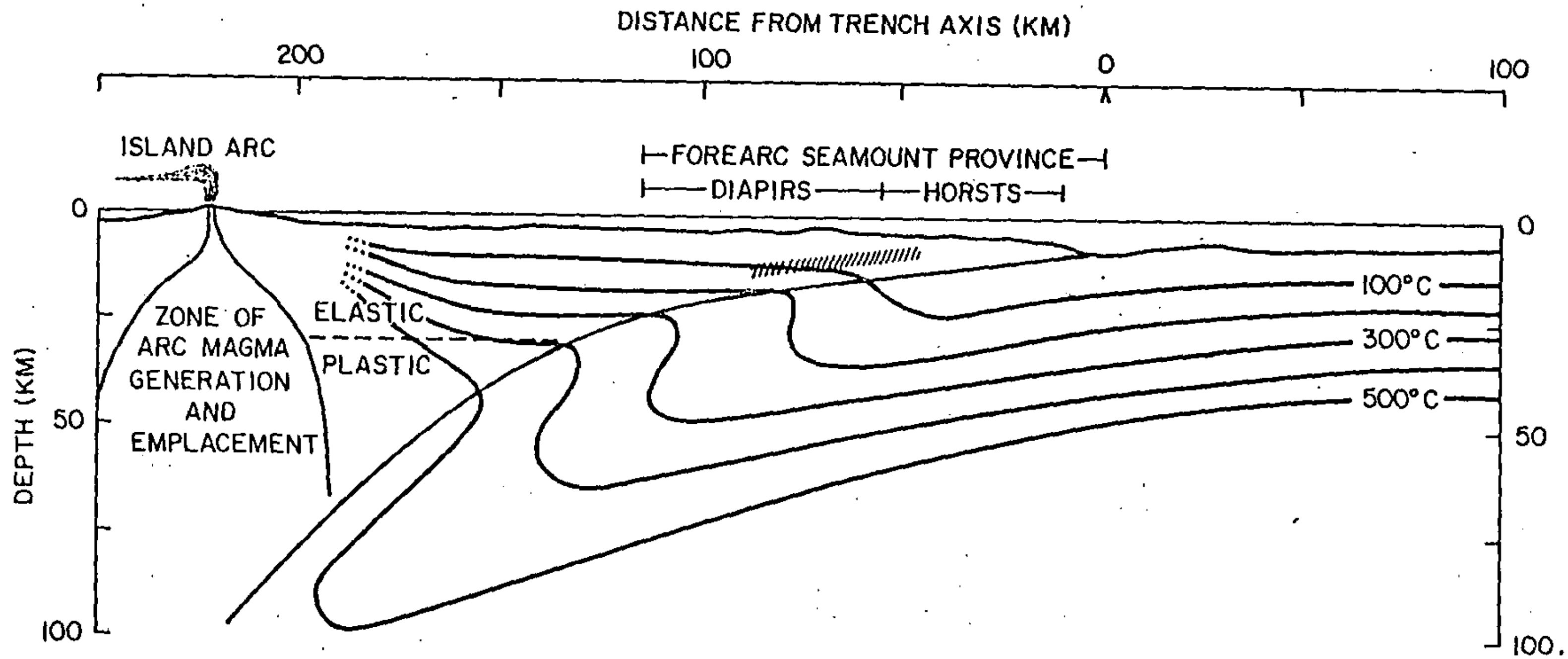
GUAM
Hummocky terrain
Scarp
Seamount or island
Boundary of sundered arc region
Trench axis

Fig



147°00' E
N
19°15' N
0
10 KM
3400
3000
3200
2700
2800
3800
4000
4200
3600
H
2900
3100
N
19°15' N
147°00' E


DISTANCE FROM TRENCH AXIS (KM)
200
100
0
100
ISLAND ARC
FOREARC SEAMOUNT PROVINCE
DIAPIRS
HORSTS
0
50
100
DEPTH (KM)
ZONE OF ARC MAGMA GENERATION AND EMPLACEMENT
ELASTIC
PLASTIC
100°C
300°C
500°C
0
50
100.

# DETERMINATION OF THE HISTORY OF VERTICAL MOVEMENTS IN FOREARCS

Janet A. Haggerty, University of Tulsa, Tulsa, OK

A prime area of interest for a workshop on western Pacific active margins is the stratigraphic record and how studies of the sediments can help determine the history of vertical motion in oceanic forearc regions. This information is essential because the magnitude of the movements, whether these be uplift, subsidence, or more likely a combination, places constraints on thermal and mechanical models for the evolution of active margins. Determination of the vertical history is therefore important to an integrated research program dealing with the processes, structure, and petrology of active margins. Drilling is the most appropriate means for obtaining a complete stratigraphic data set for interpretation of the vertical history compared to dredging or other sampling techniques.

Past sedimentological studies in active margins were directed toward determining depositional systems and processes in active margins. Studies of depositional mechanics, and comparative sedimentology of recent sediments and their associated environments with ancient sedimentary rocks has enabled sedimentologists to map the associated facies within depositional systems. Identification and distribution of environments using related biofacies and sedimentary facies has enabled sedimentologists to predict facies associations both horizontally and vertically. This phase of research on depositional systems and sedimentological processes in active margins is still developing and many major advances have been made in understanding the sequence of depositional systems in the backarc basins.

Studies of sediments for unraveling vertical tectonics of an area are fundamentally different than the past sedimentological studies that were directed toward determining depositional systems because an interdisciplinary approach is required. Data from paleontological and sedimentological studies are combined to provide time-stratigraphic information. Paleontological studies provide us with a chronologic framework for ordering the sequence of depositional (and/or redepositional) events and changes in the ecologic environment and paleodepth. The effects of global sealevel change and sediment loading must be accounted for in order to adequately estimate the vertical tectonic motion as the consequence of mechanical effects, such as underplating, or thermal effects from the subducting, cold slab.

Significant advances have been made in micropaleontology from research on samples obtained by the Deep Sea Drilling Project. Studies of the benthic microfossils have increased our knowledge on their depth distribution and ecology. Significant advances have also been made with biostratigraphic zonations of planktonic microfossils. Biostratigraphic schemes that are good for dealing with assemblages from equatorial and low latitude areas in the western Pacific are Barron (1980) for diatoms, Gartner (1977) for nannofossils, Kennett and Srinivasan (1983) for foraminifera, and Riedel and Sanfilippo (1978) for radiolarians.

The continued development of detailed biostratigraphic zonations for each of group of planktonic microfossils (Riedel, 1981) has resulted in better resolution for discerning the relative timing of geologic events (Moore and Romine, 1981). This increase in resolution has been accomplished by using a composite stratigraphy of zonations from more than one microfossil group, or by combining biostratigraphy with magnetostratigraphy or isotope stratigraphy. In addition to biostratigraphic zonations being correlated with greater precision to the relative geologic time scale, these have been merged with numerical time scales (Cohee et al., 1978). This enables us to use the geologic record of an area in a chronostratigraphic setting and place the sedimentary and environmental history "into a perspective that facilitates the interpretation of geologic processes" (van Hinte, 1978).

Geohistory analysis, the use of quantitative stratigraphic techniques to interpret the sequence and rates of geologic processes, has been used for at least the past two decades by the petroleum industry for petroleum exploration. In 1978, Jan van Hinte published the technique for constructing geohistory diagrams using paleodepth data, age, and mathematical derivations of sediment accumulation and subsidence rates. The best paleobathymetric resolution is obtained when dealing with sediment deposited in a neritic environment. These diagrams are a convenient time-depth plot for superimposing other data related to diagenesis, porosity, heat-flow, etc.

The concept of geohistory analysis was applied to the Japan forearc area (Arthur and von Huene, 1980; von Huene and Arthur, 1982) using micropaleontologic data derived by Keller (1980) as well as sedimentological data. The uplifted, outer-arc high, called the Oyashio landmass, subsided by as much as 6 km during the Neogene tectonic history of the Japan forearc and trench area.

Other techniques may also be applied to indicate vertical motion in the forearc region. Using arguments based upon characteristics of sediment from the Mariana forearc, and the relative position of paleodepth curves for the CCD in equatorial and higher latitude from the eastern and central Pacific, Karig and Ranken (1983) concluded that some uplift had occurred in the Mariana forearc. There are numerous other techniques or combinations of techniques that may be used to elucidate the history of vertical motion in an area.

In contrast to Karig and Ranken's (1983) proposition that some uplift has occurred in the Mariana forearc, several other reports cite tectonic erosion and subsidence of the same forearc (La Traille and Hussong, 1980; Mrozowski and Hayes, 1980; and von Huene and Uyeda, 1981). The conflicting data may be a result of a change in the response of the arc over time, as suggested by Karig and Ranken (1983), or even a change in response along the arc or across the arc. The question of intermittent accretion and tectonic erosion in the forearc region has never been properly addressed with an appropriate suite of samples from an intra-oceanic convergent margin.

Studies of the sediments from the forearc for vertical motion also lend themselves to addressing other problems such as the timing of volcanic or intrusive activity in the forearc region. The biostratigraphic age of the sediment can yield minimum age of volcanism or a maximum age of intrusion. If hydrothermal circulation is associated with intrusive activity, there may be a diagenetic signature in the nearby and/or overlying sedimentary strata. Diagenesis can be governed by the chemical composition of the pore waters which can change their composition during migration through the rocks. Studies of the interstitial waters retrieved from these sediments would also be valuable because they may reveal chemical changes that were undetected in the geochemistry of the sediments. The question of a diapiric origin of seamounts in the forearc region (Fryer et al., in press) may also be addressed by studying the history of the vertical motion of the strata immediately overlying the bathymetric high and comparing it to the history of an adjacent region.

A prime candidate for studying vertical motion in an intra-oceanic forearc is the Mariana convergent margin because it is the location of the best data set to date. This author recommends that a study be conducted in a more equatorial location than the previous 18°N Mariana transect because there may be better preservation of calcareous microfossils owing to a depressed equatorial CCD. The location of drill sites could be associated with a submarine canyon. A drill hole into the upper flank of a canyon would yield the younger sediments whereas a drill hole in the base of a canyon would obtain older exposed strata and perhaps igneous basement in the forearc. Other recommended drill holes are into and offset from bathymetric highs such as an outer arc high or a forearc seamount. These bathymetric highs, if above the CCD, may have better preservation of important calcareous microfossils. Turbidites shed from these bathymetric highs may also contain better preserved carbonate sediments in adjacent regions that are below the CCD. No matter where a drill site is chosen, if it is in the southern region of the Mariana forearc, it is advantageous to combine this data with a shore-based drilling program or a geologic field program on the island of Guam or Saipan. The combined data sets from the island and the drillsite(s) would yield information about the history of the vertical motion across the forearc.

This author also recommends the use of hydraulic piston coring (HPC) for drill sites where only the upper, soft sediment sequence is needed. There is better preservation of primary sedimentary structures and trace fossils, less potential for contamination to occur to the interstitial waters in the sediment, as well as less opportunity for contamination of micropaleo assemblages as the result of mixing of sediment layers than when conventional rotary coring is used. As an alternative to HPC in drill sites where interlayering of harder strata is suspected, the author recommends the use of the extending core barrel (XCB). This coring technique creates less disturbance in soft sediments than the conventional rotary drilling by having the core barrel extended in front of the drill bit. When the barrel contacts harder strata, the barrel retracts and the drill bit is rotated as in conventional rotary drilling. XCB is a method that offers the benefits of rotary drilling, while not causing extensive drilling disturbance to the soft sediment layers.

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Possible problems to be addressed by lithospheric drilling program in the western Pacific arc-backarc system:

Emi Ito, Rick Schult, Guy Smith (University of Minnesota)

The Mariana backarc exhibits several stages of rifting, possibly involving a northward propagation of the backarc spreading center (Stern et al., 1984). DSDP Legs 59 and 60 sampled several sites (451,453, 454, 455, 456) in the Central Mariana backarc basin (17-18°N) where there is a well-developed spreading center (Kroenke et al., 1980; Hussong and Uyeda, 1981). We propose 3 similar transects to the north to examine different stages in backarc spreading for comparison with mid-ocean propagating rifts (Hey et al., 1980; Sinton et al., 1983).

1. Propagation of backarc in the Mariana system

A. Variation in chemistry, igneous and metamorphic petrology, and tectonic styles of rifting should be investigated by drilling the three transects mentioned above: at 20.5°N in the northern Marianas backarc basin; at 22°N, the northern tip of the backarc basin; and at 23.5°N just north of the tip of the basin where incipient rifting has been observed (Karig and Moore, 1975). These cores will complement existing and to-be collected dredge samples. Some seismic and extensive SEAMARC data already exist to help with the planning (LaTraille and Hussong, 1980; Fryer, personal communication).

A test of the propagation hypothesis needs good control on the timing of initiation of rifting and subsequent tectonism. For example, bio- and magnetostratigraphic analysis of sediments can be used to date the seafloor. If oriented cores can be collected (using HPC), tectonic rotations could be investigated.

B. We need to compare the alteration of the backarc basement rocks with rocks from the mid-ocean ridge environment to study effects of more diffuse production of magma and higher rates of sedimentation (possibly causing early sealing of basalts).

*Guy, we need references here, Please supply.*

Detailed examination of this phenomenon and of the various consequences of propagation (chemical and petrologic variation and rate of evolution) can be accomplished by drilling a N-S transect (along the strike of the arc) in the backarc between 20.5° and 24°N.

C. We need reference data on the composition of sediments subducted into the trench because it also can influence the chemistry of the volcanic products in the arc-backarc system (Meijer, 1976; Stern and Ito, 1983). We should compare the variation in the composition of the volcanic products along the strike of the arc (and backarc) with the variation in the bulk and mineralogic composition of the sediments along the strike of the arc. Sites would be drilled on the outer rise between 20° and 24°N. (Part of the necessary information is the dewatering behaviour of the sediments.)

D. We should not neglect "normal" arcs, i.e., those with no active backarc spreading. A transect should be made across the Izu Arc and Bonin Trench at a latitude where there is no backarc spreading as a referance for the other transects.

E. The Bonin backarc system should also be studied because it provides us with an opportunity to investigate a recent rift fairly near the western edge of the active arc.

The three east-west transects and the sites described in B. are to be drilled into the basement and the sites east of the trench could be drilled just to the basement.

2. A similar investigation can be conducted in the Kermadec-Lau system. One advantage here is that Lau Basin has been the subject of several recent multi-channel seismic studies (Morton and Sleep, 1983).

3. Reconnaissance investigation of an inactive arc which has stopped subducting due to the (partial) subduction of the Caroline Ridge can be started by drilling across the Yap Trench (refs).

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# DEEP DRILLING PROJECT, WESTERN PACIFIC ARCS, BACK-ARCS AND TRENCHES

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A number of contributors have emphasized the need for a hole in the vicinity of the arc. If the technical difficulties of drilling such a hole can be overcome, the site offers a number of opportunites. Stern has emphasized the need for understanding the temporal evolution of arc mamgas, while Hawkins and Natland have discussed the importance of characterizing arc crust as an analog for ophiolite sequences. In addition, such a hole affords the opportunity to assess the geologic history of the arc, specifically:

1. Delineating periods of effusive activity, explosive activity and quiescence
2. Establishing the relative importance of volcaniclastic *vs.* pelagic sedimentation through time at a given site
3. Determining relative proportions of sedimentary and igneous rocks through time
4. Characterizing composition of the igneous component of arc crust through time.

These objectives are important in and of themselves. They are also significant in that they will allow us to:

1. Characterize the bulk composition of the island arc crust
2. Model the effects of crustal assimilation on magmas erupted in island arcs, thereby allowing a better assessment of the characteristics of arc magmas which are truly mantle-derived.

Moore has emphasized the need for holes sited especially to evaluate sedimentological processes. This is necessary for understanding sedimentation patterns in the arc region. It is also important for understanding the effect of any subducted sediment on arc magma chemistry. An important question is, how much of the arc is being recycled back into itself through sedimentary processes? An arc where the present state of magmatic evolution, along with the past geologic history and sedimentological history are all well known, provides an excellent opportunity for attempting to evaluate the question of sediment recycling and the role of volcaniclastic sediments in such a process, specifically:

1. Sediment chemistry is highly variable and to model the effects of sediment subduction we need to know as much as possible about the closest analogs to the sediments actually subducted in the arc of interest
2. We need to determine the importance of volcaniclastic sediments in sediment pile to be subducted
   (a) at what distance from the trench (= age or depth) is volcaniclastic sediment initially deposited
   (b) at the trench, what is the volume of volcaniclastic sediment as fraction of total sediment pile
3. In order to extend observations about sediment types and chemistry to other arcs, we need to know the relative importance of volcaniclastic sedimentation as a function of
   (a) age of the arc
   (b) extent of explosive activity
   (c) hydrogenous and biogenous production rates
4. Thorough evaluation of sediment contamination of arc lavas requires a broad spectrum of analytical approaches, including major and trace element radiogenic and stable isotope measurements for sediments as well as lavas.

Understanding sediment accretion and sediment subduction processes is important for understanding evolution of the fore-arc region, but also for a detailed evaluation of sediment contamination of arc lavas. $^{10}Be$ is a good tool for investigating sediment accretion in arcs where accretion is occurring. Because $^{10}Be$ is a cosmogenic isotope and has a short half-life ($1.5 \times 10^6$ years), $^{10}Be$ is concentrated in the uppermost part of the sediment pile. Analysis of sediment cores outboard of the trench will provide an inventory of the number of atoms of $^{10}Be$ available for subduction. Measurements in cores drilled in the fore-arc (with paleontological age control) will provide information about the amount of sediment transferred to the accretionary wedge, while a core in the trench may provide information about mixing of upper and lower sediments ($^{10}Be$-rich and -poor, respectively) during deformation in the trench. A project such as this cannot be carried out in the Marianas (little fore-arc, no $^{10}Be$ in the lavas) but Tonga-Kermadec may be a suitable area.

# AN AXIAL MAGMA CHAMBER ON VALU FA RIDGE, A BACK-ARC SPREADING CENTER IN LAU BASIN

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The Lau Basin is an actively spreading back-arc basin located west of the Tonga arc-trench system. The spreading center in the southern part of the basin is formed by Valu Fa Ridge, a north-north-east trending ridge situated along the eastern side of the basin approximately 40 km west of the volcanic arc. The ridge has a narrow, non-rifted crest and extends from at least lat 21° 51'S, long 176° 30'W to lat 22° 42'S, long 176° 46' W. A small offset of the ridge at lat 22° 10'S appears to be formed by an overlapping spreading center pair. Magnetic anomalies indicate that the ridge is spreading at a rate of about 7 cm/yr.

Multichannel seismic reflection profiles over Valu Fa Ridge show a strong reflection 3.5 km beneath the seafloor. The polarity of the reflection, determined by pre-stack deconvolution, indicates that the reflecting horizon represents a low velocity zone. The reflector is interpreted as the top of an axial magma chamber. The top of the chamber is flat-lying and 2 to 3 km wide. The magma chamber appears to be continuous along strike, as it is seen on each of seven cross-strike profiles spaced over 84 km of ridge crest. One profile which crosses the ridge at the overlapping spreading centers shows only one magma chamber, centered beneath the overlap basin.

The reflection coefficient for the top of the chamber, determined by comparing the amplitude of the magma chamber reflection to the seafloor reflection, indicates a low acoustic impedance (product of density and seismic velocity) for the material at the top of the chamber. If a density if 2.4 to 2.7 $gm/cm^3$ is assumed for the melt, then the velocity is approximately 1.8 to 2.0 km/sec. This velocity is considerably lower than experimentally determined velocities of basaltic and andesitic melts (about 2.5 km/sec). One possible explanation for the low seismic velocity is the presence of a small amount (approximately 1 volume percent) of exsolved gas in the melt at the top of the chamber. Fresh, highly fractionated andesitic rocks dredged from the crest of Valu Fa Ridge are highly vesicular.

Elevated concentrations of particulate and total dissolvable manganese in the water column above the ridge and ferromanganese crusts up to 10-mm thick of hydrothermal origin dredged from the ridge crest suggest that there is hydrothermal circulation at the ridge.

MS #1057

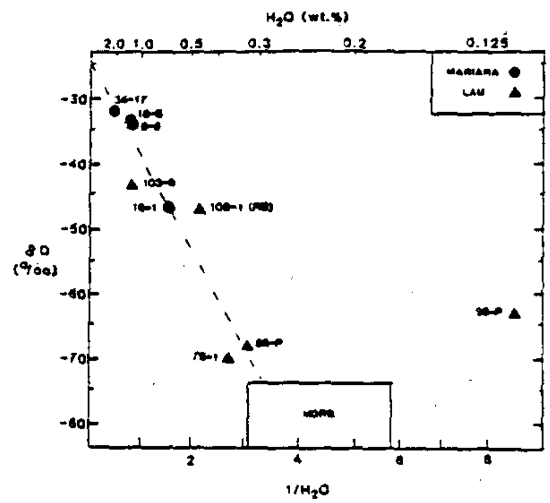
# HELIUM-3 AND DEUTERIUM IN BACK-ARC BASALTS : LAU BASIN AND THE MARIANA TROUGH

Robert Poreda


## Abstract

Samples of fresh basalt glass from the Mariana Trough and the Lau Basin were analyzed for their isotopic composition of water and helium in order to identify the sources of the volatiles in back-arc basin basalts. In the Mariana Trough basalts, the concentration (0.64 to 2.1 wt.%) and D/H ratio ($\delta D$ = -46 to -32°/₀₀) of the water provide important evidence for a water-rich component from the subducting lithosphere. Extrapolation to infinite water content gives an end-member D/H ratio of $\delta D$ = -25°/₀₀. $^3He/^4He$ ratios are, in general, similar to MORB values (~8 $R_A$) and indicate that Mariana Trough basalts represent a mixture of a MORB-type mantle and an alkali and water-rich component from the descending slab.

In contrast, the Lau Basin produces both hydrous (1.3 wt.% $H_2O$) and relatively anhydrous (0.12-0.35 wt.%) basalts. The D/H ratio ($\delta D$ = -43°/₀₀) in the hydrous Lau Basin basalt resembles those of Mariana Trough lavas. The low water contents (0.12-0.35 wt.%) and MORB-like D/H ratios ($\delta D$ = -63 to -70°/₀₀) in three of five Lau Basin samples show that the water-rich component, observed in all Mariana Trough lavas, is absent in some Lau Basin lavas and not essential for the production of back-arc basalts. The high $^3He/^4He$ ratio of Rochambeau Bank in the northern Lau Basin (11 $R_A$), confirms an earlier analysis by Lupton and Craig and provides evidence for an enriched mantle source region beneath the Lau Basin which is perhaps related to the high $^3He$ Samoan "hotspot".



$H_2O$ (wt.%)
2.0 1.0 0.5 0.3 0.2 0.125
MARIANA
LAU
-30
-40
-50
-60
-70
-80
δD (‰)
34-17
16-6
8-6
103-9
16-1
106-1 (RB)
56-P
79-1
56-P
MORB
2
4
6
8
1/$H_2O$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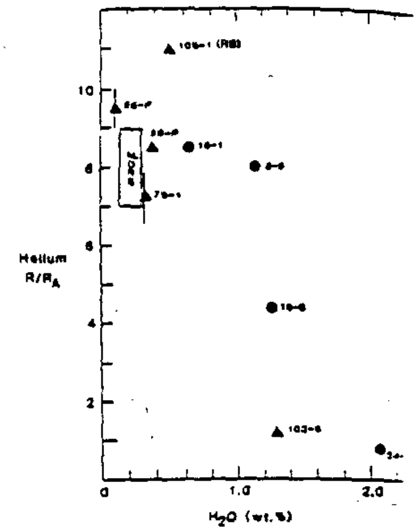

106-1 (RB)
10
56-P
56-P
16-1
8-6
79-1
MORB
8
Helium
R/$R_A$
6
16-6
4
2
103-9
0
1.0
2.0
$H_2O$ (wt.%)


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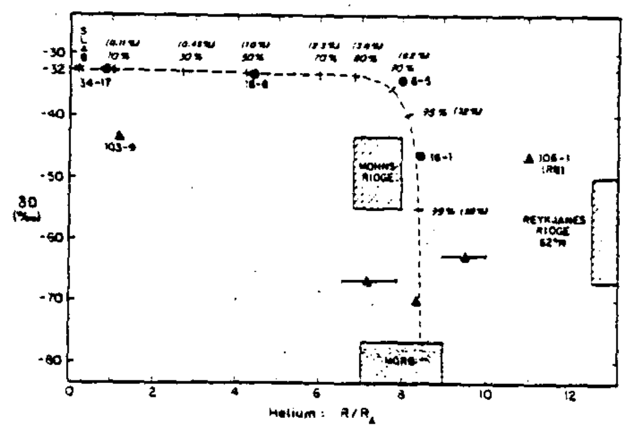

-30
-32
-40
-50
-60
-70
-80
δD (‰)
70%
30%
50%
70%
80%
90%
34-17
16-6
8-6
95%
103-9
16-1
106-1 (RB)
MOHNS RIDGE
99%
REYKJANES RIDGE 62°N
MORB
0
2
4
6
8
10
12
Helium : R/$R_A$


[illegible]

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# Helium-3 and deuterium in back-arc basalts: Lau Basin and the Mariana Trough

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## 1. Introduction

Extensional basins behind many of the world's intra-oceanic arcs erupt tholeiitic lavas which resemble mid-ocean ridge basalts (MORB) [1–4]. The precise mechanism for the generation of these back-arc basalts is not known, but in the Mariana Trough, the Lau Basin and the Scotia Sea, their intimate association with the subduction process is clearly evident. Back-arc basin basalts are roughly similar to mid-ocean ridge basalts in major element chemistry [2–4]. The $\delta^{18}O$ of "whole rock" for the Lau Basin and the Mariana Trough [7] and of the glass for the Mariana Trough [8] are identical to MORB. However, important differences do exist. Relative to normal MORB, most back-arc basalts have higher levels of large ion lithophile (LIL) elements and higher $^{87}Sr/^{86}Sr$ ratios [5,9,10]. Garcia et al. [11] showed that Mariana Trough basalts have water contents five times higher than normal MORB. Thus, it does not appear possible to produce back-arc basalts by simply melting normal MORB mantle. A component rich in volatiles and LIL elements is required to satisfy the chemical data.

Lupton and Craig [12] included two back-arc basalts from the Lau Basin in their initial study of $^3He/^4He$ ratios in oceanic basalts. They found helium isotope ratios similar to those in MORB in one sample and considerably higher than MORB in the other. Their results showed that helium in the Lau Basin basalts is dominantly "primordial" mantle helium, rather than radiogenic helium from the oceanic crust. Thus the $^3He$ data and water concentrations have contradictory implications for the origin of volatiles in back-arc basin spreading center basalts. The present study was designed to identify the sources for helium and water in basalts from the Lau Basin and the Mariana Trough, using both helium and hydrogen isotope ratios, and to place constraints on the generation of back-arc lavas.



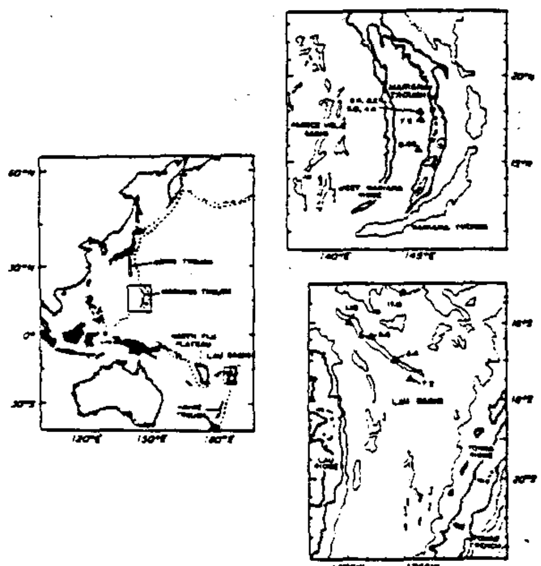

Fig. 1. [illegible] of the Mariana Trough and the Lau Basin, with the dredge locations and helium isotope ratios (in $R/R_A$) [illegible]. Map of the Mariana Trough [illegible] (1). Lau Basin map is from [illegible] [3].

region which has been the focus of most of the geochemical and geophysical studies.

Four of the six Mariana Trough samples studied, MARA 8-5, 9-2, 16-1 and 18-8, were from dredges made on Scripps Institution of Oceanography MARA Expedition during a transect of the central

## 2. Samples and analytical methods

The gases from fresh basalt glass chips (~1 mm diameter) were released by fusion at 1600°C in a Bean-type high vacuum furnace in which the tantalum crucible serves as the resistive heating element [12,13]. The average total blank, determined by heating an empty tantalum tube was $2 \times 10^{-11}$ cm³ $^4He$, $1.0 \times 10^{-10}$ cm³ Ne and 0.03 cm³ $H_2O$. The gases from one sample, RAMA 25-2, were extracted by crushing basalt glass chips in a stainless steel flask under high vacuum conditions [13]. The blank was measured as $2 \times 10^{-11}$ cm³ $^4He$. Helium concentration and isotopic measurements were carried out on a 25-cm radius, double-collecting mass spectrometer (GAD) which has a resolving power of 600 [12,13]. The $^3He/^4He$ ratios are reported relative to the atmospheric ratio ($R_A$), using air helium as the absolute standard ($R_A = 1.4 \times 10^{-6}$). The precision for $^3He/^4He$ ratios, unless otherwise stated, is 3%. Helium concentrations were determined by peak height comparison with an air standard of known size. Helium for isotope analysis was separated from neon at 37°K on activated charcoal. After the helium isotope measurement, the neon concentration was measured in the $^3He/^4He$ mass spectrometer by reducing the accelerating voltage. This method is accurate to ~20%. The neon concentration is an indication of the magnitude of the atmospheric contamination and the contribution of atmospheric helium to the measured $^3He/^4He$ ratio. In many cases, the neon peak was so small that only lower limits for the He/Ne ratio could be determined. In only one case was a significant correction for atmospheric helium necessary, in the Mariana Trough sample, RAMA 25-2, obtained by crushing.

For the analysis of the D/H ratio in basalts, the $H_2$ and $H_2O$ were collected during the gas extraction. The hydrogen was exposed to hot CuO at 600°C during the extraction and the total $H_2O$ was collected in a liquid nitrogen trap. The $H_2O$ was later reduced to $H_2$ by reaction with uranium at 790°C, volumetrically measured in a calibrated Toepler pump, and analyzed for D/H ratio in a 15 cm, spot-tube double-collecting mass spectrometer (DELILAH). All samples were measured at a mass 2 ion beam intensity of 20 volts with a processing plus instrumental precision of 0.5‰. The isotope ratios in blanks were determined by mixing the blank $H_2$ with standards of known size and isotopic composition, and calculating the isotope ratios in the blanks from measured ratios in the mixtures. The maximum blank correction was 3% in concentration and 2‰ in $\delta D$ (TWO 95-P); for all other samples, the blank correction was less than 1% in $H_2O$ and 1‰ in D/H ratio. Isotope values for hydrogen are reported relative to Standard Mean Ocean Water (SMOW) [14]. Delta values represent permil differences from SMOW as defined by:

$$\delta = [(R/R_{STD}) - 1] \times 1000$$

where $R$ is the D/H ratio.

Table 1 lists all the data on the Mariana Trough and Lau Basin basalts. Sample numbers are SIO dredge numbers, identified by expedition for the Mariana Trough, and by ship (TWO = Thomas Washington—Dredge) for the Lau Basin. The samples analyzed in this study represent all of the available basalts with fresh glass in the SIO dredge collection.

## 3. The Mariana Trough basalts

Fig. 1 shows the sample locations and bathymetry of the two basins. The Mariana Trough, located between 12°N and 21°N at 145°E, has been spreading for approximately 5 m.y. with an average rate of 1.6 cm/yr [15]. The locus of active volcanism in the Trough is confined to a central graben which parallels the trend of the volcanic arc and is located ~100 km behind the active arc. At ~4 km depth this spreading center is considerably deeper than typical mid-ocean ridges. The graben structure is best developed at 18°N, the



| |
|---|
| [illegible] |

graben at 17°57'N. One sample, RAMA 25-2, is from a dredge haul at 17°32'N in the central graben. The only sample which is not from the presumed zone of most recent volcanism is MARA 34-17 at 15°33'N, which was dredged from ~0.5 m.y. old crust, as calculated using a 1.6 cm/yr spreading rate. These samples were selected for their abundance of fresh glass and for a range of trace element concentrations and $^{87}Sr/^{86}Sr$ ratios, in order to compare helium and water measurements with the LIL variations. The basalts chosen exhibit a range of trace element characteristics, with $K_2O$ = 0.22–0.54 wt.%, Rb = 1–10 ppm, and Ba = 15–77 ppm [16,17]. The lowest LIL values overlap the MORB range while the rest of the suite shows variable degrees of enrichment relative to MORB. The rare earth patterns are flat to slightly enriched in the light elements and the $^{87}Sr/^{86}Sr$ ratios fall in a restricted range between 0.70280 and 0.70305 with an average of 0.70293 [16,17]. Most of the samples appear to be co-magmatic and controlled by crystal fractionation, although this cannot explain the complete range of variations which must relate to small differences in the parental magma [16].

### 3.1. Water and deuterium results

Table 1 shows the concentration and isotopic composition of water for the Mariana Trough basalts. Fig. 2 is a plot of the D/H ratio vs. the reciprocal of the water content in the Mariana Trough samples. The most striking features of these results are the very high water contents (0.64–2.1 wt.%) and $\delta D$ values ($\delta D$ = −32.5 to −46‰). These are the highest deuterium enrichments measured for an oceanic basalt and are quite distinct from the value of −77‰ typical of normal MORB [18]. Extrapolation to infinite water content in Fig. 2 yields an end-member isotopic composition of −25‰ for the water in the Mariana Trough basalts. MARA 16-1, the basalt with the lowest water content and $\delta D$ value, represents an approximately 50/50 mixture of normal MORB water at −77‰ and the high $H_2O$ component. All other Mariana Trough basalts are dominated by the component enriched in deuterium. Of the six Trough samples studied, MARA 16-1 has the

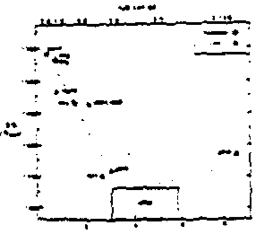

Fig. 2. Deuterium data values vs. [illegible] water of Mariana Trough (M) and Lau Basin (L) basalts. [illegible] -25‰. The unique symbol (RB) is from Rochambeau Bank.

lowing concentrations of K (0.22 wt.%) and Ba [17]. With the exception of MARA 34-17 (which is thought to represent a high degree of partial melting [17]), the increase in water content and δD are coupled with increased LIL concentrations which suggests that the source of this "heavy" δD component is also enriched in alkalis.

It appears that high water concentrations in the Mariana Trough lavas represent "intrinsic water" and are not the result of shallow-level processes such as high-temperature seawater interaction or stoping of hydrothermally altered blocks into the magma. δD values of −32‰ are significantly higher than values which are typically quoted for the water in hydrothermally altered blocks (δD = −50 to −60‰) [19]. There is no evidence in the chemistry of the lavas to suggest direct seawater interaction. The $\delta^{18}O$ of unaltered glass from the Mariana Trough is equivalent to normal MORB ($\delta^{18}O$ = +5.8 to +6.2‰) [8]. Chromium-spinel phases contained within olivine phenocrysts have $Fe^{3+}/Fe^{2+}$ ratios significantly higher than normal MORB chromites [20]. The increased $Fe^{3+}/Fe^{2+}$ ratios are indicative of an oxygen fugacity which is approximately one order of magnitude higher than QFM. This higher oxygen fugacity is thought to be due to the higher concentrations of $H_2O$ [20].

Whether these heavy δD values and high water concentrations represent primary mantle values or are the result of recycling of water from the descending slab is open to question. The isotopic composition of water from the Mariana Trough is distinct from the other oceanic mantle reservoirs, including normal MORB (−77 to −84‰) [18] and enriched MORB (the Reykjanes Ridge is −50‰ and the Mohns Ridge is −44‰) [21]. Therefore the Mariana Trough source would have to exist as a unique source for mantle water, distinct from the other MORB sources. A more likely source for the water would appear to be the hydrated oceanic crust of the descending slab. Garcia et al. [11] measured high water contents in Mariana Trough lavas (0.84–1.50 wt.%) and suggested that the source of the water must be the subducting slab and not the mantle wedge. However, the δD value of −32‰ is much more positive than the values thought to represent altered oceanic crust (−50 to −70‰) [19]. This presumed value for altered oceanic crust comes from the work of Magaritz and Taylor [22] on Franciscan schist rocks (δD = −30 to −40‰) and Wenner and Taylor [23] on oceanic serpentinites (−50 to −60‰). These studies are not a direct measure of the isotopic composition of water in the descending slab, as δD values in Franciscan schist rocks may be altered by meteoric water and oceanic serpentinites may not be representative of the entire oceanic crust.

If the source of the water in Mariana Trough basalts is the descending slab, then the slab has a much heavier δD value than proposed by Taylor [19] or the process by which water migrates from the slab fractionates the hydrogen isotopes. One possible fractionation mechanism would be segregation of an $H_2O$-rich fluid from residual hydrous phases in the slab. Experimental studies by Suzuoki and Epstein [24] showed that fractionation of up to 20‰ could occur between water and $OH^-$ in hydrous phases at mantle temperatures, with the fluid water enriched in deuterium relative to the hydrous phase. It has been postulated previously that the chemical composition of a fluid phase would differ radically from a silicate melt, being principally enriched in alkalis but not in some of the other magmaphile elements such as Ti, Ta and Nb [25]. In this way, water liberated from the descending slab into the mantle wedge would enrich the mantle in both water and alkalis. The composition of Mariana Trough basalts reflects these higher concentrations of water and alkalis, relative to MORB, but not higher values for Ti and Nb [17]. Thus, it appears that the concentration and isotopic composition of the water is consistent with an interpretation that water from the descending slab alters the composition of normal MORB mantle and produces Mariana Trough basalts.

## 3.2. Helium isotope results

Fig. 3 is a plot of the helium isotope ratios vs. the water content. Although all Mariana Trough basalts appear to be dominated by a high $H_2O$

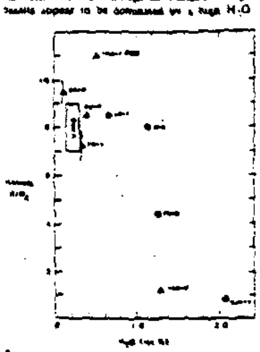

Fig. 3. Helium isotope ratios (as $R/R_A$) plotted vs. water content for Mariana Trough (M) and Lau Basin (L) basalts. The unique symbol (RB) is from Rochambeau Bank.

descending slab, the helium isotope data [illegible] MORB signature for MARA (8.4, 8.2 [illegible]) RAMA 25-2 of between 7.6 and 7.8 $R_A$ [illegible] (mean Pacific MORB value for [illegible] data is 8 ± 1 $R_A$). As shown in the [illegible] decrease in $^3He/^4He$ from 8.4 to 7.3 $R_A$ [illegible] samples is coupled with increasing $K_2O$ [illegible] reflect an increase in an alkali, water-[illegible] $^3He/^4He$ component from the slab. The [illegible] component dominates the [illegible] only an 8% effect on the $^3He/^4He$ ratio [illegible] the fact that the $He/H_2O$ ratio in the [illegible] MORB components are quite different [illegible] and water concentrations in normal MORB [illegible] typically $3 \times 10^{-5}$ cm³/g, between [illegible] water [18,21,26,27] for a $He/H_2O$ [illegible] $\sim 2 \times 10^{-3}$. Hydrated oceanic crust [illegible] ≤ 1 wt.% $H_2O$ [19] while production of [illegible] and Th decay equals $\sim 2 \times 10^{-4}$ cm³ [illegible] m.y. for 100 ppb U. The "slab" $He/H_2O$ [illegible] $10^{-5}$ is nearly 20 times lower than typical [illegible] value and therefore a "slab" component [illegible] produce only small changes in the $^3He/^4He$ [illegible] of normal MORB mantle, while causing [illegible] D/H ratio. Fig. 4 illustrates the effect of [illegible] MORB source of δD = −80 and $R/R_A$ [illegible] a "slab" component with δD = −32 and [illegible]

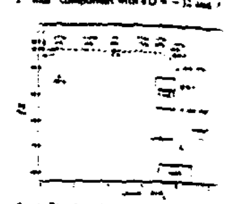

Fig. 4. Deuterium data values vs. helium isotope $R/R_A$ values for the Mariana Trough (M) and [illegible] (L). Fields for MORB, the Mariana [illegible] and the [illegible] Ridge are from [illegible] [14 and 28]. The [illegible] (RB) is from Rochambeau Bank. [illegible] mixing of MORB helium and water [illegible] "MORB-slab" mixture.



0.2. To produce a reasonable fit to the data, a $He/H_2O$ ratio in MORB vs. "slab" must be ~100.

Of the basalts at 18°N, only MARA 18-8 with a $^3He/^4He$ ratio of 4.4 $R_A$ has a value much lower than normal MORB. The high $H_2O$ content and K concentration indicate a significant "slab" component, but the initial helium concentration in the mantle from which this sample was derived must have been lower such a larger change in the $^3He/^4He$ ratio is observed. For the basalt at 16°N, MARA 34-17, the MORB helium signature has been completely lost; the $^3He/^4He$ ratio of 0.6 $R_A$ indicates that the mantle source for this basalt had been almost completely degassed of its primordial helium signature before melting occurred. Correction for possible post-eruptive production of $^4He$ by uranium decay, given a U concentration of 150 ppb, a Th/U of 3 [5, Newman, personal communication] and a maximum age of 1.0 m.y., equals 28% of the total $^4He$ and yields a corrected ratio of 1.1 $R_A$. In Fig. 4, the percentage of the MORB helium component drops rapidly to 30% for MARA 18-8 and to < 10% for MARA 34-17. Based on the helium concentration estimates for normal MORB ($5 \times 10^{-5}$ cm³/g), the slab component would require unrealistically high concentrations of helium ($\sim 5 \times 10^{-5}$ cm³/g) to reduce the measured $^3He/^4He$ to 0.6 $R_A$ in MARA 34-17. Thus, the initial helium concentration in the mantle which produced MARA 34-17 and 18-8 must have been lower. Fig. 3 also shows the correlation of decreasing helium isotope ratios with increasing water contents. Reduction in $^3He/^4He$ ratios, coupled with the increases in alkalis and water, appears to result from degassing of a component from the downgoing slab, but for MARA 18-8 and 34-17 the mantle source has been previously degassed to produce a greater change in the $^3He/^4He$ ratio.

## 4. The Lau Basin basalts

The Lau Basin (Fig. 1) is an active extensional basin between the Tonga Ridge (the active arc) and the Lau Ridge (the remnant arc) [3,5,6]. The onset of back-arc spreading began approximately 3 m.y. ago [28]. The Lau Basin is relatively shallow, 2–2.5 km, with no well-characterized spreading axis; rather it appears to have numerous sources of volcanism [4]. Magnetic and topographic data do not provide a unique model for the evolution of spreading in the Lau Basin [3,29,30].

Four of the five samples analyzed in this study are from the Peggy Ridge, a prominent SE-NW trending feature, which represents either a zone of active extension [29] or a "leaky" transform fault [3,30]. The fifth sample, TWO 106-1, is from Rochambeau Bank, a seamount in the northernmost part of the basin near the intersection of the Lau Basin and the westward extension of the Tonga Trench. This region is characterized by high heat flow, indicative of recent volcanic activity [3].

Samples were selected on the basis of whole rock chemistry and the abundance of fresh glass. They represent a diverse rock suite, in contrast to the narrow range of chemistry observed in Mariana Trough lavas. Three of the five samples, TWO-95, 96 and 79 are olivine normative basalts with very low alkali contents (0.02–0.15 wt.% $K_2O$). TWO 95-P shows extreme light rare earth element (LREE) depletion, and due to its very low $K_2O$ content (0.02 wt.%) and high MgO (11.0 wt.%) has been termed a basaltic komatiite [6,17]. TWO 103-9 represents the only quartz normative tholeiite measured. This dredge series is characterized by strong LREE enrichment and very high alkali contents ($K_2O$ = 1.01 wt.%) with the whole rock chemistry resembling the hydrous basalts of the Mariana Trough [17]. TWO 106-1, from Rochambeau Bank, is nepheline normative with LREE enrichment and $K_2O$ contents of 0.32 wt.%. It appears that TWO 106-1 is distinct from the other four Lau Basin basalts in terms of location, tectonic setting and chemistry. All $^{87}Sr/^{86}Sr$ ratios on whole rock samples for the Lau Basin of 0.7032–0.7036 are significantly higher than normal MORB and Mariana Trough values [5,6,17].

### 4.1. Water and deuterium: the Lau Basin

The concentration and isotopic composition of water and helium for the Lau Basin basalts are tabulated in Table 1. Fig. 2 shows that the water content (0.12–1.30 wt.%) and isotopic composition (δD = −70 to −41‰) for the Lau Basin samples display a wide range of values from MORB levels (0.2 wt.%; δD = −77‰) to Mariana Trough values (1.0–2.0 wt.%; δD = −32‰). Three samples, TWO 95-P, 96-P and 79-1, with 0.12–0.35 wt.% $H_2O$ indicate that high water contents in the source are not essential for the production of back-arc lavas. In fact, the value of 0.12 wt.% for TWO 95-P is the lowest water concentration measured at SIO for a submarine basalt. The chemical data suggest that this basalt was produced by a large degree of partial melting, in a relatively anhydrous environment [6]. The isotopic composition of the water in samples TWO-95, 96 and 79 ranges from −63 to −70‰, slightly higher than normal MORB (−77‰) [18], but quite distinct from the value of −32‰ measured for the Mariana Trough. As noted earlier, these three basalts display low alkali contents ($K_2O$ = 0.02–0.15 wt.%). Thus the alkali and water-rich component, present in all Mariana Trough samples, is absent or a very minor component of TWO 95-P, 96-P and 79-1. It is unnecessary to invoke a component from the altered oceanic crust of the descending slab to produce these lavas.

The water content (1.30 wt.%) and isotopic composition (δD = −41‰) of TWO 103-9 are similar to the Mariana Trough lavas. The elevated $K_2O$ content (1.01 wt.%) also reflects the presence of an alkali and water-rich component which is presumed to come from the descending slab. Based on the chemistry [6], TWO 103-9 is a fractionated basalt. This may account for some of the $H_2O$ and $K_2O$ enrichments, but crystal fractionation will not change the D/H ratio. Thus it appears that the Lau Basin erupts both anhydrous (TWO 95-P, 96-P, 79-1) and hydrous basalts (TWO 103-9). All four of these samples are from the Peggy Ridge and if this ridge does represent the most recent extensional feature in the basin, then both anhydrous and anhydrous basalts erupt simultaneously in the Lau Basin. In this case, the low $^3He/^4He$ ratio of 1.33 $R_A$ in TWO 103-9, similar to MARA 34-17, would reflect a mantle which has been previously degassed of its primordial $^3He$. Alternatively, if the Peggy Ridge is not a "zero-age" feature, then the location of TWO 103-9 at the western margin of the Lau Basin would suggest that this basalt may be up to 3 m.y. old. The low $^3He/^4He$ ratio would relate to in situ [illegible] of $^4He$ in the basalt, since 3 m.y. is sufficient to generate all of the $^4He$ from U and Th [illegible] hydrous basalts do represent the oldest [illegible] the basin, then there has been an age [illegible] from hydrous to relatively anhydrous [illegible]

### 4.2. Helium isotope results: the Lau Basin

Two of the Lau Basin samples (TWO [illegible] Peggy Ridge and TWO 106-1 from Rochambeau Bank) were the same glasses analyzed by Lupton and Craig [12]. The Rochambeau sample was re-analyzed because of [illegible] $^3He/^4He$ ratio reported previously [illegible] greater than MORB. The results reported [illegible] $R_A$ and 11.0 $R_A$) are 10% lower than [illegible] and Craig results (9.3 $R_A$ and 12.0 $R_A$), also are the present data for MORB (8 [illegible] $R_A$). This is due to the fact that the air used in the initial study for comparison [illegible] while almost no care was given [illegible] sampled [13]. The need to use air standard [illegible] effect of lowering the measured $^3He/^4He$ [illegible] 10% and therefore the $^3He/^4He$ ratios [illegible] air, in samples without neon was overestimated [illegible] 10%. With the exception of TWO [illegible] $^3He/^4He$ values measured for the Lau Basin [illegible] from 7.2 to 11.0 $R_A$. Two samples, TWO [illegible] TWO 106-1, have ratios significantly higher [illegible] average MORB (8 ± 1 $R_A$), again [illegible] radiogenic $^4He$ from the descending slab [illegible] significantly influence the measured [illegible] ratio. The ratio of 11 $R_A$ for TWO 106-1 [illegible] that the Rochambeau Bank in the northern [illegible] Basin produces basalts with $^3He/^4He$ [illegible] range of enriched mantle sources. The enrichment of Rochambeau Bank [illegible] MORB (11 $R_A$ vs. 8 $R_A$) is very significant [illegible] probably related to the proximity of the [illegible] to the Samoan hotspot, a "high" $^3He$ [illegible] characterized by helium with $R/R_A$ [illegible] Further study of this relationship is [illegible] underway with work in both Samoa and [illegible] Basin.

The enriched character of TWO 106-1 [illegible] tends to its D/H ratio. Fig. 4 shows [illegible] 106-1 is distinct from the other Lau Basin [illegible] in both D/H and $^3He/^4He$ ratios (shown for comparison in this plot are the fields for MORB, the Mohns Ridge and the Reykjanes Ridge). As is seen in Fig. 4, the sample from Rochambeau Bank most clearly resembles the enriched basalts from the Reykjanes Ridge in $^3He/^4He$ and D/H ratios. The possibility exists that the δD of −47‰ represents a mixture of −70‰ material with a deuterium-rich source similar to the one seen in the Mariana Trough. However, one must still invoke an enriched source region to explain the elevated $^3He/^4He$ ratios. The La/Sm ratios, relative to chondrites, of ~1.2 and the $^{87}Sr/^{86}Sr$ ratio of 0.7032 also reflect an enriched source region in the range of many oceanic island or enriched MORB provinces [6,17]. The elevated $^{87}Sr/^{86}Sr$ ratios cannot be related to a high-$^{87}Sr$ component from the subducting slab ($^{87}Sr/^{86}Sr$ of 0.704 to 0.709) since the low potassium and water contents for three of the samples limits the contribution of any possible "slab" component. Thus, the correlation of $^3He/^4He$ ratios higher than MORB with high $^{87}Sr/^{86}Sr$ ratios and high δD values indicates the presence of an enriched source region beneath the Lau Basin.

The Lau Basin presents a complicated picture of the petrogenesis of back-arc basin basalts. Clearly, TWD-103-9 resembles the Mariana Trough lavas in water content and isotopic composition and indicates that there is a significant contribution from the downgoing slab. The four other Lau Basin basalts show minimal "slab" influence and appear to result from a mixture of an enriched source region with a MORB source rather than as a mixture of slab-derived material and MORB.

## 5. Comparison Mariana Trough vs. Lau Basin

The volatile signatures of the Lau Basin and Mariana Trough are quite distinct for both helium and water. The importance of a component from the descending slab in the generation of each suite of basalts varies. Evidence for a significant "slab" contribution in water for the Mariana Trough basalts appears quite convincing. The high water contents and δD values coupled with reduced $^3He/^4He$ ratios and increased K contents indicate that the chemistry of Mariana Trough basalts has been altered by a fluid or melt degassing from the slab. However, the geophysical evidence makes it difficult to introduce a fluid phase from the slab directly into the mantle beneath the Mariana Trough. The path of the descending slab, as defined by earthquakes, becomes nearly vertical at 200 km depth and is at a depth of greater than 500 km beneath the axis of the Mariana Trough [32]. The fluid or melt would have to be advected laterally to the west to produce melting in the mantle beneath the Mariana Trough. Beneath the Lau Basin, the descending slab is at a depth of approximately 250 km, but the evidence for slab influence in the water or helium is minimal for all samples except TWD 103-9. One cannot rule out a slab contribution for the other samples, such as TWD 95-P, but with 0.12 wt.% $H_2O$ and 0.02 wt.% $K_2O$ the effect must be very small. Thus, the presence of the descending slab at a reasonable depth beneath the back-arc does not ensure production of basalts with enriched water and alkali contents.

The answer to this apparent dichotomy may be found in the history of each arc. The Marianas region has had three generations of arc volcanism dating back ~42 m.y. [11,33]. Forty million years of subduction and slab degassing may have metasomatized the mantle beneath the Marianas arc-trough complex, enriching it in water and LIL elements. The ultimate source of the water and alkalis is still the altered crust of the descending slab, but the metasomatism has occurred over the 40 m.y. of subduction. Convection in the mantle wedge, as proposed by Sleep and Toksoz [34], causes upwelling of this metasomatized mantle, partial melting and production of the Mariana Trough lavas. The high water contents facilitate melting by reducing the solidus temperature of the mantle peridotite.

In contrast, the Lau Basin–Tonga Arc is a relatively young arc-trough system. Arc volcanism in the region began approximately 15 m.y. ago with the formation of the Lau Basin beginning at 3 m.y. Thus, the mantle beneath the Lau Basin has not had time to be extensively metasomatized and thus the chemistry more closely reflects its original mantle source character. The low $H_2O$, δD and $K_2O$ in three of the five samples indicates little contribution of an alkali- and water-rich component either directly from the descending slab or from a metasomatized mantle source. For these three samples, water does not play an important role in magma genesis. However, the Lau Basin also erupts basalts, such as TWD 103-9, which has high water and alkali values, similar to the Mariana Trough basalts. If both hydrous and anhydrous basalts erupt simultaneously in the Lau Basin, then it indicates that the mantle wedge beneath the Lau Basin maintains small scale heterogeneities in alkali and water contents. Alternatively, hydrous basalts, such as TWD 103-9, may represent the initial stage of magma production in the back-arc. TWD 103-9 does occur on the western margin of the basin, presumably the oldest part of the Lau Basin, as do other basalts with similar enrichments in alkalis and silica [17]. After an initial period of eruption of hydrous basalts, the mantle beneath the Lau Basin becomes depleted in alkalis and water and the magmas which are produced, such as TWD 79-1, 86-P, 95-P, become more anhydrous and less alkali-rich.

The differences between the Lau Basin and Mariana Trough also extend to the mantle source regions. For the Mariana Trough, the helium and strontium isotopes are completely consistent with a water and alkali-rich fluid or melt mixing with a normal MORB mantle. For four of the Mariana Trough samples, the helium isotope ratios equal normal MORB levels. The $^{87}Sr/^{86}Sr$ ratios of 0.7029 [16], at the upper limit of normal MORB ratios, may be indicative of a minor addition of slab-derived material (0.704–0.709). In the case of the Lau Basin, enriched $^{87}Sr/^{86}Sr$ ratios of 0.7032–0.7038 [6] cannot be accounted for by mixing of a slab component with normal MORB mantle, since the low water and alkalis preclude a significant slab contribution. An enriched mantle source region, with higher $^{87}Sr/^{86}Sr$ ratios, typical of oceanic islands must exist beneath the Lau Basin. The $^3He/^4He$ ratios in Lau Basin basalts (up to 11 $R_A$) which are higher than MORB (~8 $R_A$) also support the hypothesis of an enriched mantle source region.



## 6. Conclusions

This study shows that there is no unique model or source for back-arc magma production. The isotopic and chemical signatures of the volatiles (and presumably the magmas) depend on the original source composition of the mantle wedge, the history of the arc back-arc region, and the contribution of the descending slab. For Mariana Trough basalts, the elevated $H_2O$ contents (up to 2.1 wt.%) and the distinct δD values (to −32‰), coupled with enrichments in alkalis, indicate the presence of a component from the descending slab. However, while the water content and isotopic signature are dominated by the component from the slab, the helium isotope ratios for most of the samples reflect typical MORB values (8.4–7.5 $R_A$). Therefore, the Mariana Trough basalts very probably represent a mixture of a MORB mantle with an alkali and water-rich component from the descending slab. Three of five Lau Basin samples have low $H_2O$ contents with δD values resembling MORB (−65 to −70‰). For these samples, there is little or no evidence for the alkali and water-rich component seen in the Mariana Trough and indicates that high water contents are not essential for production of back-arc magmas. However, the Lau Basin also produces the hydrous basalts (1.3 wt.% $H_2O$) which resemble Mariana Trough lavas. The $^3He/^4He$ ratios in the Lau Basin (7.2–11.0 $R_A$) resemble an enriched mantle source region rather than the MORB mantle seen in the Mariana Trough.

## Acknowledgements

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PLANNING CONFERENCE
OCEAN DRILLING PROJECT STUDIES IN ACTIVE WESTERN PACIFIC TRENCH-ARC-BACKARC SYSTEMS

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Pavlis and Bruhn (1983) suggested that the uplift along broad forearc ridges may be due to the ductile flow of rocks in the subduction complex at depths greater than 15-20 km and that this flow may lead to the exposure of high P/T metamorphic rocks. The active western Pacific trench systems have been active for various lengths of time so that drilling on sites along the forearc ridges may be used to test this hypothesis.

Figure 1 plots the geotherms used by Pavlis and Bruhn (1983) on the tentative P/T fields for the metamorphic facies proposed by Turner (1968). The rocks of the subduction complex would be expected to grade from unmetamorphosed rocks through zeolite and prehnite-pumpellyite facies to glaucophane-lawsonite or greenschist metamorphism, depending on the heat flow and the depth of burial. Also plotted on Turner's diagram is the position of the brittle-ductile transition, estimated by Pavlis and Bruhn (1983) to be at 15-20 km depth. This is seen to straddle the prehnite-pumpellyite field.

Vertical uplift rates for areas in the Pacific have recently been summarized by Yonekura (1983). The data indicates about an order of magnitude difference between the maximum uplift rates in continental arcs and those of island arcs. Yonekura (1983) noted that the two types could roughly be divided by the average uplift rate of 0.5 mm/a, but that the average maximum uplift rate in continental arcs was 1.5-2.5 mm/a. Pavlis and Bruhn (1983) suggest a maximum uplift along broad forearc ridges of 1 mm/a down to 0.2 mm/a observed along the Barbados Ridge of the Lesser Antilles. Uplift times assuming constant uplift rates of 2mm/a and 0.2 mm/a have been noted on figure 1 to bracket the observed rates. At the highest rates, only about 10 Ma would be required to exhume glaucophane-bearing rocks.

If deep-seated ductile flow is a mechanism for bringing high P/T metamorphic rocks to the surface, then the rocks near the surface in old broad forearc ridges should be of higher metamorphic grade than rocks exposed in younger forearc ridges. The resolution of this test will increase with increasing uplift rate (i.e., the same change in metamorphic grade which takes 5 Ma at 2 mm/a will take 50 Ma at 0.2 mm/a), so drilling the broad forearc ridges associated with continental arcs with their higher uplift rates would best test the mechanism. The youngest forearc ridges should have exposed unmetamorphic or zeolite facies rocks which show only signs of brittle deformation while the oldest ridges should be composed of blueschist or greenschist rocks that show evidence of synmetamorphic ductile deformation. Knowing the average uplift rate and age of the ridge, the metamorphic grade of the rocks near the surface can be predicted with this model and then tested by drilling or by study of the islands along the forearc ridge.

Drilling along the broad forearc ridges of island arcs could be done to contrast with the information obtained from the forearc ridges of continental arcs. With a very old island arc, one may be able to establish if deep-seated ductile flow is a possible mechanism for uplift along these oceanic boundaries. In addition, one might consider hydrofracture experiments or borehole deformation studies in both settings to supplement earthquake focal mechanism solutions in order to compare of the stress transferred to the subduction complex in the two types of trench-arc systems.

Uyeda and Kanamori (1979) divided trench-arc systems into continental arcs and island arcs, based on the formation of back-arc basins in the latter systems. They proposed that this represents two fundamentally different modes of subduction characterized by a stronger coupling of the two plates in continental arcs. Pearce (1985?) discriminates continental arc basalts from oceanic arc basalts on the basis of Zr/Y vs. Zr. The stronger coupling of the plates in the continental arcs would effectively squeegee off the sediments from the subducting plate. The resulting chemistry of the eruptive volcanics will depend on the interaction of the converging plates (e.g., angle and rate of subduction, the amount of sediment subducted with the downgoing plate vs. the sediment accreted to the overriding plate) (Yonekura, 1983).

Sediments incorporated in the subducting complex can, in fact, dewater at shallower depths than the subducting oceanic lithoshpere. The waters then percolate up into the overlying lithosphere, enriching the lithosphere in hydrophilic elements. Island arc volcanics and pelagic sediments show distinct depletions in Nb and Ta and enrichments in LIL elements (K, Rb, Ba) and Sr compared to MORBs (figures 2 and 3 from Pearce, 1982; 1983). Specifically, LIL elements are enriched in all island arcs, while the Ti-group elemts (Nb, Ta, Ti) are enriched in continental margin arc settings but not in oceanic arc settings, suggesting that the comparatively thick continental lithosphere somehow is a factor.

Li-Be-B, considered individually and as a group, can potentially provide a powerful insight into the role of sediments in island arc magmas. Li-Be-B are enriched in pelagic sediments and clays relative to fresh MORBs and unaltered oceanic crustal material; also, Li and B are good indicators of hydrothermal circulation through erupted lavas as they have cooled (table 1, Leeman and Rideout, compilation from published data). Subduction of and incorporation of these materials in island arc magmas will provide a diagnostic enrichment of such lavas relative to non-enriched sources. Using 10[Be], Brown et al. (1983) concluded that some ocean floor sediment is being subducted and incorporated into island arc volcanics erupted on oceanic and continental crust (figure 4). Li-Be-B are also incompatible elements, and thus should be enhanced in the magmas through further process-related enrichment, by partial melting or fractional crystallization, for example.

Suggested regions for such studies to assess the magnitude of sediment involvment and subsequent signature in eruptive volcanics could possible involve drilling a transect across the Sunda Arc with its two trenches vs. a section across the Banda Arc where one trench is present (figure 5, Varne, 1985) and comparing the results, keeping in mind that the Recent sediments sampled on the present day location may not be truly representative of what was previously subducted and incorporated in the past to generate the observed lavas.

Given that a chemical difference exists between continental arcs and island (oceanic) arcs, a possible site for assessing such differences would be a locale where the back-arc basin pinches out and dies out (figure 6), showing a continous transition from oceanic to continental arc. Changes in the stress regime within the subduction complex would be expected and should be tested with hydrofracture or borehole deformation studies. If the continental arc is acting as a better squeegee than the oceanic arc, one might expect a larger volume in the accretionary complex of the continental arc (less material being subducted). Porewater and (subsequent) eruptive volcanic chemistries would vary relecting mass balance in the reactive components present (e.g., partioning of elements among phases present, metasomatic and hydrothermal fluids).

North Marianas vs. South Marianas would be a good locale to study chemical variations as the result of changes in the coupling between the plates at the convergent boundary. At such a location, rates of subduction, polarity and angle of subduction, sediment source and volume entering the trench are roughly equivalent between the two segments of the trench. The only variable would be the coupling of the two plates and its relationship to the volume of sediments subducted. Any difference in the chemistry of the eruptive volcanics behind the two segments would have to be related to differences in the amount sediment allowed to pass between the two plates. Previously suggested chemical mass balance studies within the accretionary complex would aid in understanding the origin of the eruptive magmas as well as helping to understand the mechanics of the complex itself.

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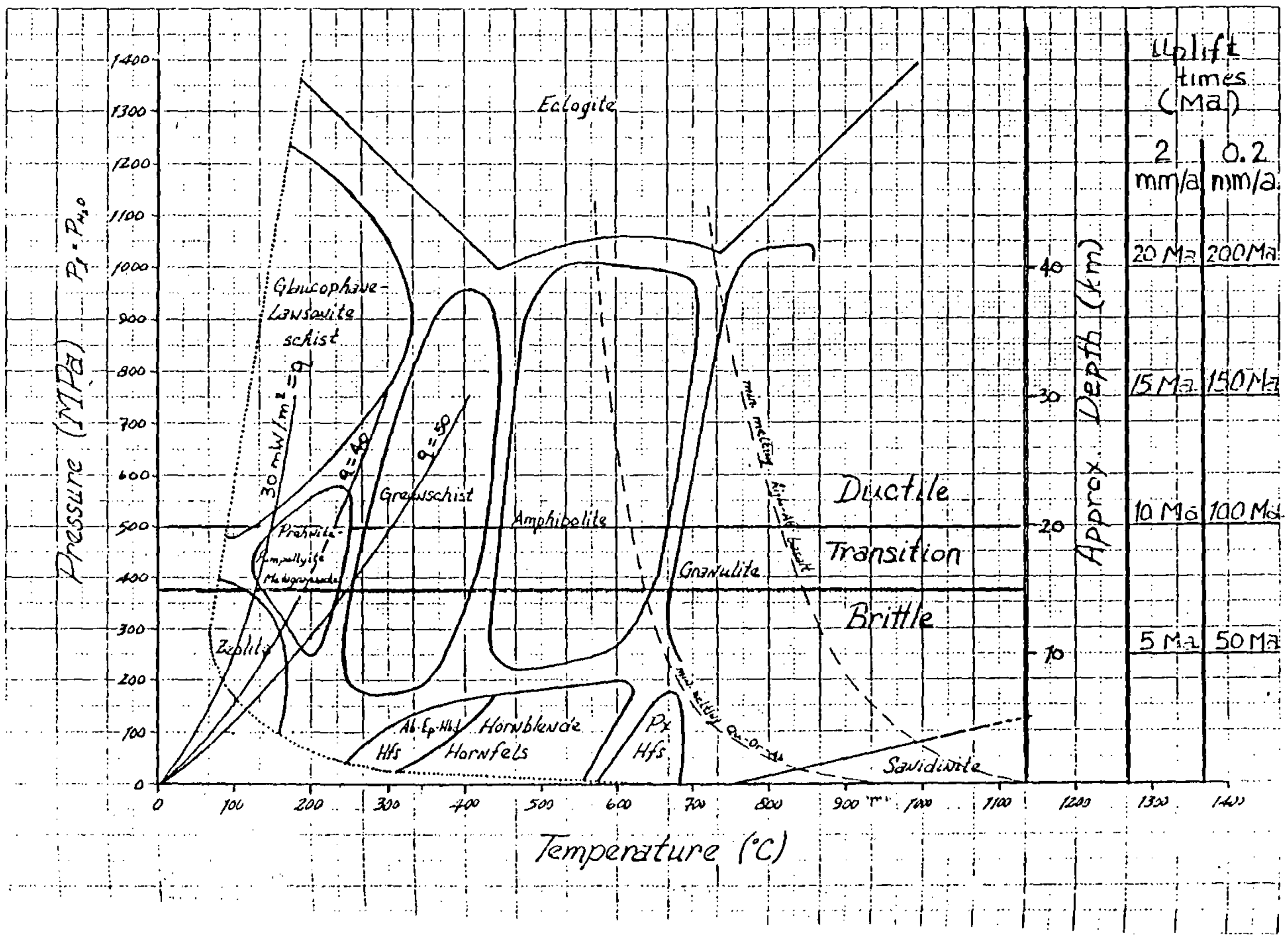


Uplift times (Ma)
2 mm/a
0.2 mm/a
20 Ma 200 Ma
15 Ma 150 Ma
10 Ma 100 Ma
5 Ma 50 Ma
Approx. Depth (km)
40
30
20
10
Pressure (MPa) $P_f = P_{H_2O}$
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Temperature (°C)
Eclogite
Glaucophane-Lawsonite schist
30 mW/m² = q
q=40
q=50
Greenschist
Amphibolite
Granulite
Prehnite-Pumpellyite Metagreywacke
Zeolite
Ab-Ep-Hbl Hfs
Hornblende Hornfels
Px Hfs
Sanidinite
min. melting high-Al basalt
min. melting Qz-Or-Ab
Ductile
Transition
Brittle

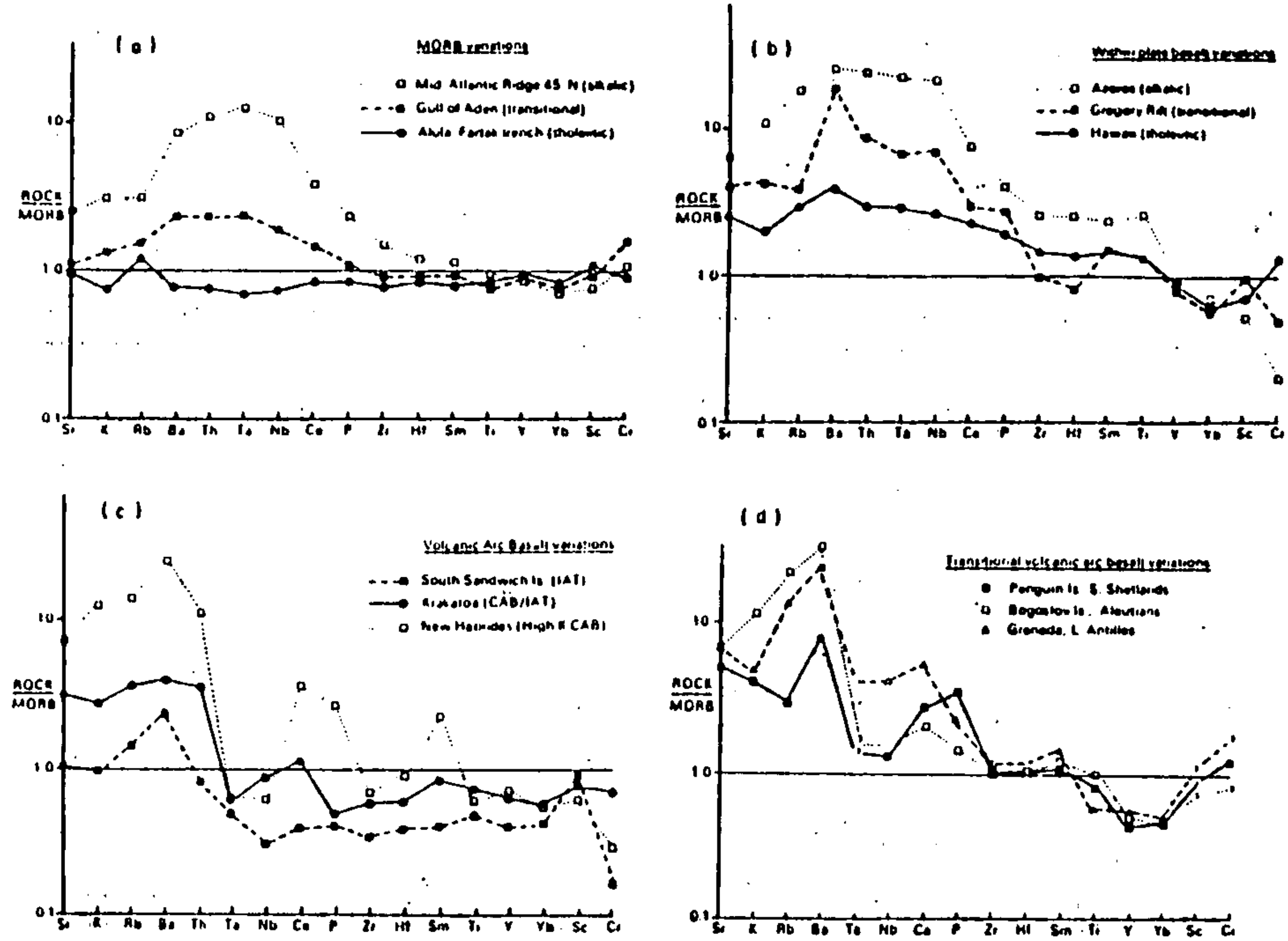



Fig. 1 Mid-ocean ridge basalt-normalized trace element patterns for some typical basalts unrelated ((a) and (b)) and related ((c) and (d)) to subduction. Normalizing values: Sr = 120 p.p.m.; $K_2O$ = 0.15 per cent; Rb = 2.0 p.p.m.; Ba = 20 p.p.m.; Th = 0.2 p.p.m.; Ta = 0.18 p.p.m.; Nb = 3.5 p.p.m.; Ce = 10.0 p.p.m.; $P_2O_5$ = 0.12 per cent; Zr = 90 p.p.m.; Hf = 2.4 p.p.m.; Sm = 3.3 p.p.m.; $TiO_2$ = 1.5 per cent; Y = 30 p.p.m.; Yb = 3.4 p.p.m.; Sc = 40 p.p.m.; Cr = 250 p.p.m. Analyses by the author except Mid-Atlantic Ridge 45°N (Wood *et al.*, 1979b), New Hebrides (Gorton, 1977), Penguin Island (Weaver *et al.*, 1979), Bogoslov Island (Kay, 1977), and Grenada (Shimizu and Arculus, 1975)

# FIGURE 2

***from Pearce, 1982***

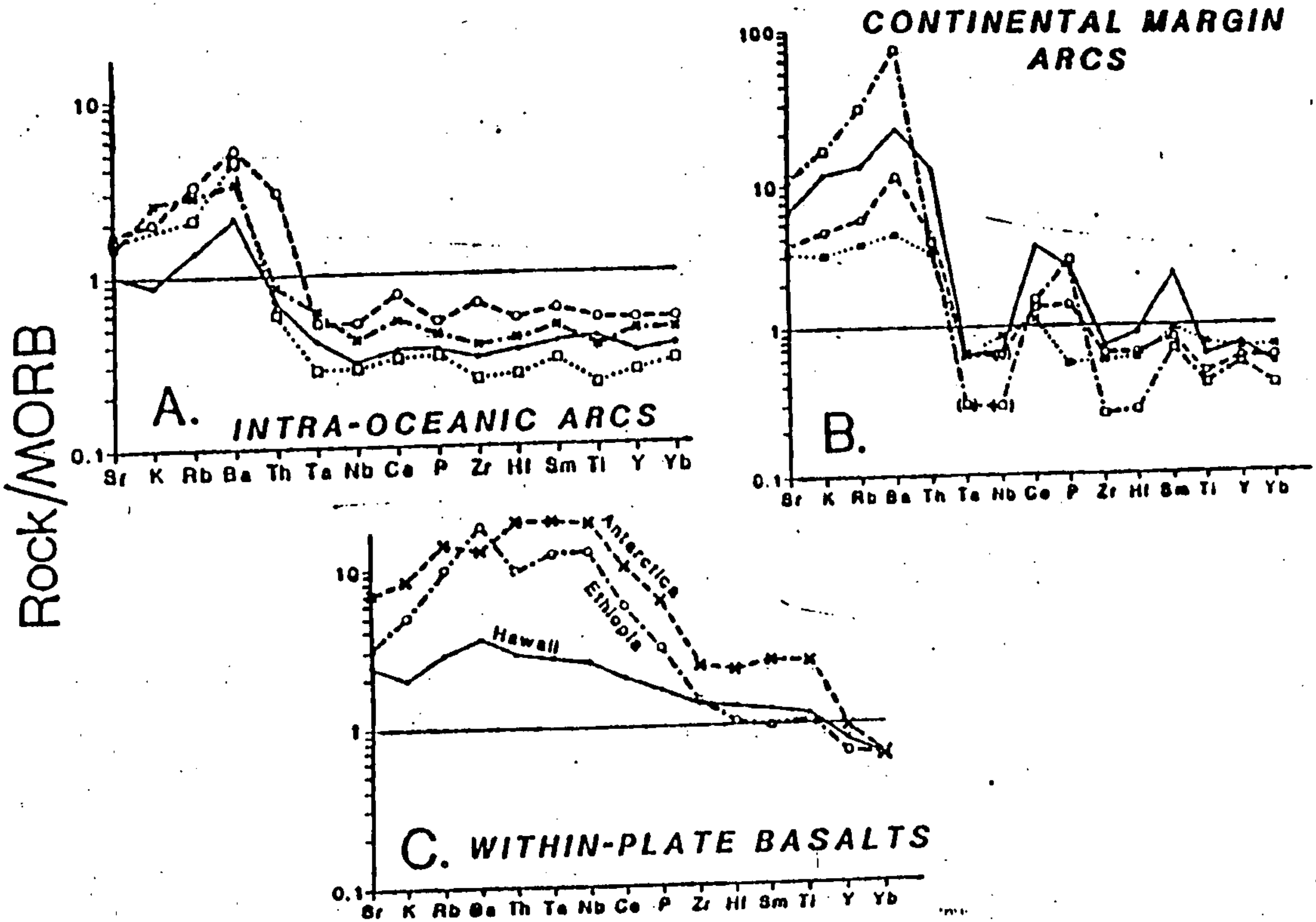

Rock/MORB
A. INTRA-OCEANIC ARCS
10
1
0.1
Sr K Rb Ba Th Ta Nb Ce P Zr Hf Sm Ti Y Yb
CONTINENTAL MARGIN ARCS
100
10
1
0.1
B.
Sr K Rb Ba Th Ta Nb Ce P Zr Hf Sm Ti Y Yb
C. WITHIN-PLATE BASALTS
Antarctica
Ethiopia
Hawaii
10
1
0.1
Sr K Rb Ba Th Ta Nb Ce P Zr Hf Sm Ti Y Yb

FIGURE 3

Estimated distribution of B, Li, and Be

| Hypothetical Reservoirs | B ppm | Li ppm | Be ppm |
|---|---|---|---|
| Fresh periodotites | 0.5[a] | 2[b] | 0.002-0,2[h] |
| Serpentinized ultramafic rocks | 24-110[d,e] | tr-19[c] | >0.2(?) |
| Fresh MORB | 2[d,f] | 9[g] | 0.1(?) |
| Altered MORB (variable with degree of alteration and/or metamorphism) | ~8[d,f] | 20[g] | >0.1(?) |
| Marine sediments | | | |
| Shales | 120[h] | 40-340[c] | 1-10[h] |
| MAG-1[i] | 130 | 78 | 3.0 |
| MORB source calculated assuming 30% p.m. and $K_d$ 0 | 0.6 | 2.7 | 0.03 |
| Oceanic crust (variable with degree of alteration) | ≥5[h] | ≥10[h] | 0.2(?) |
| Oceanic lithosphere calculated as 10% oceanic crust + 90% MORB source | 1 | 3.4 | 0.05(?) |
| Continental crust | ≥10[h,j] | 22[b] | 1-2[h]<br>1.3[k] |

Data sources: [a] Higgins and Shaw (1984); [b] Shaw (1980); [c] Shaw et al. (1977); [d] Thompson and Melson (1970); [e] Bonatti et al. (1984); [f] Humphris and Thompson (1978); [g] Stoffyn-Egli and MacKenzie (1984); [h] Handbook of Geochemistry, Wedepohl (1974); [i] Govindaraju (1974); [j] Truscott et al. (in press); [k] Shaw et al. (1967)

Values followed by (?) are our estimates used here due to insufficient published data.

# TABLE 1

*Leeman and Rideout, unpublished*

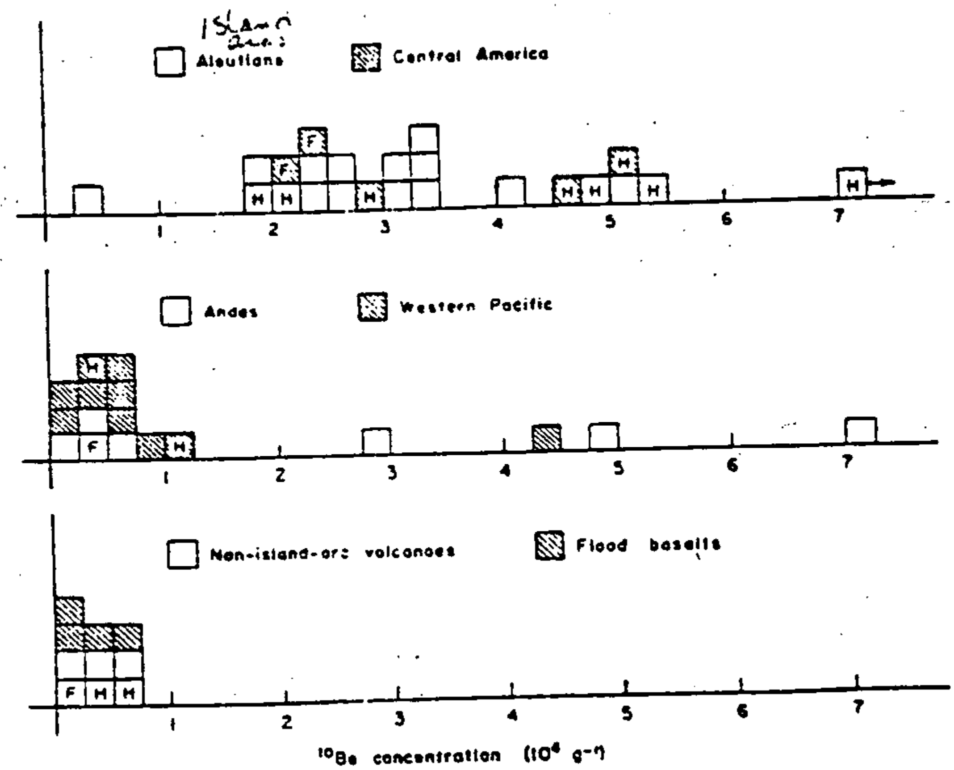



Fig. 1. Histogram of measurements of $^{10}$Be concentration in fifty samples of lava. Samples from historical flows are designated by *H* and those taken soon after eruption by *F*. Of the western Pacific samples, seven are from Japan, two from Iwo Jima, and one from Taiwan.

# FIGURE 4

***from Brown et al., 1983***

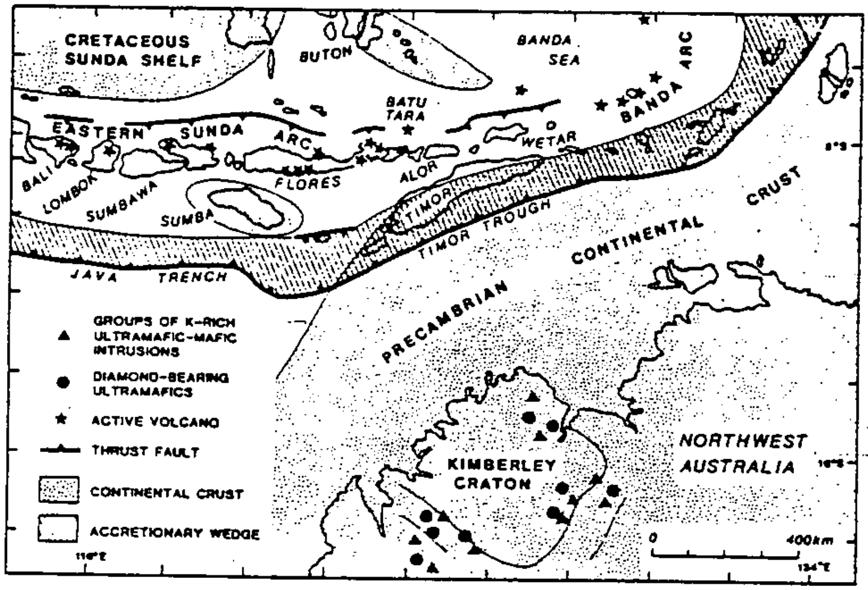
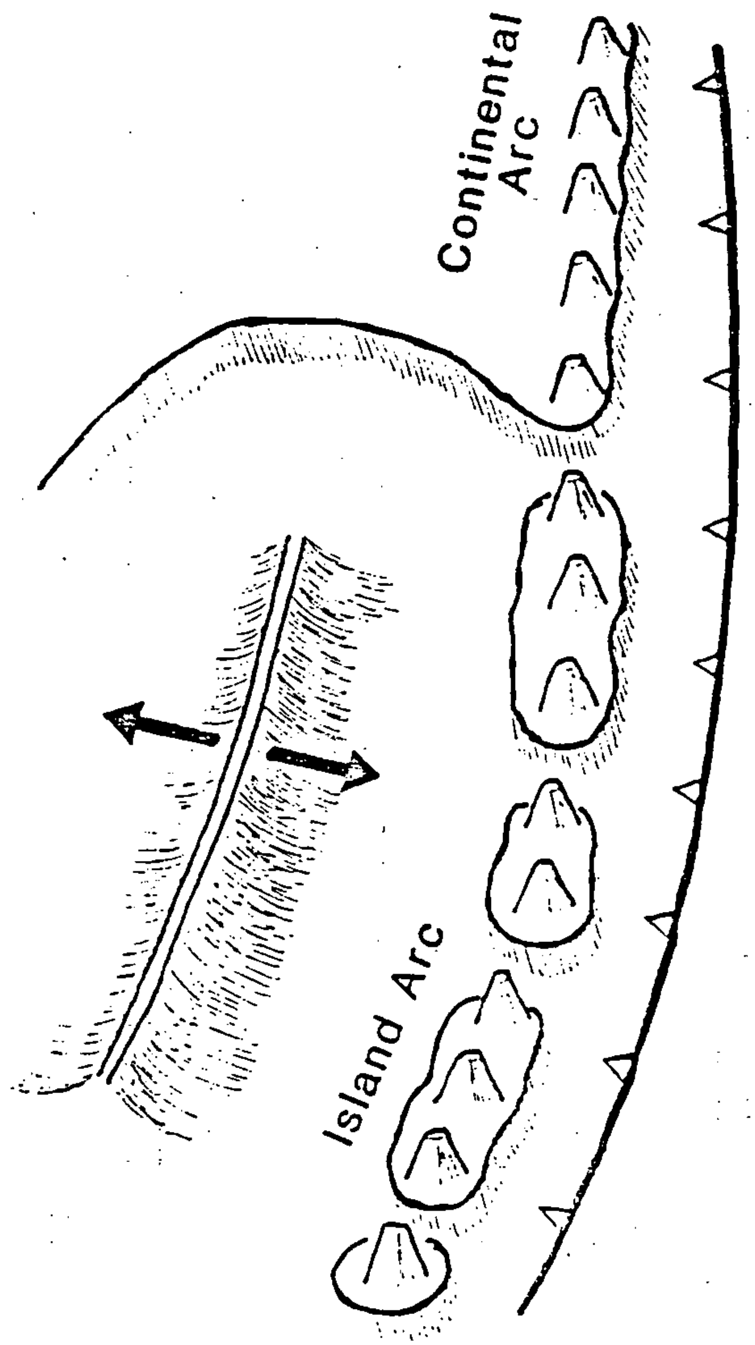



Figure 1. Sketch map showing eastern Indonesia and northwest Australia. Distribution of continental crust after Hamilton (1979) and Pigram and Panggabean (1983); location of accretionary wedge from Silver et al. (1983); back-arc thrusts from Hamilton (1979) and Silver et al. (1983); distribution of continental ultrapotassic ultramafic-mafic association of northwest Australia, including West Kimberley suite, after Atkinson et al. (1984).

# FIGURE 5

***from Varne, 1985***

# IN THE BROAD FOREARC RIDGE, ARE THERE CHANGES IN




Stress?

Mechanics of deformation

Chemistry?

Volume?

FIGURE 6

DRILLING TARGETS IN BACK-ARC BASIN CRUST: RECOMMENDATIONS FROM THE LAU BASIN

by Debra Stakes, University of South Carolina

The proposed ODP legs in the Western Pacific will provide the opportunity to characterize oceanic crust produced in non-mid-ocean ridge environments (as well as other geological problems discussed elsewhere). There are basic objectives that should be considered in the selection of all sites to be placed in back-arc environments. These basic objectives seek to clarify fundamental ambiguities in models for the construction, metamorphism and preservation of oceanic crust in both mid-oceanic and back-arc basin settings. The Lau Basin seems especially appropriate as a drilling target to address these basic objectives, as well as addressing geological problems more specific to the Lau-Tonga-Kermadec region. The objectives that are described here are based on information from the variety of back-arc basin settings that are known in any detail, with additional comparisons to ophiolite terrains (Oman and Cyprus, especially) and accreted continental terrains. The specific site objectives for the Lau Basin are to reaffirm my recommendation that this area be given high consideration for the Western Pacific programs.

General goals for ODP targets in back-arc basin regions.

The foremost "hard-rock" objective for any back-arc basin drill target is to determine how similar or different this crust is to that produced at a mid-ocean ridge spreading center. An obvious secondary requisite to question how much variability actually exists between these two "end-members". A simplistic prediction would be that for either environment: a) fast-spreading ridges would be characterized by large magma chambers represented by continuous plutonic sequences and somewhat homogenous eruptive units; b) slow-spreading ridges would be characterized by small, ephemeral magma chambers represented by discontinuous plutonic sections, perhaps at variable depths, and extrusive units that cannot be petrochemically related to each other, perhaps interlayered with sediments that were deposited during periods of volcanic quiescence. This igneous stratigraphy could be complicated by propagating rifts, cross-cutting transforms and island-arc type magma leaking into the back arc basin.

It is extremely important to have 1-3 sites to sample mature back-arc basin crust down to a depth of 1-1.5 km. The site(s) should be selected to minimize the complications of island arc type liquids and transforms. It is already known from the Bonins and the Mariana Trough that in young basins island arc and back-arc basin type liquids can erupt at the same time and place. The resulting lava stratigraphy would not only be difficult to interpret, but would add little to the existing DSDP results. In fact, the timing and fine-scale stratigrphy in these immature basins would be better detailed by the use of submersibles.

The advantage of drilling a core would be to recover the entire crustal package from a few well-chosen spots: the eruptive carapace, the dike feeder system and at least the top of the underlying plutonic section. If complicated volcanic stratigraphy exists even in mature basins, then at least some of the timing may be more explicable by examination of the lower intrusive rocks. And these samples could only be recovered by drilling. These sites would thus be long term re-entry holes that are situated to provide information on as many aspects of back-arc basin development as possible.

Guidelines gleaned from ophiolite terrains.

Sections of ancient oceanic crust exhumed as ophiolite slices may have originated in mid-ocean, back-arc or island arc settings. Criteria for distinguishing between different tectonic regimes of ophiolite origin is based upon trace-element chemistry of the shallow eruptive units and the nature of the upper plutonic sections. Most of the evidence for back-arc vs island arc vs mid-ocean ridge is deduced from the top 0.5-1.5 km of the ophiolite lithostratigrapy.

The Semail ophiolite in Oman has many of the same igneous structures described in smaller, more tectonically disrupted ophiolite assemblages, such as those in California and Oregon. Thus the charateristics Semail ophiolite can be used to assess the relative value of a deep corehole vs several shorter cores. The bulk of the ophiolite is tectonized harzburgite, the mantle rocks that still carry the deformation fabric formed at the spreading axis. The crustal section varies from 6 km to 3.5 km in total thickness, and includes layered and unlayered gabbroic rocks that presumably formed within and on the roof of, respectively, the axial magma chamber. The deeper layered gabbro is rather monotonous in mineralogy, as a result of intermixing and buffering by repeated inputs. Intrusive contacts within the layered gabbro that might result from diachronous magma chambers would be very subtle and unlikely targets for drilling. Recent mapping and drilling in the Troodos ophiolite in Cyprus, however, has only now recognized the discontinous nature of the plutonic complex.

The conductive lid on the magma chamber (BAB, MOR, or IA) is quite distinctive isotropic gabbro. This characteristically has an extremely heterogeneous texture and is cross-cut by pegmatite veins, as liquid is partially crystallized, distilled, thermally cracked, reintruded, and partially assimilated in this contact zone between the magmatic convective system and the hydrothermal system. The width of this zone is a crucial parameter for cooling models of oceanic crust. The hydrothermal vein minerals contain information on the temperature and composition of the earliest and highest temperature fluid to form. Petrofabrics contain information on the degree of interaction between the hydrous phases and later high-temperature melts to assess the extent of assimilation. The isotropic gabbro layer would lie at a depth of less than two kilometers, and perhaps less than 1.5 km in the marginal basins. This horizon should be a feasible drilling target for the new drill ship.

Above the isotropic gabbro is the hydrothermally altered sheeted dikesthat are the feeder conduits for the overlying eruptive sequences. Multiple generations of eruptive sequences should be mirrored in crosscutting dike relationships of similar chemical variability. For example, a seamount or incipient arc may be characterized by a capping volcanic sequence compositionally unlike the underlying eruptive units. Beneath the seamount a late mafic dike swarm may intrude the earlier dike complex, baking the intrusive margins to hornfels and creating a new high-temperature hydrothermal system. This is the situation observed in Oman (Stakes et al, 1985). Thus, valuable information regarding the timing of the intrusive events may be derived from drilling within the dike complex.

One of the outstanding differences between the rock types in most ophiolite sequences and that thought to comprise MOR-type crust is the prescence of large gabbro-diorite-plagiogranite (tonalite) assemblages in the former. These silicic intrusive complexes vary in dimensions, abundance and depth, although they are most commonly associated with the dike-gabbro margin. They have been interpreted by workers in Oman as late distillates of the axial magma chamber (Hopson et al), intrusions of island arc liquid that postdates the axial chamber (Alabaster et al, 1983), or flank seamounts that may begin contemporaneously with the magma chamber but have continued intrusions along fault-controlled conduits (Stakes and Taylor 1984 and in prep). In Oman, the largest late intrusive complex is actually intruded into the base of the pillow lavas, at a depth of less than one km. Late felsite dikes from the top of this intrusive complex could erupt pumice and dacite if they reached the surface. It would be extremely valuable to drill into one of these late high level magma chambers to ascertain whether they are an arc-related feature or if they form in back-arc environs also.

Seafloor hydrothermal systems and massive sulfide deposits.

A fundamental question regarding oceanic lithosphere is how much of the crust is metamorphosed and to what mineralogy? The answer to this question impacts models of the nature of the lithosphere that gets subducted, the crustal content of volatiles that may get recycled into the mantle and the distribution and size of metal sulfide deposits. Ophiolites are extremely metamorphosed: 80-100% of the extrusives and dikes to zeolite and greenschist grade mineralogies and 40-100% of the gabbroic rocks to upper greenschist and higher. There is also evidence of multiple alteration events associated with secondary hydrothermal systems. It is important to assess how much of this metamorphism represents the state of all oceanic crust and how much is unique to ophiolites formed in IA or BAB settings. This assessment requires a deep drill hole near a BAB spreading axis untainted by IA intrusions to characterize axis-associated alteration. This could then be compared to a similar site on a MOR. Secondary or multiple intrusive events associated with IA intrusions could also be distinguished by comparison to the axis-only site.

A second goal is to determine the site of formation of large massive sulfide deposits now exposed in ophiolites. In both Cyprus and Oman, these deposits are spacially associated with the late silicic intrusive complexes, although the genetic relationship is still highly controversial. These late high level intrusive complexes represent a shallower heat source than the gabbroic layers, and may be a shallow cupola 2-9 km in width. This latter heat souce may be responsible for concentrating the sulfides into large deposits as well as generating the secondary intense metamorphism. These features (high level intrusive complexes, intense metamorphism, chlorite-quartz stockwork systems, and sulfide concentrations) would be easily distinguished in drill core samples and could be compared to the results of the Cyprus drilling program. Once again, a intermediate-depth site near silicic eruptives or a seamount may provide a good target for this type of rock assemblage.

Recommendations for the Lau Basin.

The tectonic evolution of the Lau Basin is fairly well known and recent and scheduled cruises are providing bathymetric and petrologic detail of this mature BAB. Within the Lau Basin the spreading center is fairly well-located, and reflections from the roof of and active magma chamber have been described for the Valu Fa Ridge in the southern Lau Basin. Basalt chemistry suggests that the central Lau Basin is relatively untainted by IA type lavas (Hawkins, 1976) and is dissimilar only in trace elements to MORB (Gill, 1976). The Lau Basin offers a useful comparison the the Mariana Trough as it is long and straight rather than arcuate. It does not have the fine-scale mixing between IA and BAB lavas that the Mariana has. Silicic rocks found to the northern end of the basin at Zephry Shoals may be the surface expression of a late silicic extrusive comples. Several hard-rock cores from the same Basin would also be useful to assess the inherent variablity in crustal-forming processes. I recommend that at least three hard-rock sites be designated, with the goal of at least one to reach the bottom of the dike complex and into the isotropic gabbro. The drill sites are a) one in the center of the basin near the northern spreading axis in MORB-like crust (L-11), b) in the south near the Valu Fa magma chamber (L-9) and near Zephyr Shoals for possible silicic plutons at depth (L-10).

The Earliest Stages of Island Arc and Back-Arc Basin Development: A Call for Study.

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Our understanding of the evolution of intra-oceanic island arc (IA) and back-arc basin (BAB) systems has improved considerably during the last 15 years. Contributions have come largely from dredging operations and on-land geologic studies, especially for IA systems. Considerable information on BAB has come from geophysical surveys and dredge sampling, but detailed coring studies such as DSDP Legs 59 and 60 have been crucial in furthering our understanding of the evolution of BAB and their relationships with IA. The kinds of information we can gain from studying cores from these environments, especially regarding their temporal evolution, simply cannot be gathered in any other way. The possibility that ODP will core IA and/or BAB in the western Pacific represents a remarkable opportunity to build on the present data base.

One of the most glaring deficiencies in our knowledge of these systems concerns the earliest stages in the formation of BAB and IA. In the case of the more evolved BAB, such as the Mariana Trough at 18°N, thick accumulations of sediment obscure the igneous and sedimentary rocks and attendant structures developed during and immediately after the commencement of rifting. The core of DSDP Site 453 in the western part of the Mariana Trough has given us a glimpse of the sorts of catastrophic sedimentation that accompany early rifting events, but other than this we have little direct evidence regarding the very early stages in BAB formation.

Another deficiency concerns our understanding of the earliest stages in the formation of intra-oceanic arcs. Studies of active, subaerially exposed volcanoes have contributed fundamentally to our understanding of especially magmatic evolution in these systems. However, this understanding is flawed in that it is based on the uppermost parts of the largest central volcanoes in a given arc; the vast bulk (> 95%) of these active arcs is submerged. Considering arcs that are completely exposed above sea level, such as the Cascades where major differences are observed between the larger strato-volcanoes and the intervening, more extensive lava fields both in terms of composition and eruptive style, it is extremely unlikely that our understanding of the evolution of the larger volcanoes in IA is representative of the entire arc. To a lesser extent, the same criticism holds true for studies of submarine arc volcanoes. These are also central volcanoes, albeit smaller ones, and we need to know how representative of the early stages of IA development are the lavas erupted from the central volcanoes. We cannot assess this until we know the composition of the deeper parts of the magmatic arc, the platform on which the central volcanoes rest. Are these parts of the arc composed of fissure-fed basalt fields as is the case for the Cascade Arc? Or is the arc amagmatic between the central volcanoes, composed of older arc material similar to that of the frontal arc with a veneer of volcaniclastic sediments shed off the central volcanoes? We will not know the answers to these questions until we core the active arc between the central volcanoes.

An attempt to look at the composition of the Mariana active arc between the central volcanoes was made during DSDP Leg 60. Site 457 failed to penetrate coarse, poorly lithified volcaniclastic sediments shed off the surrounding subaerial volcanoes of Alamagan and Pagan. Since the larger volcanoes have evolved to the stage where they can generate more fractionated, siliceous magmas that are likely to be erupted in a pyroclastic mode, and since these volcanoes are also sources of large volumes of sediment eroded by waves and rainfall, drilling between the larger volcanoes can generally be expected to encounter difficulties similar to those of DSDP Site 457. To minimize these difficulties we need to drill between the smaller submarine arc volcanoes, where less evolved magma compositions and hydrostatic pressure will not allow for pyroclastic volcanism; there also wave-and rainfall-induced erosion can be neglected as a source of coarse sediments. In these regions, sedimentation should be dominated by biogenic and finer volcaniclastic material deposited relatively slowly. These sediments should be much better lithified than those at Site 457, and penetration and recovery should be correspondingly enhanced.

It is important to understand the earliest stages in the evolution of IA and BAB not only for the purpose of reconstructing modern tectonic, petrogenetic, and sedimentological processes, but also to better decipher ancient ones. The rock associations developed in the early stages of IA and BAB are in a very favorable tectonic position to be sutured to continents during collisonal orogenesis, and, being structurally deep, they are also likely to escape erosion. Many of the "ophiolitic" successions exposed in the world's orogenic belts must represent early stages of IA and BAB development, and we will only be able to understand the significance of these ancient complexes after we have studied their modern analogues.

It is critical that we core IA and BAB complexes in their earliest stages of development. One area where this could be accomplished is in the northernmost part of the Mariana IA/BAB system. A good case can be made that the Mariana BAB extensional regime has been propagating northward at a rate of 5-10 cm/y, and that the Mariana BAB there is much younger than that cored during DSDP Leg 60, at 18°N. If true, then the region between 21° and 23°N is in the earliest stages of rifting. Since arc volcanism terminates during BAB formation as the older volcanic centers are carried away on the remnant arc, the submarine volcanoes on the Mariana IA immediately east of the forming BAB should be in the earliest stages of a new arc magmatic cycle. Thus, the area enclosed by the rectangle in Fig. 1 is a region in which ODP coring can be expected to contribute substantially to our understanding of the earliest stages in the evolution of IA and BAB. The only other western Pacific system where this work could be carried out is the southern part of the Kermadec Arc and Havre Trough. The northern Mariana system is preferred because of the greater amount of work that has already been completed (DSDP Leg 60, marine geophysical and geologic studies, on-land studies of the frontal and active arcs) or is in progress for this system compared to the present state of knowledge of the Kermadec/Havre System.

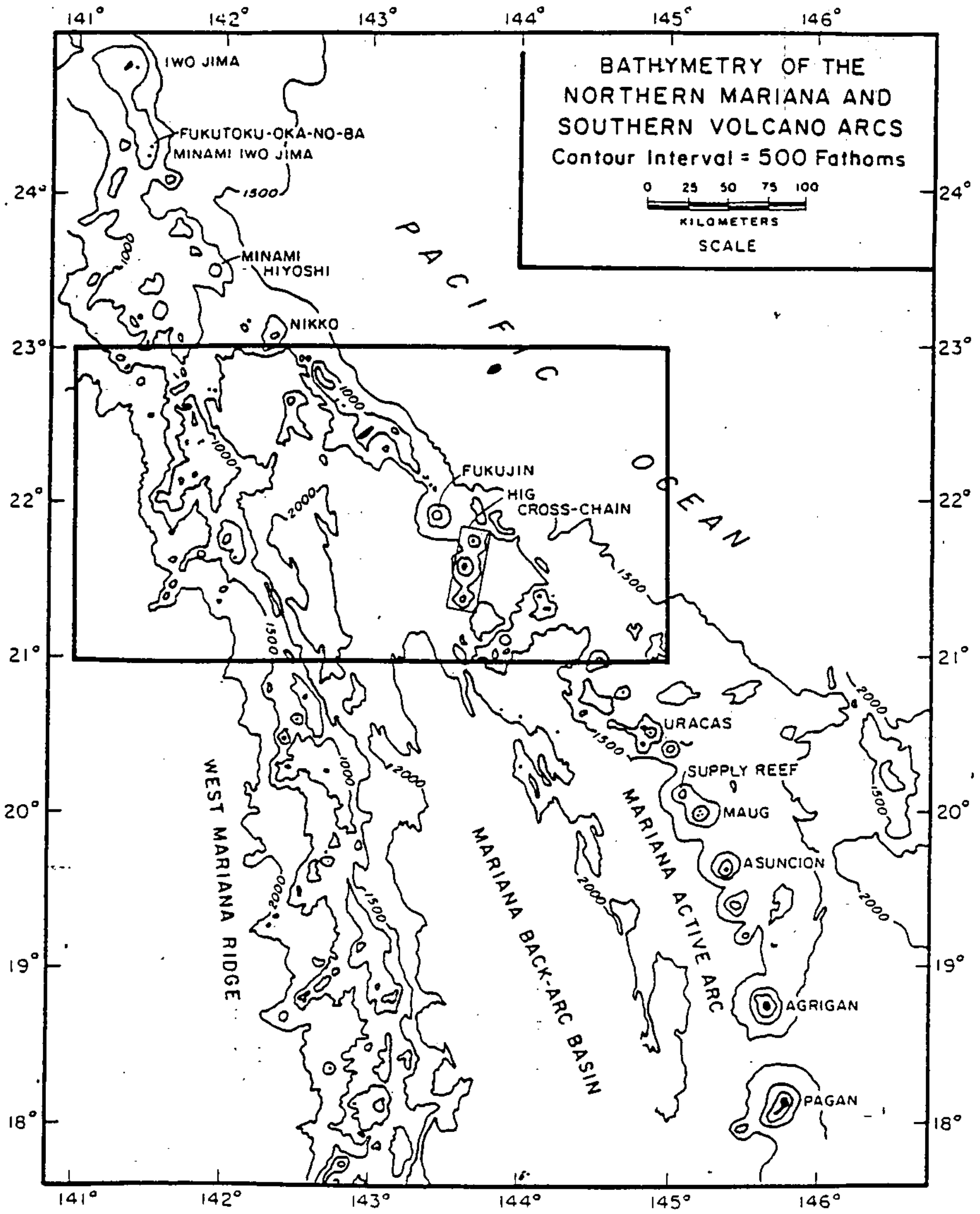


FIG. 1: RECTANGLE SHOWS THE LOCATION OF THE PROPOSED ODP SURVEY AND CORING TO STUDY THE ORIGIN OF THE EARLIEST STAGES IN THE EVOLUTION OF BACK-ARC BASINS AND ISLAND ARCS.