NOTE TO REVIEWERS

This is a joint proposal between the University of Hawaii and the University of Tulsa, using the R/V FRED MOORE of the University of Texas. The Co-Principal Investigators are Brian Taylor at the University of Hawaii and Gregory Moore at the University of Tulsa. The funding requested over two years in this proposal is as follows:

University of Hawaii:	$244,941
University of Tulsa:	$245,000
University of Texas:	$235,020

TOTAL	724,961

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NATIONAL SCIENCE FOUNDATION

PROJECT SUMMARY

FOR NSF USE ONLY			
DIRECTORATE/DIVISION	PROGRAM OR SECTION	PROPOSAL NO.	F.Y.

NAME OF INSTITUTION (INCLUDE BRANCH/CAMPUS AND SCHOOL OR DIVISION)

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Brian Taylor

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TITLE OF PROJECT

Multichannel Seismic Investigation of the Bonin Arc-Trench System

TECHNICAL ABSTRACT (LIMIT TO 22 PICA OR 18 ELITE TYPEWRITTEN LINES)

We propose to conduct a multichannel seismic investigation of an intra-oceanic arc-trench system, specifically to determine the seismic stratigraphy, basement morphology, and crustal structure of the Bonin system, including the back-arc rifts, the arc/forearc basin/outer arc high, and the inner trench wall. We plan to collect 2600 nm of 2 ms, 96-channel, 48-fold MCS data together with 40 to 50 long-range sonobuoy refraction lines. Major questions to be addressed include:
(1) How does arc lithosphere rift?: does extension occur via normal slip on low-angle detachment surfaces or by overall stretching and thinning?
(2) how does arc/forearc lithosphere form and evolve? a) was the 200 km-wide forearc formed by anomalous initial arc volcanism, was it superimposed on preexisting oceanic crust and/or was it later modified by forearc spreading or other volcanism? b) what is the crustal structure of the forearc and how does it compare to that of ophiolites? c) what is the differential vertical motion history across the forearc and how does the forearc lithosphere respond to flexural loading by arc volcanoes and by coupling with the subducting plate? d) what controls the systematic mass wasting of the forearc, in particular the timing and locus of submarine canyon formation?
(3) a) are the domes along the lower slope terrace serpentinite diapirs or local culminations along a lower slope completely remobilized by subduction-related dewatering, and (b) is subduction erosion of the lower slope occurring, and if so, is it by extensional collapse and/or by interaction with subducting horsts and graben?

This investigation will provide the remaining necessary site survey for planned ODP drilling in the Bonins.

RESULTS FROM PRIOR NSF SUPPORT (B. TAYLOR)

a) OCE 83-09757, $386,919, 1/1/84 - 6/30/86

b) Active Margin Processes in the Izu Arc - Bonin Trench System

c) This project studied the rifting of an island arc and the formation of large forearc canyons in the absence of continental sediment supply. It included reconnaissance studies of the lower slope and of two arc volcanoes. The 1984 shipboard program, using SeaMARC II bathymetry and sidescan, successfully swathmapped i) the Bonin arc and rifts between 29°and 31.5°N, ii) the forearc and submarine canyon system adjacent to Aoga Shima, and iii) three lower slope "diapirs" between 31.5 and 32°N. We dredged 13 submarine volcanoes in the Sumisu and Tori Shima rifts, and collected samples from the adjacent island arc volcanoes, including the first ever from Sumisu Jima. We were unsuccessful in our attempt to sample deep stratigraphic sections of the forearc basin: piston cores of the canyon walls recovered only Quaternary material.

The primary findings of this project are the following:

1) The major zone of rifting is immediately west of the active volcanic chain, but some arc volcanoes near 29°N are surrounded by rifts. The backarc rifts are semi-continuous along strike, being segmented by structural highs and chains of submarine volcanoes extending westwards from the island volcanoes. The rifts are structural graben, 30 to 40 km wide, bounded by tilted horst blocks of arc basement and partially filled with volcanoclastic sediments. The locus of maximum uplift and backtilting of the bounding horsts varies back and forth along strike between the two sides of the Bonin rifts. Major cross-rift faults are also present. The last two observations suggest that arc lithosphere extension may occur by detachment faulting, but MCS profiling of deep structures will be required to verify this.

2) Volcanism is continuing along both the active and "remnant" arcs. Volcanic centers have also developed in the rift basins and their location is structurally controlled. Sumisu Jima and Tori Shima are dominantly composed of tholeiitic arc basalts. Their chemical variation can be explained by closed system fractionation with variable plagioclase flotation. Lavas in the back-arc rift are dominanted by tholeiitic basalts, but andesite, dacite, and rhyolite also occur. The rift lavas have similar K and Ba contents to the arc lavas, but lower ratios of alkalis and alkaline earths relative to high field-strength elements. Whereas the volcanic islands 100 km apart lie virtually on the same liquid line of descent, the rift volcanics, though closer to the islands, are chemically distinct from them. The rift basalts are nearly identical to basalts erupted at the Mariana back-arc spreading center. Thus distinct mantle sources (IAT, BABB), in close horizontal proximity, are present during the earliest stages of back-arc rifting. The volcano-tectonic environment is similar to that in which Kuroko-type deposits form.

3) Canyon systems in the Bonin forearc have a dendritic drainage pattern and evidence numerous submarine landforms indicating mass wasting primarily by headward erosion. The canyons deeply incise the gentle slopes of the

upper forearc but lose bathymetric definition on the steep slopes of the trench inner wall (from which most of the sedimentary cover has been eroded), apparently being unable to cut into the igneous basement. We propose a testable model that canyon location is not structurally controlled in the upper forearc, but that major canyon spacing is controlled by the location of structural offsets and low points along the outer-arc high. Chloritized/serpentinized mafics and ultramafics dredged from one of the volcaniform highs spaced along the lower-slope terrace support the model that these highs result from subduction-related dewatering remobilizing forearc basement material.

d)

Taylor, B., and C. Smoot, 1984, Morphology of Bonin forearc submarine canyons, Geology, 12, 724-727.

Brown, G., and B. Taylor, 1986, Seafloor mapping in the Sumisu Rift, Bonin island arc, Geol. Surv. Japan Spec. Pub., in press.

Zhang, Y., C. Langmuir, and B. Taylor, 1986, Petrogenesis of volcanic rocks from Tori Shima and Sumisu Jima volcanos, Izu arc, Contrib. Miner. Petrol., submitted.

Taylor, B., D. Hussong, and P. Fryer, 1984, Rifting of the Bonin Arc, Eos, Trans. Am. Geophys. Un., 65, 1006.

Taylor, B., P. Fryer, D. Hussong, and C. Langmuir, 1985, Active volcanism in the Izu arc and Rift: tectonic setting, Eos, Trans. Am. Geophys. Un., 66, 421.

Zhang, Y., C. Langmuir, B. Taylor, P. Fryer, and D. Hussong, 1985, Active volcanism in the Izu Arc and Rift, II: The volcanic front, Eos, Trans. Am. Geophys. Un., 66, 421

Fryer, P., C. Langmuir, B. Taylor, Y. Zhang, and D. Hussong, 1985, Rifting of the Izu Arc, III: Relationship of chemistry to tectonics, Eos, Trans. Am. Geophys. Un., 66, 421.

Papers on the petrochemistry of the rift volcanics and the structure and submarine geology of the Sumisu and Tori Shima rifts are in preparation by Fryer et al. and Taylor et al., respectively. The forearc data and some of the rift data form the basis of Mr. Glenn Brown's Ph.D. research, which will be completed in 1988.

RESULTS FROM PRIOR NSF SUPPORT (G. F. Moore and T. H. Shipley)

a) OCE 8024402 and 8414401, $214,268, 11/1/81 to 4/30/84

b) "High Resolution Studies of Sediment Accretion and Subduction Along the Middle America Trench"

c) Below is an excerpt of the "summary of completed project" for the most recently completed NSF program.

Convergent margins have been the subject of intense interest since the first simple dynamic models for accretion at the base of inner trench slopes were published by Seely et al. and Karig in 1974. The mechanics of the accretion process remain obscure, partly because of the lack of high-resolution data from the base of trench slope.

The purpose of this project was to conduct an integrated high-resolution (broad-band) digital single channel seismic reflection and Sea Beam bathymetric study of three sites along the Middle America Trench. The combination of techniques provided an excellent method to study structural variations over large areas of the sea floor.

The primary results of this project are the following: (1) Off Costa Rica, we can demonstrate that the subducting plate fabric actually has little influence on the subduction and accretion processes; (2) Examination of the region off Guatemala, where erosion is postulated on the lower slope, the bathymetric trace of the deformation front is linear and at an angle to oceanic plate fabric. If erosion occurs at the base of slope, the trace of the slope base should be indented where horst blocks are being subducted. Thus erosion may not be occurring, at least at this shallow level; (3) Further north, off Mexico, the trench contains more sediments and folds form in the trench floor associated with ramping of the decollement. The folds tend to parallel the underlying plate fabric but as they are accreted, they reoriented to the trend of the base of slope. This implies that the decollement may be locally directed by plate fabric or by physical properties in the sediments draped over the basement, but that the dominant convergence direction determines the gross trend of the trench.

d) Silver, E. A., Ellis, M. J., Breen, N. A., Shipley, T. H., 1985, Comments on the growth of accretionary wedges, Geology, v. 13, pp. 6-9.

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Shipley, T. H., Buffler, R. T., 1986, Costa Rica Continental Margin, in von Huene, ed., Comparative anatomy of Pacific Trenches, GAPA/IOC, in press.

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Moore, G. F., Shipley, T. H., Lonsdale, P. F., 1986, Subduction erosion vs. sediment offscraping at the toe of the Middle America Trench off Guatemala, Tectonics, in press.

Moore, G. F. and Shipley, T. H., 1982, Morphology and Structure of the Middle America Trench From Multibeam Echo Sounder and Seismic Reflection Data, Geol. Soc. Am. Abs. Progs., v. 14, p. 570.

Shipley, T. H., Moore, G. F., Volpe, A. M., 1982, Sediment Offscraping Along the Middle America Trench, Trans. Am. Geoph. Un., v. 63, p. 1112.

Shipley, T. H., Moore, G. F., Volpe, A. M., 1983, Spatially Varying Sediment Offscraping in the Middle America Trench, OJI Int. Symposium, Japan, p. 13.

Moore, G. F., Shipley, T. H., Lonsdale, P. F., 1983, Sedimentary and Tectonic Processes in the Middle America Trench off Southern Mexico, Trans. Am. Geoph. Un., v. 64, p. 833.

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MULTICHANNEL SEISMIC INVESTIGATION OF THE BONIN ARC-TRENCH SYSTEM

OVERVIEW

We propose to conduct a multichannel seismic (MCS) investigation of an intra-oceanic arc-trench system, specifically to determine the seismic stratigraphy, basement morphology, and crustal structure of the Bonin system, including the back-arc rifts, the arc-forearc basin-outer arc high, and the outer forearc/inner trench wall. Major questions to be addressed include:
(1) how does arc lithosphere rift?: does extension occur via normal slip on low-angle detachment surfaces or by overall stretching and thinning?:
(2) how does arc/forearc lithosphere form and evolve?: a) was the 200 km-wide forearc formed by anomalous initial arc volcanism, was it superimposed on preexisting oceanic crust and/or was it later modified by forearc spreading or other volcanism? b) what is the crustal structure of the forearc and how does it compare to that of ophiolite? c) what is the differential vertical motion history across the forearc and how does the forearc lithosphere respond to flexural loading by arc volcanoes, and by coupling with the subducting plate? d) what controls the systematic mass wasting of the forearc, in particular the timing and locus of submarine canyon formation?
(3) a) are the domes along the lower slope terrace serpentinite diapirs or local culminations along a lower slope completely remobilized by subduction-related dewatering? and b) is subduction erosion of the lower slope occurring, and if so, is it by extensional collapse and/or by interaction with subducting horsts and graben?

Our MCS program will provide the remaining necessary site survey for planned (1-2/3 legs) ODP drilling in the Bonins and, together with the drilling results, should provide first-order answers to most of the questions outlined above. The Bonin region was chosen for ODP drilling and our proposed MCS survey of an intra-oceanic arc-trench system because it is the only region with all the tectonic elements that we wish to investigate (including back-arc rifts, a well developed forearc cut by major submarine canyons, and forearc diapirs), without the complications of arc reversal or collision events, and with a large existing data base of geological and geophysical information including both SASS and SeaMARC II swathmapping.

TECTONIC SETTING

Subduction of Pacific lithosphere beneath the West Philippine Basin (Figure 1) began in the Early Eocene (Karig, 1975), and through the Early Oligocene formed an intra-oceanic volcanic arc and a 200-km-wide forearc of arc volcanic material (tholeiites and boninites), possibly superimposed on previous oceanic crust (Wood et al., 1981). Mid-Oligocene rifting split the arc and Late Oligocene-Early Miocene back-arc spreading in the Parece Vela and Shikoku Basins isolated the remnant arc (Palau-Kyushu Ridge) from the active Bonin-Mariana arc and forearc (Kobayashi and Nakada, 1979; Mrozowski and Hayes, 1979). The rifting and initial spreading was time transgressive, starting in the center of the Parece Vela Basin and at the northern end of the Shikoku Basin, resulting in the bowed and V'd shape of those basins, respectively. This process is being repeated. The southern part of the arc split again in the Late Miocene, and 6 to 8 my of seafloor spreading in the Mariana Trough has isolated the active Mariana arc from, and increased its curvature with respect to, the remnant West Mariana Ridge (Karig et al., 1978; Hussong and Uyeda, 1981). Spreading in the Mariana Trough may be propogating to the north, "unzipping" the Mariana arc from the West Mariana Ridge (Stern et al., 1984). In contrast, the Izu-Bonin arc is still in the rifting stage of backarc basin formation. It is undergoing extension along most of its length and is not simply rifting apart as the Mariana Trough propogates northward (Honza and Tamaki, 1985). The major zone of rifting is immediately west of the active volcanic chain, but some arc volcanoes near 29°N are surrounded by grabens (Taylor et al., 1984). Volcanism is continuing along both the active and "remnant" arcs. Volcanic centers have also developed in the rift basins. Their chemistry indicates a basalt--rhyodacite association, with the basalts having similar major and trace-element compositions to Mariana Trough tholeiites (Fryer et al., 1985b). The backarc rifts are semi-continuous along strike, being segmented by structural highs and chains of submarine volcanoes extending westwards from the island volcanoes (Taylor et al., 1985). Similar volcanic cross chains occur west of the Mariana volcanoes, and older chains extend west into the Parece Vela and Shikoku Basins from the West Mariana Ridge-Bonin arc.

The difference in arc/back-arc evolution between the Marianas and Bonins has produced corresponding differences in their forearcs. The Bonin Forearc has experienced little structural disruption since its inception (Honza and Tamaki, 1985). A broad forearc basin has accumulated volcaniclastic and hemipelagic sediments behind an outer-arc high. The onlap of strata onto this high, together with Eocene shallow-water fossils found on the Bonin islands (Hanzawa, 1947), indicates that it has been a relative structural high since early in the history of the arc. A mature, dendritic, submarine canyon system has developed by mass wasting and headward erosion, incising many deep canyons across the forearc, cutting as much as 1 km into the 1.5 to 4 km thick sedimentary section (Taylor and Smoot, 1984). In contrast, the Mariana forearc has not behaved as a rigid plate, but has undergone extension tangential to its curvature (Karig et al., 1978). This has produced radial fractures and, together with the disruption caused by numerous seamounts on the subducting plate, easy pathways for diapiric intrusions of serpentinised mafic/ultramafics of arc affinity. Eruption of these diapirs onto the seafloor, together with uplift of forearc material due to their subsurface intrusion, has formed a broad zone of forearc seamounts (up to 2500 m high and 30 km in diameter) 50 to 120 km from the trench axis (Fryer et al., 1985a). In the Bonins, however, domal bodies of chloritised/ serpentinised mafic/ultramafics occur along a narrow zone which controls the location of a lower-slope terrace. This zone may be the oceanic forearc analog of overpressured dewatering zones in accretionary sedimentary wedges. Possibly because most of the sediment has slumped off the trench inner wall, the large forearc canyons die out on the middle slope and do not cut across the lower-slope terrace (Taylor and Smoot, 1984). Only very minor, and probably ephemeral, accretionary complexes occur at the base of the inner wall of both the Bonin and Mariana Trenches (Honza and Tamaki, 1985; Mrozowski et al., 1981).

AVAILABLE DATA

A majority of the public data in the Bonins has been collected by the Geological Survey of Japan, particularly since their systematic surveys of the area began in 1979 (Honza et al., 1981, Figures 2 and 3). A regional multichannel seismic grid was completed by the Japan National Oil Co. in 1978/79 (Figure 4). Swath mapping by NAVOCEANO has provided detailed SASS bathymetry (Taylor and Smoot, 1984; Figures 5 and 18). In 1984, HIG SeaMARC II surveyed the arc and rifts between 29° and 31.5°, the forearc adjacent Aoga Shima, and the three lower-slope "diapirs" south of 32° N (Taylor et al., 1984, Figures 5 and 14). Since 1982, the Geological Survey of Japan has had two 40-day cruises to the region as part of an ongoing 5-year program investigating the geology and potential hydrothermal deposits along the arc and rifts. These surveys have been coordinated with the Hydrographic Office of Japan, which is responsible for preparing detailed bathymetric charts of the region, and which has run their geophysical survey lines between those of the Survey. Figure 5 summarizes the underway geophysical data base (3.5 kHz, single channel seismics, gravity, magnetics) for the Torishima-Hachijo Jima region, but purposely omits the Hydrographic Office tracks in the arc/rift area as these bisect the 2-mile grid of the Geological Survey and produce an illegible chart. Extensive coring and dredging (>100 sites), together with heat flow measurements and bottom photography, have been carried out in this same region. We have been funded by NSF for a program of ALVIN dives in the Sumisu Rift, which is scheduled for August 1987.

The seismic data on which proposed ODP sites (Figure 6) are presently located are shown in Figures 7-12. Site 7 (located on one of the shallowest diapirs) is SASS surveyed (Figure 18), but is presently without reflection seismics across it. Clearly these data are inadequate for detailed site selection, estimation of drilling times, and safety panel review. Minimum safety panel requirements for the rift and forearc sites include crossing MCS lines.

RIFTING ARC LITHOSPHERE

The processes associated with the rifting and subsequent separation of continental lithosphere have been a major research focus and drilling objective. Recently, Wernicke (1981) and many others have challenged the widely accepted model of lithospheric stretching popularized by McKenzie (1978), suggesting instead that lithospheric extension is mainly accomodated by normal slip on low-angle detachment surfaces. A recent article by Lister et al. (1986) well summarizes the arguments:

INTRODUCTION

There is widespread acceptance of the lithospheric stretching model proposed by McKenzie (1978) to explain the crustal thinning, rifting, and subsidence that predate and accompany continental breakup and lead to the development of passive continental margins. Evidence for such stretching comes from (a) crustal thinning and (b) normal fault geometries that require large extensions (Bally, 1981; Le Pichon and Sibuet, 1981). Geophysical modeling of this phenomenon has been based entirely on symmetrical, pure-shear extension models (McKenzie, 1978; Sclater and Christie, 1980; Le Pichon and Sibuet, 1981). Such models, with variations induced by depth-dependent strain (Keen et al., 1982) or depth-dependent rheology (Vierbuchen et al., 1982), allow prediction of the crustal thickness, subsidence histories, and gravity profiles of extended terranes.

Symmetric extension models, however, do not predict the wide variation in gross continental margin architecture, crustal thinning, and continental uplift reported, for example, by Kinsman (1975) or Falvey and Mutter (1981). Features such as marginal plateaus, outer highs, detached continental ribbons, and submerged continental fragments remain largely unexplained, although sophisticated multilayer modeling (Keen et al., 1982; Vierbuchen et al., 1982) addresses some of these questions (e.g., the origin of outer highs; Schuepbach and Vail, 1980). More important, there is a notable absence of symmetrical rift structures in reflection seismic profiles (as pointed out by Bally, 1981, 1982), and opposing margins do not generally exhibit identical structures. We conclude, therefore, that symmetrical extension models have limited applicability. Structural asymmetry may be a general feature of passive margin development.

Structural asymmetry on a range of scales is a feature of many of the models recently proposed for continental extension in the Basin and Range province of the western United States. These models are based on detachment faults and/or shallow-dipping crustal shear zones (Wernicke, 1981, 1985; Wernicke and Burchfiel, 1982; Davis, 1983).

DETACHMENT MODELS FOR CONTINENTAL EXTENSION

Several authors have recognized similarity of passive margin structures to those recognized in the Basin and Range province. However, there is an important element of Basin and Range–style tectonics that has not been recognized on passive margins: detachment faults associated with the formation of metamorphic core complexes and/or (mylonitic) detachment terranes (Crittenden et al., 1980). Metamorphic core complexes, or mylonitic detachment terranes, consist of a largely brittle upper plate overlying ductilely deformed igneous and metamorphic rocks. The upper plate is truncated at its base by low-angle faults of large areal extent which appear to be normal-slip *detachment* faults on which substantial relative displacements have occurred (e.g., Reynolds and Spencer, 1985). The upper plate has been extended 100%–400% (see Davis et al., 1980; Miller et al., 1983) as the result of movements on listric normal faults and/or dominolike rotations of fault blocks bounded by initially high-angle normal faults (see Wernicke and Burchfiel, 1982; Jackson and McKenzie, 1983). As it is dragged to the surface, the lower plate is subject to intense ductile deformation in intracrustal zones of noncoaxial laminar flow (Lister and Davis, 1983). The lower-plate rocks record a history of rapid uplift while, enigmatically, sedimentation may continue on the upper plate.

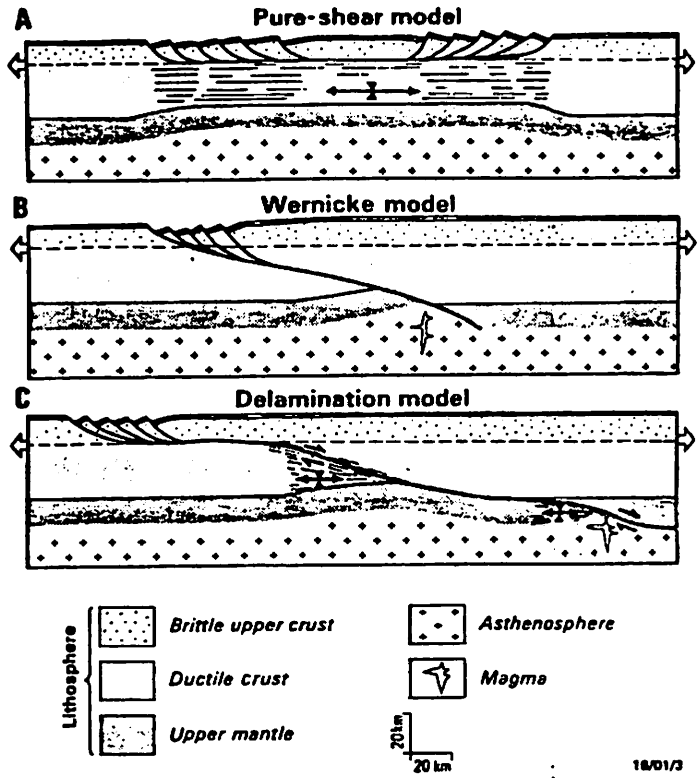

Figure 1. Three models for continental extension.

There is still some argument about the exact role detachment faults play in the continental extension process. Symmetric pure-shear models assume that the detachment fault represents the brittle-ductile transition (e.g., Miller et al., 1983). The brittle upper crust, typified by rotated tilt blocks, is shown extended over a more uniformly stretched ductile lower crust (Fig. 1A). There is increasing support, however, for models based on shallow-dipping movement zones (Wernicke, 1981, 1985; Davis, 1983; Davis et al., 1986). Wernicke suggested that detachment faults represent low-angle normal faults that cut through the entire lithosphere (Fig. 1B). An alternative separation geometry (Fig. 1C) would involve delamination of the lithosphere, the detachment zone running horizontally below the brittle-ductile transition, steepening, and then again running horizontally at the crust-mantle boundary. We are aware that detachment faults may be merely upper crustal manifestations of major ductile shear zones at depth (Davis et al., 1986) and that the concept of a single lithospheric dislocation may be a gross oversimplification.

Lister et al.'s discussion and the three-dimensional geometries of continental rifts illustrated in Figure 13 concur with presentations by numerous authors (including Project Probe results from East Africa) at the Fall 1984 and Spring 1985 AGU special sessions on rift tectonics (Eos, 65, 1114-1116; 66, 364-365).

Several questions immediately come to mind when considering lithospheric extension in an arc rather than a continental environment. Does extension of island arc lithosphere prior to back-arc spreading differ significantly from extension of continental lithosphere prior to mid-ocean spreading? What effect does the presence of the line of active volcanoes have on the processes? Which model, simple shear (detachment) or pure shear (stretching and thinning), best fits the data? Major testable differences between the two models include 1) a lateral offset in the locus of maximum crustal vs. mantle thinning in the detachment model, likely resulting in 2) structural asymmetry and 3) the presence of transfer zones linking master faults of opposing asymmetry along strike (see Figure 13).

With respect to the questions above, the data from the most densely surveyed arc rifts are equivocal. The Sumisu Rift, between the islands of Sumisu Jima and Tori Shima, is a structural graben, 30 to 35 km wide, bounded by tilted horst blocks of arc basement and partially filled with volcanicalstic sediments (Figures 7, 14, and 15). The line of active arc volcanoes occurs 10 to 15 km east of the eastern rift boundary. The latter is a steep north-trending fault scarp north of 31^{o}05'N, and is a relatively less steep composite fault scarp trending NNW south of 31^{o}05'N. The rift graben is divided into four blocks with different basement depths by two crossing fault zones. An arc-parallel normal fault zone bounds the west side of the deep inner rift (Figure 1). A NE-trending right-lateral normal fault offsets the southern half of the graben down and west, and intersects the east rift wall at its change in trend.

To date, no seaward-dipping seismic reflectors, documented on ODP Leg 104 to represent massive outpouring of volcanic material, have been recognized in back-arc basins. However, SeaMARC II surveys in the Bonins have revealed widespread syn-rift volcanism not only on the active and "remnant" arcs, but in the rift basins as well (Figures 7, 14, and 15). Dredged samples are commonly tholeiitic basalts, but also include andesites, dacites and rhyolites. The basalts are almost identical to Mariana Trough basalts, which means that there is an available source of back-arc basin basalts (as against island arc tholeiites) during even the rifting stage of back-arc opening.

The distribution of active volcanoes in the rift graben and on the remnant arc is structurally controlled. All but a few of the large seamounts are elongated parallel to the north-trending faults, and clusters of vents are commonly aligned in this direction, as are the inner rift 4-km flow at 30^{o}51'N and the en-echelon volcanic ridges centered at 31^{o}05'N (Figure 14). Furthermore, the NE-trending cross fault localizes a volcanic maxima near 31^{o} N, and the inner-rift en-echelon ridge together with three relatively large seamounts define a 025^{o} trend of uncertain significance.

The locus of maximum uplift and backtilting of the bounding horst blocks varies back and forth along strike between the eastern and western sides of the Bonin rifts. Adjacent to Tori Shima, the rift narrows and the high block is on the western side, but to the north and south it is on the east (e.g., Figure 15). In a view consistent with the detachment model of rifting, the NE-trending cross fault and the 025° seamount linement may be considered part of a transfer zone linking an eastern master fault in the north to a more symmetric structure in the south (profiles 8-11), which may in turn link to a western master fault adjacent to Tori Shima (profile 12 and others further south). Alternately, from a stretching model perspective, the Sumisu Rift may be viewed as a fairly symmetrical graben with some differential subsidence of the inner rift. The variation in uplift of the east horst block along strike may be ascribed to loading by the arc volcanoes.

Existing MCS profiles across the Sumisu Rift do not image clearly the deep structures of the graben (Figure 16). Well processed, deeply penetrating multichannel seismic profiles both along and across strike are required to determine whether master detachment surfaces and transfer zones are really present in the Sumisu Rift.

ARC/FOREARC DEVELOPMENT

The Bonin island "arc" forms a straight chain of volcanoes spaced 20 to 90 km apart, extending from Iwo Jima at 25°N to O Shima at 35°N. In the area of interest (Figure 5) it includes four volcanic islands and two submarine volcanoes, several of which have been active this century. Shoal bathymetry and basement highs to the east of Tori Shima, Sumisu Jima and Aoga Shima (Figure 5) are inferred from gravity and magnetics data to be an older (Eocene?) frontal arc, similar to the Guam-Saipan group in the Marianas (Honza and Tamaki, 1985). The seismic stratigraphy laps onto and reverses dip over the frontal arc blocks (Figures 3, 8, and 16). Between frontal arc blocks the morphology of the forearc basement is obscured on present data by the thick sequence of overlying sediments. Only as the basin sequence laps onto and thins over the outer-arc high is basement clearly imaged again. The outer-arc high is a persistent arc-parallel structure along the whole length of the Bonin arc, with significant right-stepping offsets just north of 32°N and south of 30°N (Figure 2, Honza and Tamaki, 1985). Its relief varies along strike; where exposed on the Bonin Islands, it consists of Eocene boninites (Shiraki et al., 1980). Taylor and Smoot (1984) proposed that the spacing of the major submarine canyons which incise the forearc was controlled by the location of saddles along the length of the high; i.e., that the canyons nucleated on the steep slopes seaward of the outer-arc high and were first able to cut arcward by mass wasting and headward erosion where the ridge was relatively low (e.g. Figure 12a). The dendritic drainage pattern of the canyons on the upper forearc does not appear to be structurally controlled in that sedimentary sequences are continuous beneath the canyons (Figure 10). The forearc basin sediments are pervasively normal faulted, but contain numerous seismic horizons (especially unconformities) which are regionally correlatable (Figures 3, 9-11, and 16). Some strong reflectors suggest that flows or sills occur in parts of the forearc (Figure 16).

With the exception of a few dredges from trench inner walls (Bloomer, 1983) our direct knowledge of intra-oceanic forearc basement is derived from only three island chains and two IPOD sites. The Mariana and Tonga frontal arc islands (Guam-Saipan and 'Eua) expose Late Eocene arc volcanics (Tracey et al. 1964, Ewart et al., 1977). Eocene boninites crop out in the islands on the Bonin outer-arc high (Shiraki et al., 1980), and Leg 60 sites 459 and 458 sampled Eocene arc tholeiites and Lower Oligocene boninites and arc tholeiites, respectively, from the Mariana outer-arc high. Basement beneath the thickly sedimented forearc basin between the frontal arc and outer arc high has never been sampled, nor has the outer forearc basement beneath the carapace of interbedded arc pillow lavas, flows and sills. Several alternate models have been proposed to explain the 150-200 km wide Bonin-Mariana forearc: the frontal arc and outer-arc high were formerly contiguous and subsequently separated by forearc spreading, they were built separately but near synchronously on former West Philippine Basin oceanic crust, or they are part of a continuous Eocene arc volcanic province, possibly with overprints of later forearc volcanism (Hawkins et al., 1984; Leitch, 1984; Wood et al., 1981). Associated with these different scenarios of forearc basement development is the question of the crustal structure of forearcs and their possible relationship to ophiolite sheets. Many authors now ascribe a majority of ophiolites to arc settings because of their chemistry and associated sediments. However, the analogy is incomplete because of our woefully inadequate knowledge of the crustal structures of this and all other intra-oceanic forearcs (Figure 17, La Traille and Hussong, 1980). Two reversed refraction lines suggest consistent depths to Moho of 15 to 16 km at 32°N, but significantly different velocity-depth sections.

The presence of arc igneous rocks near the trench, together with observations of normal faulting in the forearc (Mrozowski and Hayes, 1980) and interpretations of outer-arc subsidence, was cited as evidence for large scale removal of Mariana forearc material since the late Eocene by tectonic erosion (Hussong and Uyeda, 1981). This analysis has subsequently been questioned by Karig and Rankin (1983) and Hussong himself (pers. comm.), who infer that the Mariana forearc has not undergone significant tectonic subsidence or erosion. Likewise, in the Bonin forearc the shallow water Eocene fossils on the Bonin Islands, together with the well-developed submarine canyon system and lower-slope terrace, do not suggest tectonic subsidence and erosion, but rather fairly stable conditions possibly since the Oligocene. One test of this hypothesis would be to determine the uplift-subsidence history across the forearc, using backstriping techniques on cored/logged holes and seismic stratigraphic analyses of interconnecting MCS profiles. Determining the forearc vertical displacement field would also provide information on the flexural response and thermo-mechanical state of arc/forearc lithosphere. To distinguish between local (e.g., subducting seamounts) and regional effects, and between linear and point loads will require data from along as well as across the forearc.

OUTER FOREARC TECTONICS

Lower Slope Domes

A lower-slope terrace, 20 to 30 km wide, occurs along the inner wall of the Bonin Trench (Figures 3 and 5, Taylor and Smoot, 1984). Swathmapping shows that this feature is not simply a linear structural ridge but rather is comprised of a series of individual domes spaced at intervals of 15 to 40 km, with summit depths between 4 and 7 km (Figures 5 and 18). Salients on some of the domes appear geomorphologically similar to rift zones on volcanic seamounts (Figure 18). Seismic reflection profiles along and across the domes reveal an acoustically chaotic basement with thin or no sediment cover (Figures 3, 12, 16, and 19). Other sediments are unconformably ponded behind and around the domes up to their inter-high spill points. Dredging the dome just south of 32° recovered chloritised/serpentinised mafic and ultramafic plutonic rocks.

The domes along the Bonin lower slope appear similar to the seamounts in the Mariana outer forearc. Where dredged, the latter consist of serpentinised/chloritised arc mafics/ultramafics that have been attributed to diapirism in the forearc basement, and may represent a general region of forearc remobilization in response to subduction-related dewatering (Bloomer, 1983; Bloomer and Hawkins, 1983; Fryer et al., 1985a). A major difference between the Bonin and Mariana outer-forearc seamount provinces is that the former is much broader, covering the inner wall and outer-arc high and extending arcwards up to 120 km from the trench. We attribute this to two factors: the Bonin forearc does not have the curvature and associated radial fractures of the Mariana forearc, and the Pacific Plate being subducted at the Bonin Trench is noticeably devoid of seamounts relative to that being subducted in the south. The Marianas appear unique in these respects, and the large trench-slope break diapirs have not been observed in other oceanic forearcs. In contrast, lower-slope domes have been swathmapped by limited Seabeam in the Tonga Trench (P. Lonsdale, pers. comm.) and near the Japan Trench-Bonin Trench-Sagami Trough triple junction (K. Nakamura, pers. comm.).

The Bonin lower-slope zone may be the oceanic forearc analog of overpressured dewatering zones in accretionary sedimentary wedges. We do not know whether the domes are truly diapirs (albeit sediment-mantled) like those in the Marianas, some of which erupt serpentinite flows onto the seafloor (Fryer et al., 1985a). SeaMARC II swaths of the three domes south of 32° N indicate sedimented slopes with some radial debris flows, and the dredge seemed to sift through unconsolidated surface material while collecting the occasional rock. Crustal velocities beneath the lower-slope terrace (estimated by MCS stacking, refraction, and velocity pull-up of the lower plate reflector) are only 3.5 to 5 km/sec. The Bonin domes are only 5 to 10 km above the subducting plate (Figure 17). The emplacement mechanism, structure and sub-surface petrology of the domes is unknown. Are they fed by a serpentinite flow which entrains forearc wall rock and spreads out on the surface, forming a mushroom shape, or are they local highs along a completely remobilized lower slope? "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 inferences they provide concerning conditions at depth" (D. Karig, WPAC ODP

Workshop Report). Furthermore, they may provide a model for emplacing some alpine-type ultramafic bodies (common in accreted terrains) pre- rather than syn/post-collision.

Subduction Erosion

The imbricate thrust model of sediment accretion to the trench inner wall (Karig, 1974; Seely et al., 1974) was shown by deep sea drilling to be inapplicable to many intra-oceanic and other arc-trench systems characterized by thin sediments on the subducting plate (e.g., Hussong and Uyeda, 1981; Auboin et al., 1984). The drilling data were interpreted as evidence for large-scale subduction erosion of the trench slope. Two mechanisms for this erosion have been published. Auboin et al. (1984) have proposed a convergent-extension model whereby the slope is under tension and collapses by slumping/listric faulting into the trench axis. Hilde (1983) proposed that, where trench sediment volumes are small compared to the volumes of grabens that are being subducted, any accreted sediments will slump into the graben and be subducted. Furthermore, the base of the landward trench slope would bulldoze sediment from the tops of horst blocks and redeposit it into the adjacent graben. However, Shipley and Moore (1986a and b) and Moore et al. (1986) have shown that, in two areas of the Middle America Trench off Costa Rica and Guatemala, large-scale slumps are not active, and trench sediment fill is sufficient to bury the 100 to 200 m high horst blocks, effectively isolating them from the overriding plate.

In contrast, in the Bonins the horst blocks are much higher and most of the sedimentary cover has been eroded from the steep slopes of the trench inner wall (Figures 3, 12, 16, and 19). Presumably this material has been subducted beneath the forearc because, although there appear to be small accretionary complexes along parts of the basal slope, their volume is trivial compared to the amount of sediments removed. Potentially, therefore, the Bonins is an excellent region to see the process of subduction erosion in operation -- indeed Hilde (1983) considered it a type area. However, as previously discussed, there is evidence to suggest long-term stability of the Bonin forearc, and hence net steady-state sediment subduction, rather than subsidence and erosion. Better imaging of the trench landward slope is required to determine which model is appropriate.

PROPOSED RESEARCH

We propose to conduct an MCS survey of the Bonin intra-oceanic arc-trench system at 31-32°N. This is the region of proposed ODP drilling to address the processes of arc rifting, forearc development (magmatism, structure, stratigraphy and vertical tectonics), and outer forearc diapirism. These processes are major thematic objectives that the Lithosphere and Tectonics panels of ODP would like to see addressed by drilling in the western Pacific (see Appendix A). The Western Pacific Panel of ODP at its August 1985 meeting voted Bonin drilling its coequal first priority, and at its February 1986 meeting recommended that 1-2/3 legs of a nine-leg drilling program in the western Pacific be devoted to it (WPAC minutes). The Planning Committee at its late May meeting approved WPAC's nine-leg program as the basis for continuing planning (Larson, pers.

comm). Our survey would serve as both a site-specific and regional survey (Figure 20).

Site-Specific Objectives: to clearly image the seismic stratigraphy and basement morphology of the arc-trench system in order to:

a) allow optimum location of sites (where thematic objectives could be met with minimum drilling)
b) provide accurate estimates of velocities, depths, and drilling times, and
c) provide crossing MCS profiles for safety panel evaluation.

Regional Objectives

1) To determine how arc lithosphere rifts: does extension occur via normal slip on low-angle detachment surfaces or by overall stretching and thinning?

Major testable differences between the two models include a lateral offset in the locus of maximum crustal vs. mantle thinning in the detachment model, likely resulting in structural asymmetry and the presence of transfer zones linking master faults of opposing asymmetry along strike. de Voogd et al. (1986) recently used COCORP MCS data to reveal the presence of a listric master fault bounding the eastern side of the Albuquerque Basin of the Rio Grande Rift.

2) To determine the nature and evolution of the arc/forearc basement.

a) What proportion of the forearc is preexisting oceanic crust, how much was constructed by initial Eocene arc volcanism, and has there been subsequent forearc spreading or other volcanism?

b) What is the crustal structure across the forearc and how does it compare to that of ophiolites?

The main observational constraints on these questions will be the reflection character, internal layering, and velocity-depth structure of the basement. We do not pretend that we will be able to directly answer the first question, but variations in the above three parameters should allow us, for example, (i) to determine if there is a thin carapace of arc basalts overlying oceanic crust, (ii) to determine if there are major different crustal types beneath the frontal arc, forearc basin, and outer-arc high, and (iii) to define the areal extent of different basement types determined by drilling.

c) What is the differential vertical motion history and flexure of the forearc?

Seismic stratigraphic analysis of the grid of MCS profiles linking the drill sites will allow site-specific sedimentary and uplift/subsidence histories to be extended regionally. Furthermore, the geometry of basement and sedimentary horizons (including onlap and other unconformable relationships) will provide direct evidence of the flexural response of the forearc lithosphere to applied loads, and indirect evidence of its varying thermo-mechanical state through time (e.g. ten Brink and Watts, 1985). The seismic stratigraphy, together with existing gravity and geoid data, will provide tight constraints on flexural models of forearc evolution which we will undertake in cooperation with Gary Karner and Jeff Weissel at Lamont. Questions which we will address in the modelling include: (i) is the forearc basin a flexural moat with respect to the line load of the arc volcanoes? (ii) has the flexural response changed from that of a continuous elastic plate to that of a cantilevered beam due to the rifting of the arc? (iii) is the outer arc high a flexural bulge maintained by outer forearc coupling to the subducting plate?

d) What controls the systematic mass wasting of the forearc, in particular the timing and locus of canyon formation?

Single-channel seismic data suggest that canyon locations are not structurally controlled in the forearc basin (e.g., Figure 10). However limited seismic data along the outer-arc high suggest that canyons, nucleated on the lower slope, first breached the outer-arc high at relative low points along its length, and that these locations provided the starting points for subsequent headward erosion into the forearc basin sedimentary sequence (e.g., Figure 16b). We will test whether these relationships hold true for Aoga Shima canyon by making several N-S MCS crossings of the canyon system, from the outer-arc high to the upper forearc (Figure 20). The maximum age on canyon cutting will be found by determining the deepest stratigraphic level that the canyon erodes.

3. a) To determine the structure of the lower slope terrace and the domes along it.

Are these domes, from which chloritised/serpentinised mafics and ultramafics have been dredged, similar to the serpentinite diapirs in the Marianas, or are they local highs along a lower slope completely remobilized by subduction-related dewatering (Fryer et al, 1985a)? The external morphologies and (lack of) internal structure of diapirs is well known and easily recognized (e.g., Jackson and Talbot, 1986). Our survey will provide the first MCS images along and across these features.

b) To determine whether subduction erosion is occurring, and if so, by what mechanism.

Subduction erosion would have predictable manifestations on the lower trench slope. Both Hilde's (1983) saw-tooth model and Auboin et al.'s (1984) convergent-extension model would predict the presence of large-scale slumps and listic faults if the lower slope is eroding. Hilde's model however would predict their presence only when a graben is beneath the lowermost slope. Furthermore, Hilde's model would suggest that sediments should be sheared off the top of horst blocks as they encounter the base of the trench slope, whereas Auboin et al. suggest that the overriding plate is largely decoupled from, and would probably not influence, the subducting plate. If subduction erosion is not occuring then, although the lower slope may be normally faulted, there should be no evidence of major lower slope collapse.

DATA ACQUISITION

To determine the seismic stratigraphy, basement morphology, and crustal structure of the Bonin arc-trench system we propose to collect 2600 nm (4800km) of high-quality MCS data together with 40 to 50 long-range sonobuoy refraction lines. The proposed MCS tracks are shown in Figure 20. They include:

1) Seven E-W crossings of the arc and back-arc rifts: one line north of Tori Shima where the western horst is dominant, two lines near 31°N where the rift geometry is most symmetrical and bounded by a composite fault scarp on the east, one line south of Sumisu Jima where the eastern horst is dominant and bounded by two closely-spaced steep faults, one line north of Sumisu Jima where back-arc rifts are not yet developed, and two lines south of Aoga Shima where rift development is just beginning. These seven lines also cross the uppermost forearc in areas where frontal arc highs are both present and absent.

2) Three N-S crossings of the back-arc rift: one line along the crest of the eastern horst block, one line along the depocenter of the rift graben, and one line along the western outer rift traversing the cross fault and the proposed transfer zone. A fourth N-S line would connect the two frontal arc highs east of Sumisu Jima and Tori Shima.

3) One long N-S line in the forearc basin to tie the stratigraphy of the northern and southern transects.

4) Ten E-W crossings of the forearc. These include two transects of closely-spaced lines in the north (one along the deep Aoga Shima canyon system and one along the inter-canyon high adjacent Myojin Sho), and one transect of two lines near 31° N. The latter transect continues eastward to the trench outer bulge on the Pacific Plate. These lines also include eight crossings of the lower slope and trench, both directly over and between the lower slope domes, and also across the trench axis in areas of relatively thin and thick sediments and where both subducting horsts and graben intersect the lower slope.

5) Two long N-S lines along the lower slope terrace, one crossing the crests of the domes and one along their sedimented inner flank.

6) Five N-S lines spaced across the forearc from the outer-arc high to the upper forearc, traversing Aoga Shima canyon and the inter-canyon high adjacent Myojin Sho.

These tracks will provide over 60 MCS crossing points from which to choose ODP drill sites.

The sonobuoy refraction lines will be shot along the MCS lines, particularly on the N-S strike lines, but also on all the crossings of the forearc basin. Although each refraction line will not be reversed, lines on adjacent tracks will be shot in opposing directions, eliminating the possibility of not recognizing regional dip. We recognize that a two-ship program collecting expanding spread profiles (ESP's) would better image the deep crustal structures. However, we believe that such expensive programs are better run after MCS reflection and sonobuoy refraction data have first been anlyzed, rather than going into an area blind.

We have requested 28 days of ship time from U.T. Austin on the R/V FRED MOORE from Yokohama to Yokohama in 1987. This includes 22 days of MCS data collection (2600 nm at 5 knots), 1 day of MCS deployment/retrieval/

contingency, 2 days of transit and 3 port days. A description of the MOORE's technical capabilities is included as Appendix B. Particularly important for our seismic experiment are the

1) GPS and Loran-C navigation system
2) 2 x 30 m tuned sub-arrays of six air guns, totalling 2130 in^3
3) The compressor capacity (1200 scfm at 2000 psi) to fire these arrays every 8 seconds (we will only need rep rates of ~13 seconds).
4) Litton 96-trace, 3200 m LRS streamer (33 1/3 m groups) with Syntron depth control and compass system.
5) GUS 4200 seismic recording system with realtime demultiplexing and 6250 bpi, SEG-D recording.

We will use this system to collect 96-channel, 48-fold, 2-ms data with generally 8-second record length (plus water column delay).

Taylor and Moore are both experienced at shipboard MCS operations and will be jointly responsible for at-sea operations. Taylor has ongoing cooperative projects with Japanese scientists at the Ocean Research Institute and Geological Survey of Japan and, as when previously operating in Japanese waters, will invite one participant from each institution.

DATA PROCESSING AND INTERPRETATION

All MCS reflection processing will be done at the University of Tulsa under the direction of Moore. Because of the complex structures we plan to image, migration is essential. Depth conversion is also necessary for proper structural interpretations.

The Tulsa processing system is based on a VAX11/750 and uses PHOENIX processing software from Seismograph Service Corporation. The system was configured by SSC and also includes a CSPI MAP-300 array processor, three tri-density Telex tape drives, and a 22-inch 100 dot/inch Versatec plotter. SSC is a Tulsa-based company and, therefore, excellent software and hardware support is always readily available. In addition, we can use SSC's 36-inch 200 dot/inch Versatec plotter for a nominal charge. Final film plots will be generated on SSC's Geospace camera plotter.

The 33-1/3 m section spacing of the streamer means that the CDP interval will be ~16.7 m (111 CDPs per mile). The following processing sequence will be performed on the demultiplexed 2 ms, 96-channel, 48-fold data:

1. Edit bad traces
2. CDP sort and plot near trace section
3. Velocity analysis (at least 1 per 40 CDPs)
4. Deconvolution
5. Apply NMO
6. Mute
7. Stack (48-fold)
8. Filter
9. Scale
10. Plot
11. Finite Difference Migration (at least 75% of all data)
12. Depth Conversion (selected portions of the data)

Another Tulsa-based company, Geoscan, Inc., will install a SAXPY 1-M supercomputer in late 1986. Geoscan plans to have their migration before stack (MBS) and depth migration programs running on the SAXPY by the end of 1987. Although CPU charges have not been set by Geoscan, they expect to charge less than 20% of typical CRAY CPU charges, even though the SAXPY is a faster machine. Geoscan has agreed to give T.U. geosciences personnel access to their software at reduced rates. We plan to run MBS and depth migration on critical portions of the data.

Data reduction, modeling, and interpretation of the refraction data will be done at HIG by Patricia Cooper, a marine seismology post-doc. Initial velocity-depth interpretation to feed back into the Tulsa MCS stacking will be done using standard travel time/amplitude analysis with the aid of 2-D ray tracing (e.g., Ambos and Hussong, 1985). For areas of complex structure, 2-D full waveform reflectivity modeling developed by Neil Frazer will be applied. The results will be available to input into the MCS migration and depth conversion in 1988. Computer codes for all these methods are implemented on the HIG Harris computer and Floating Point System array processor, as well as through the HIG RVAC to the San Diego Supercomputer.

Integrated data interpretation and final report writing will be carried out jointly by Taylor and Moore with due regard to the extensive existing data sets, including SASS and SeaMARC II. They (and their students) will divide the effort thematically, with Taylor taking the lead on arc rifting, Moore being primarily responsible for outer forearc tectonics, and both jointly interpreting forearc development. Taylor will undertake the forearc flexural model studies in cooperation with Gary Karner and Jeff Weissel at Lamont during part of his 1988 sabbatical.

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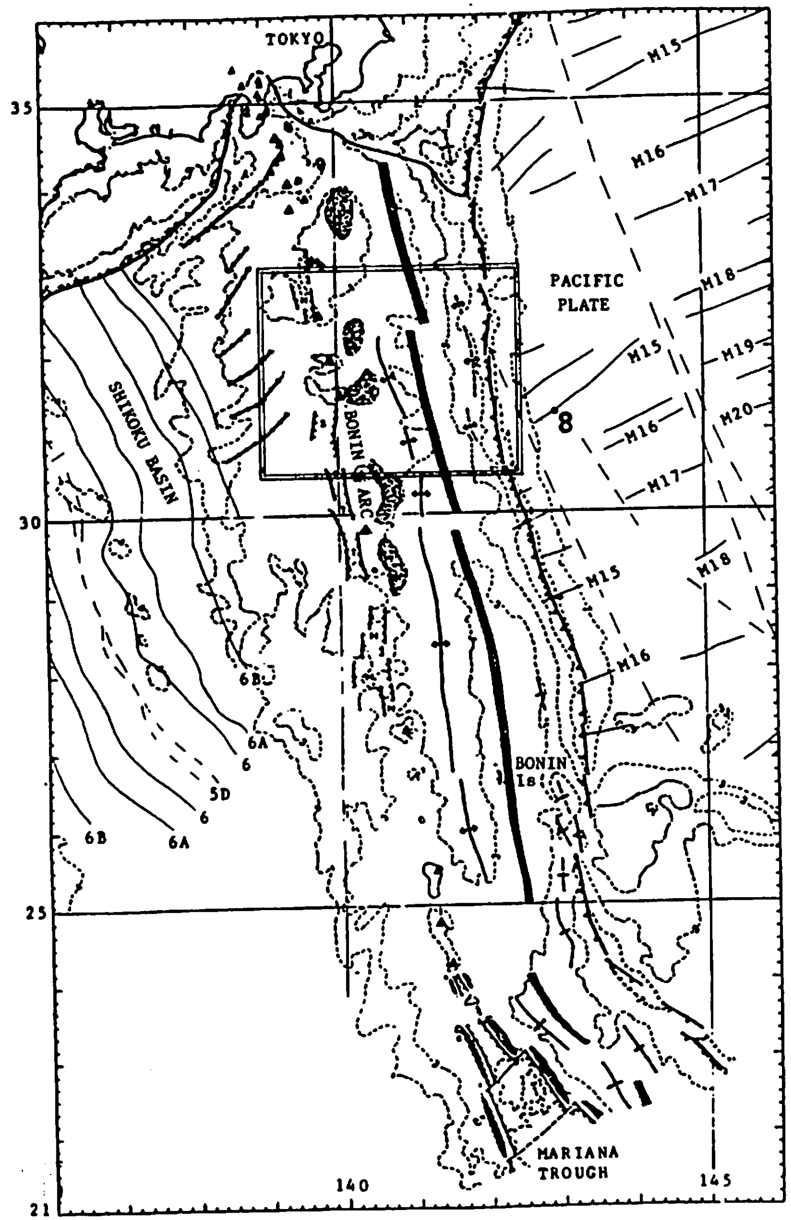


Figure 2a. Tectonic elements of the Bonin arc-trench system (modified after Honza and Tamaki, 1985).

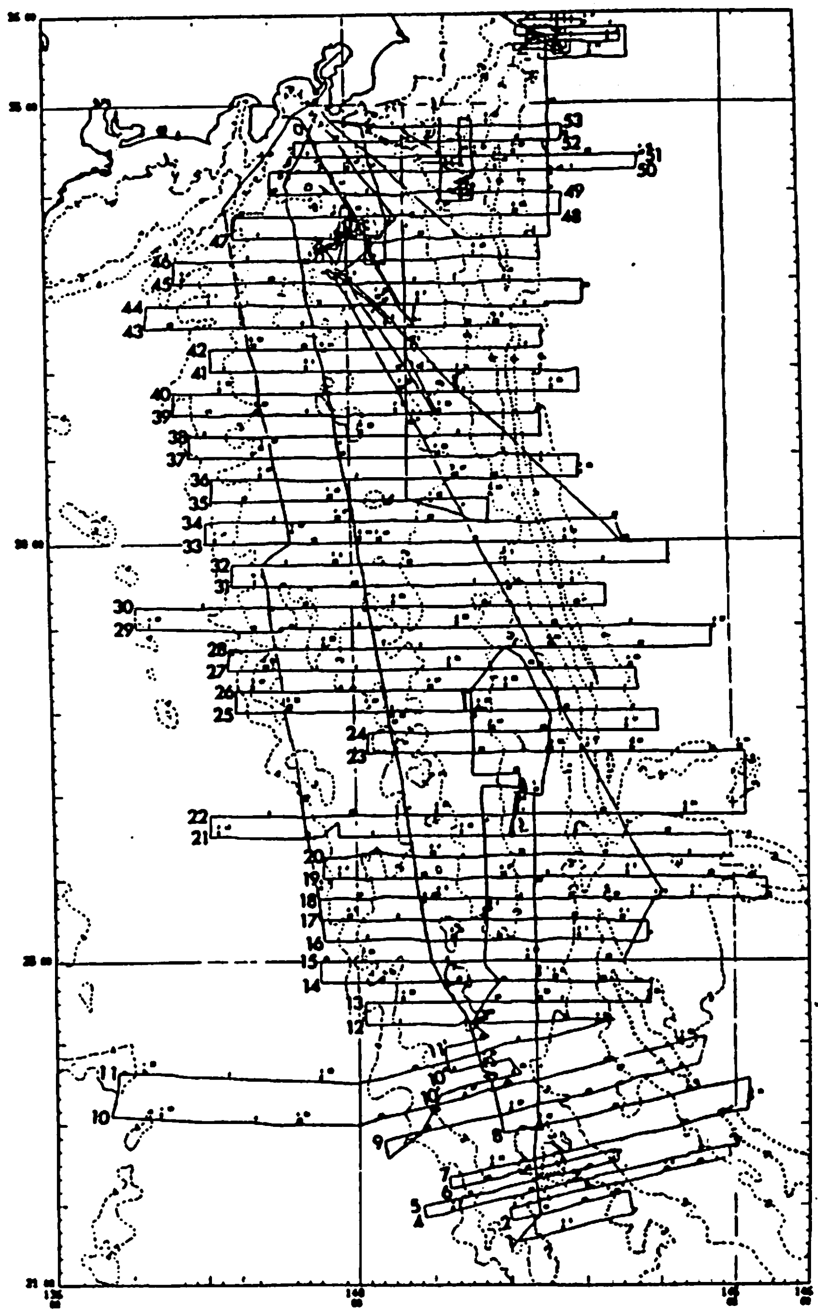


Figure 2b. Survey tracks by the Geological Survey of Japan (GH79-2, 3, 4, and GH80-3 cruises of R/V Hakurei Maru).

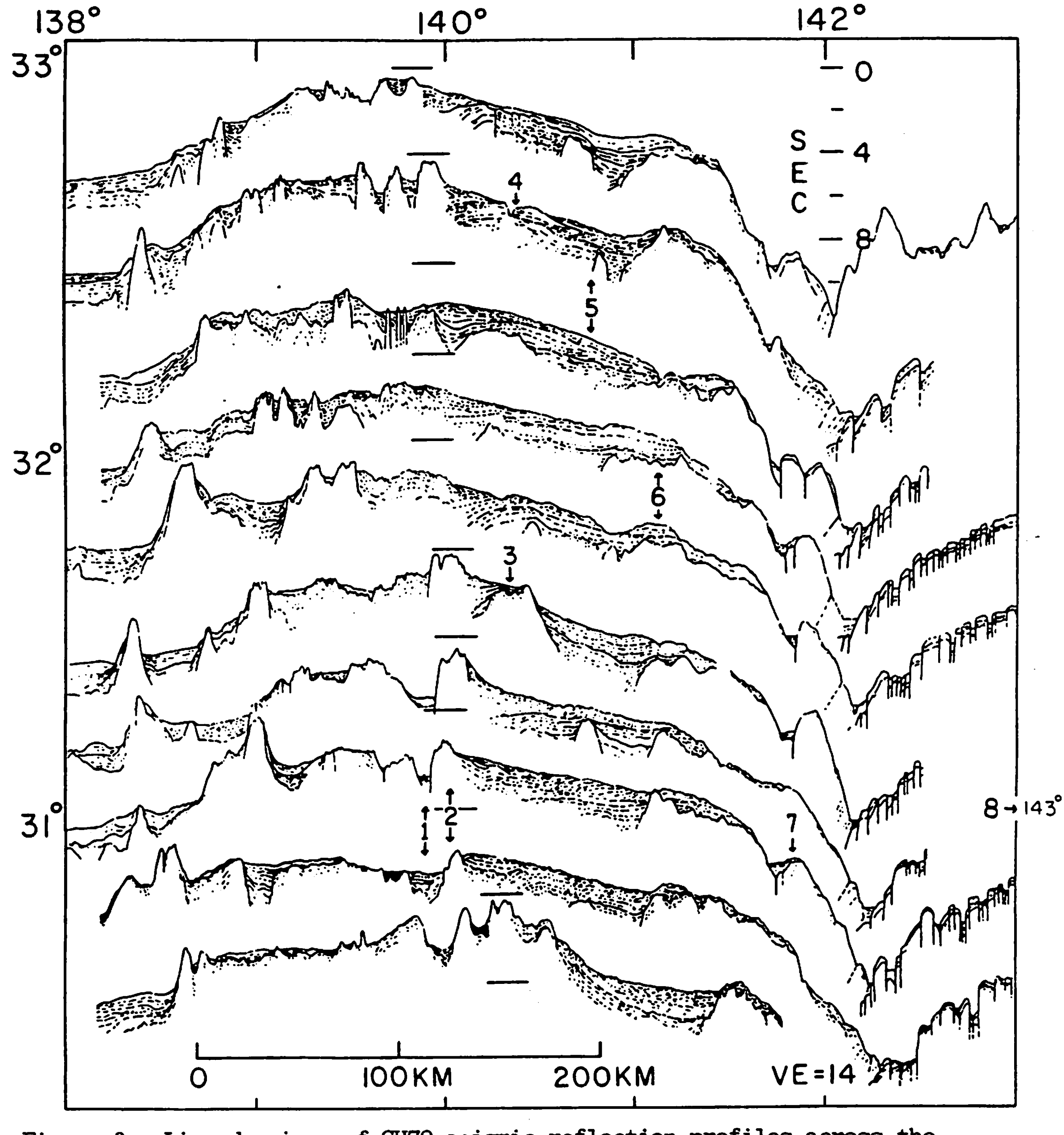


Figure 3. Line drawings of GH79 seismic reflection profiles across the Izu Arc-Bonin Trench system between 30.5° and 33° N(Honza and Tamaka, 1985). From east to west, the characteristic structural elements of this active margin include: (a) a lower slope terrace on the trench inner wall, (b) a thick 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 eight proposed ODP sites on or between the seismic lines are indicated by single or double arrows respectively.

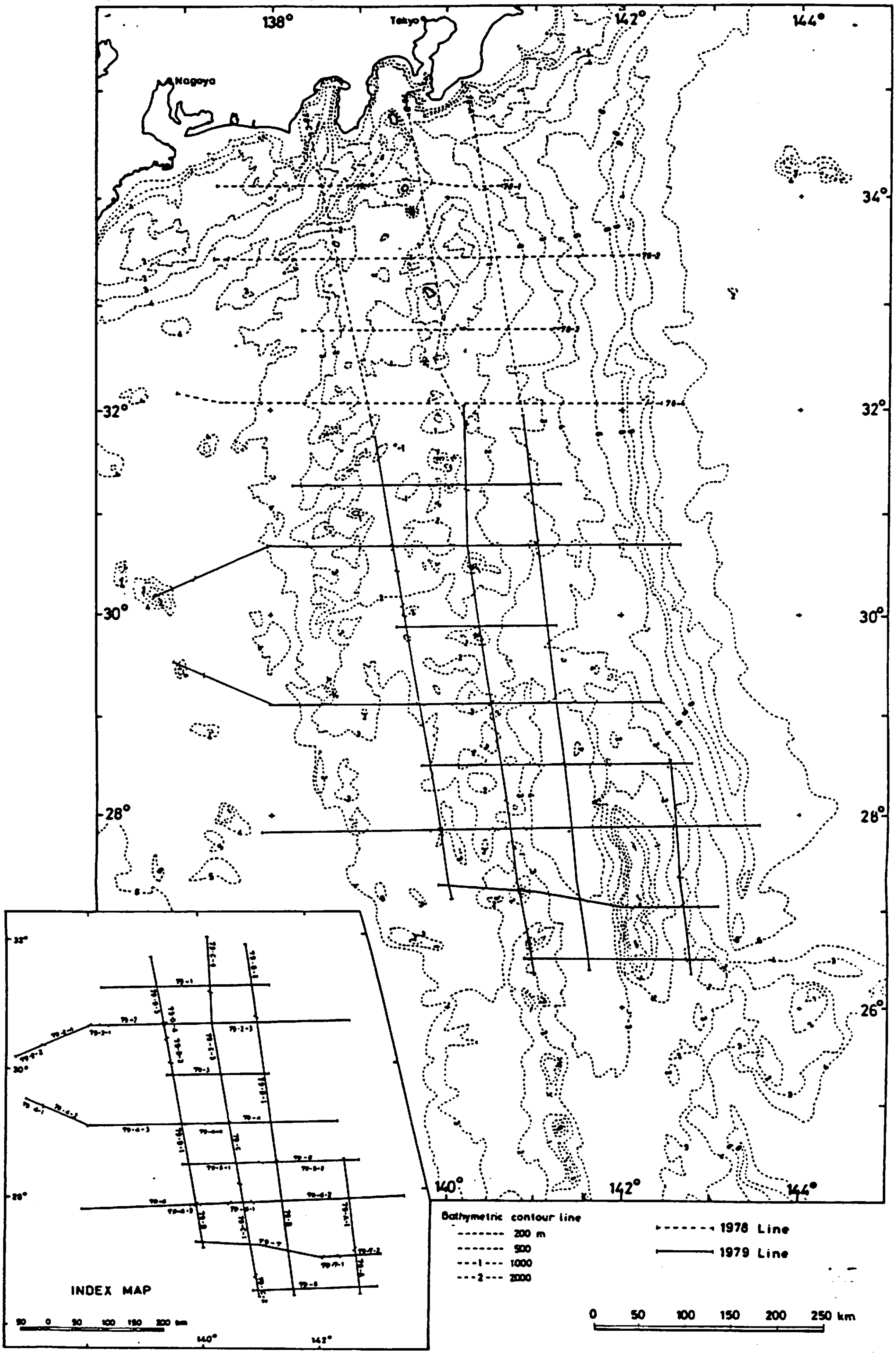


Figure 4. Japan National Oil Co. multichannel seismic lines in the Bonin region.

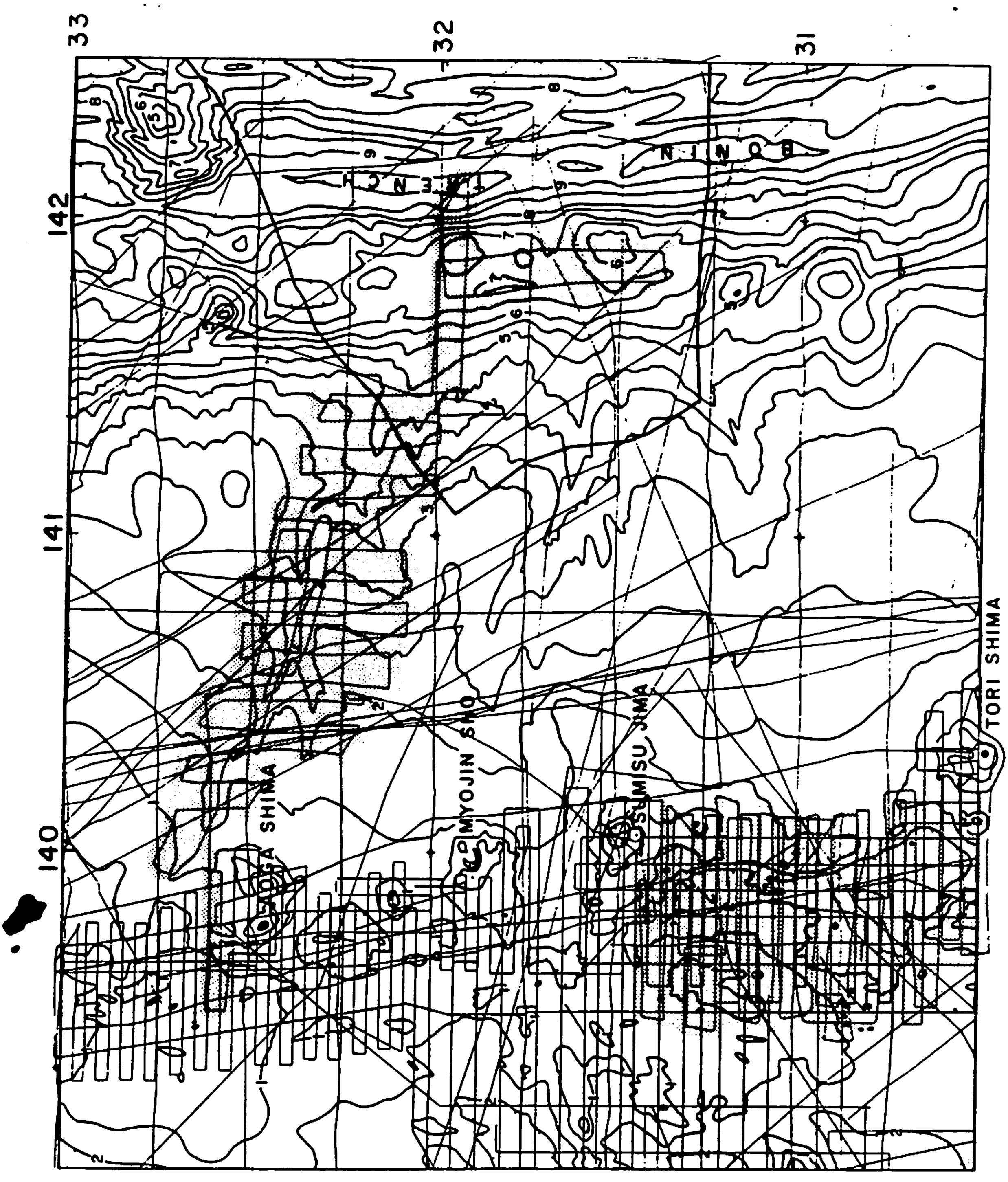


Figure 5: Bathymetry (500 m contours) and marine geophysical ship track coverage of the Bonin transect region. Aoga Shima Canyon, Sumisu Rift and the three lower slope domes south of 32°N have complete SeaMARC II coverage (stippled). The heavy track line locates C2005 MCS. JNOC MCS tracks are not shown.

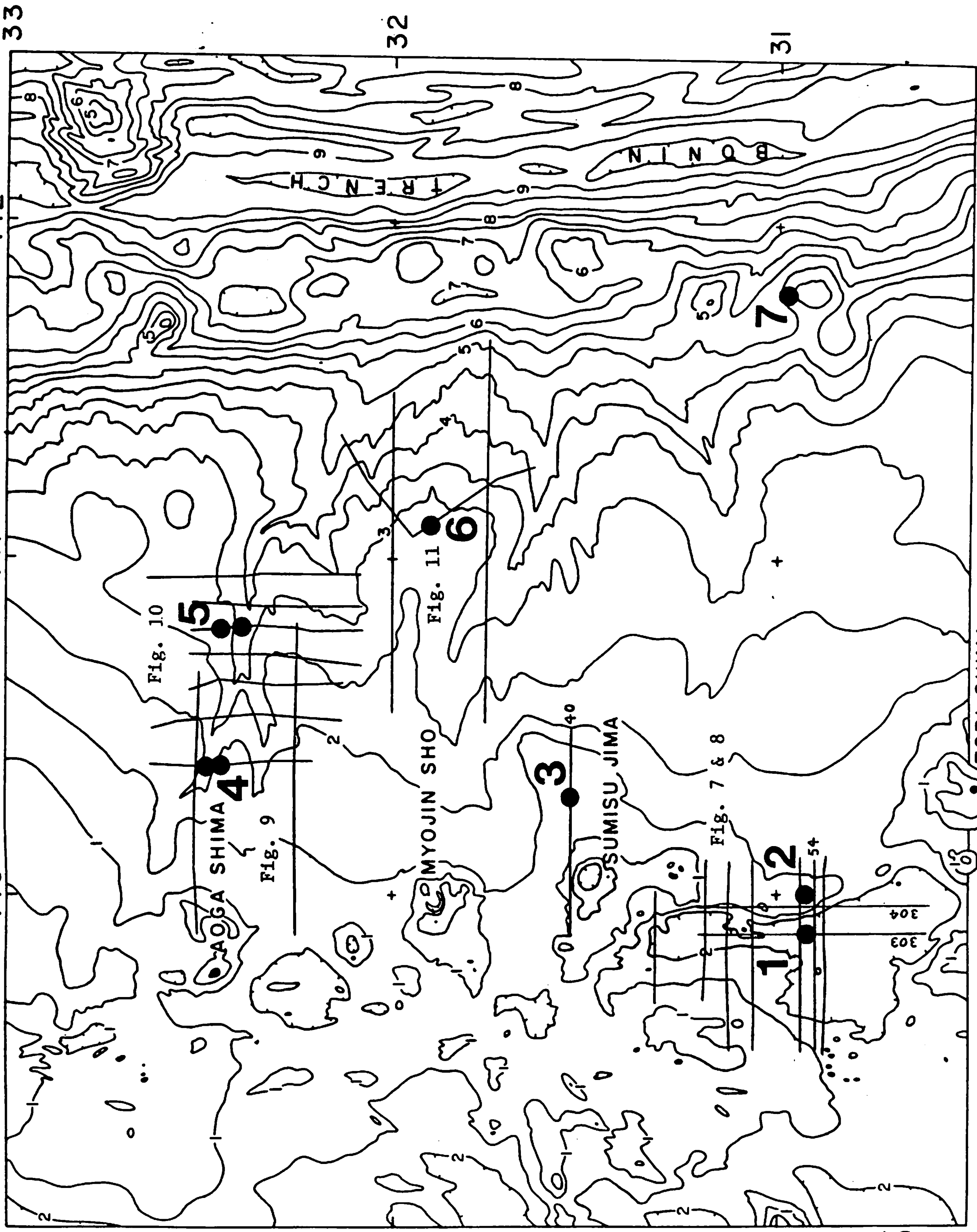


Figure 6. Location of proposed Bonin sites 1-7 together with those track segments whose seismic sections are illustrated in Figures 7-11.

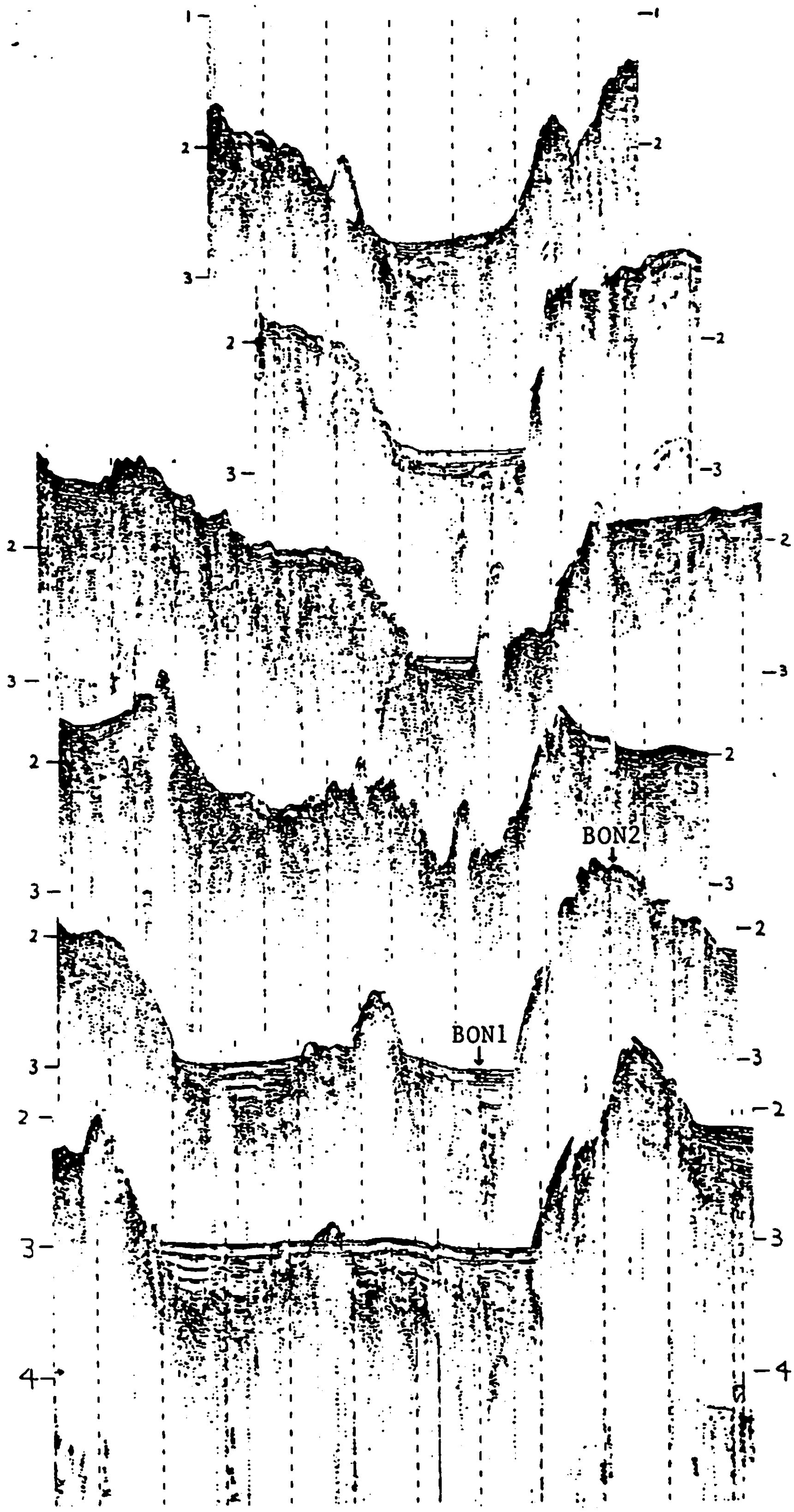


Figure 7. Geological survey of Japan unpublished seismic profiles across the Sumisu rift. V.E.≈14

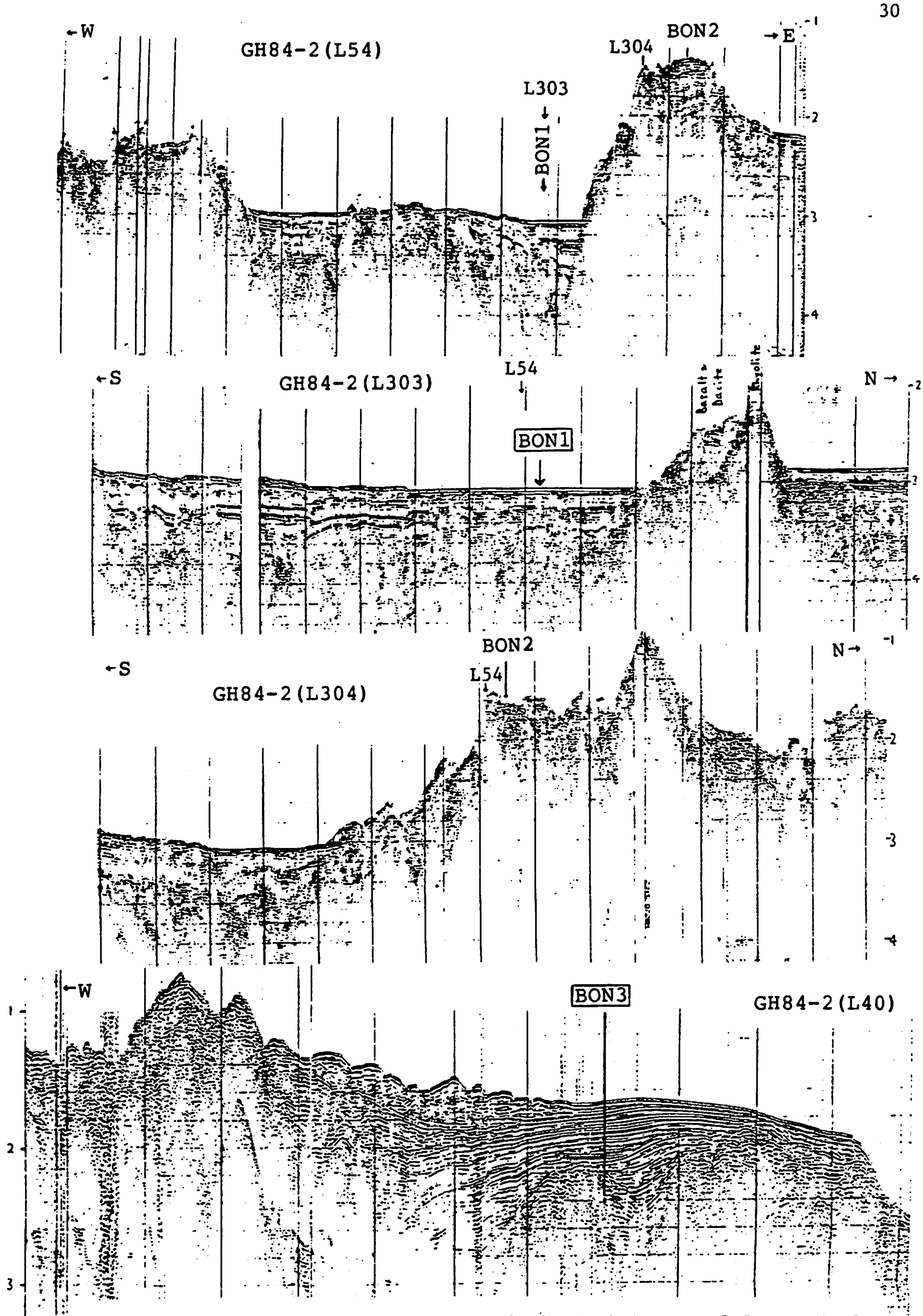


Figure 8. Sites BON 1 to 3 on or near Geological Survey of Japan single channel seismic profiles (located in Figure 6).

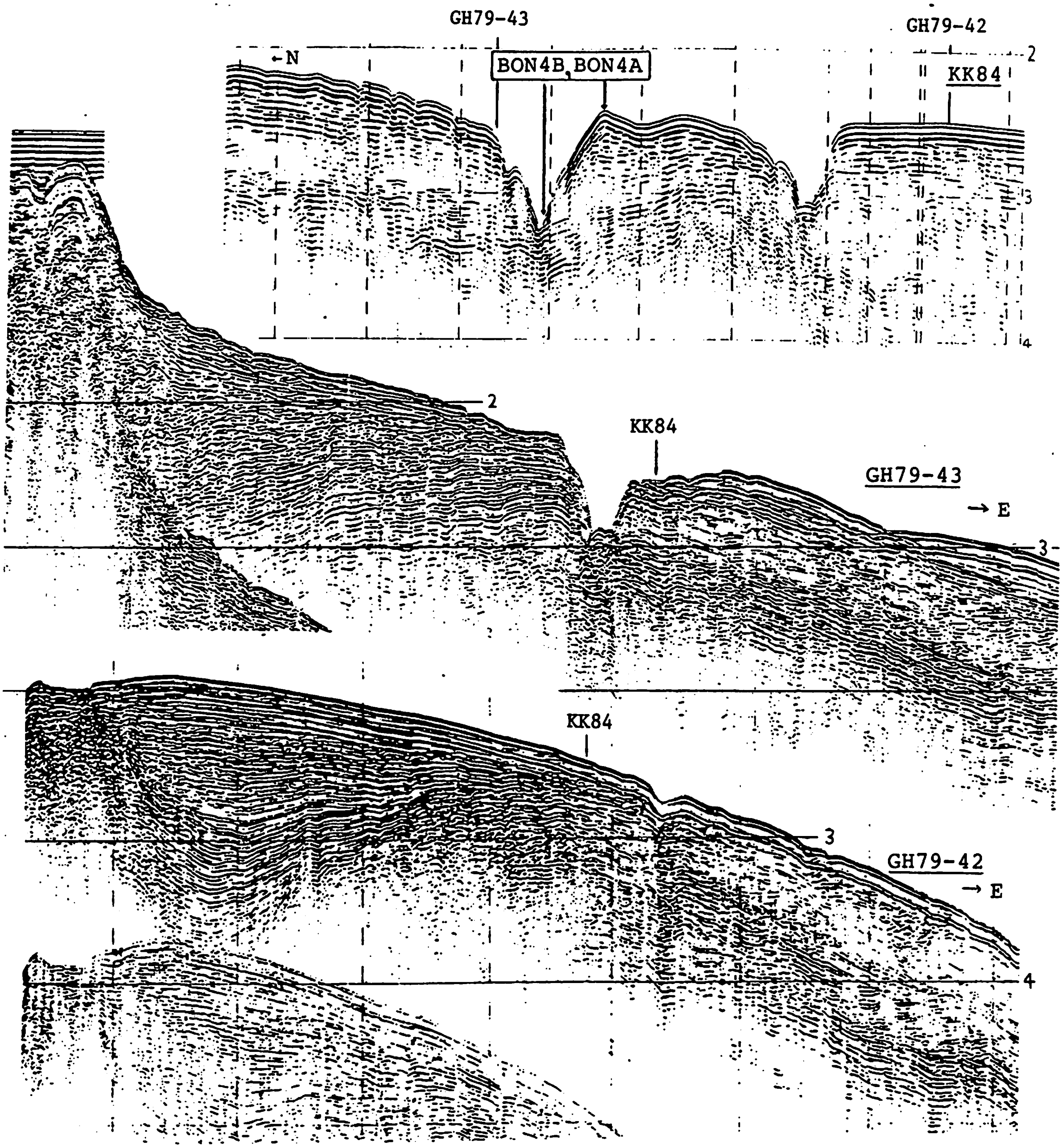


Figure 9. Sites BON 4A to 4B on HIG and between GSJ single channel seismic profiles (located in Figure 6).

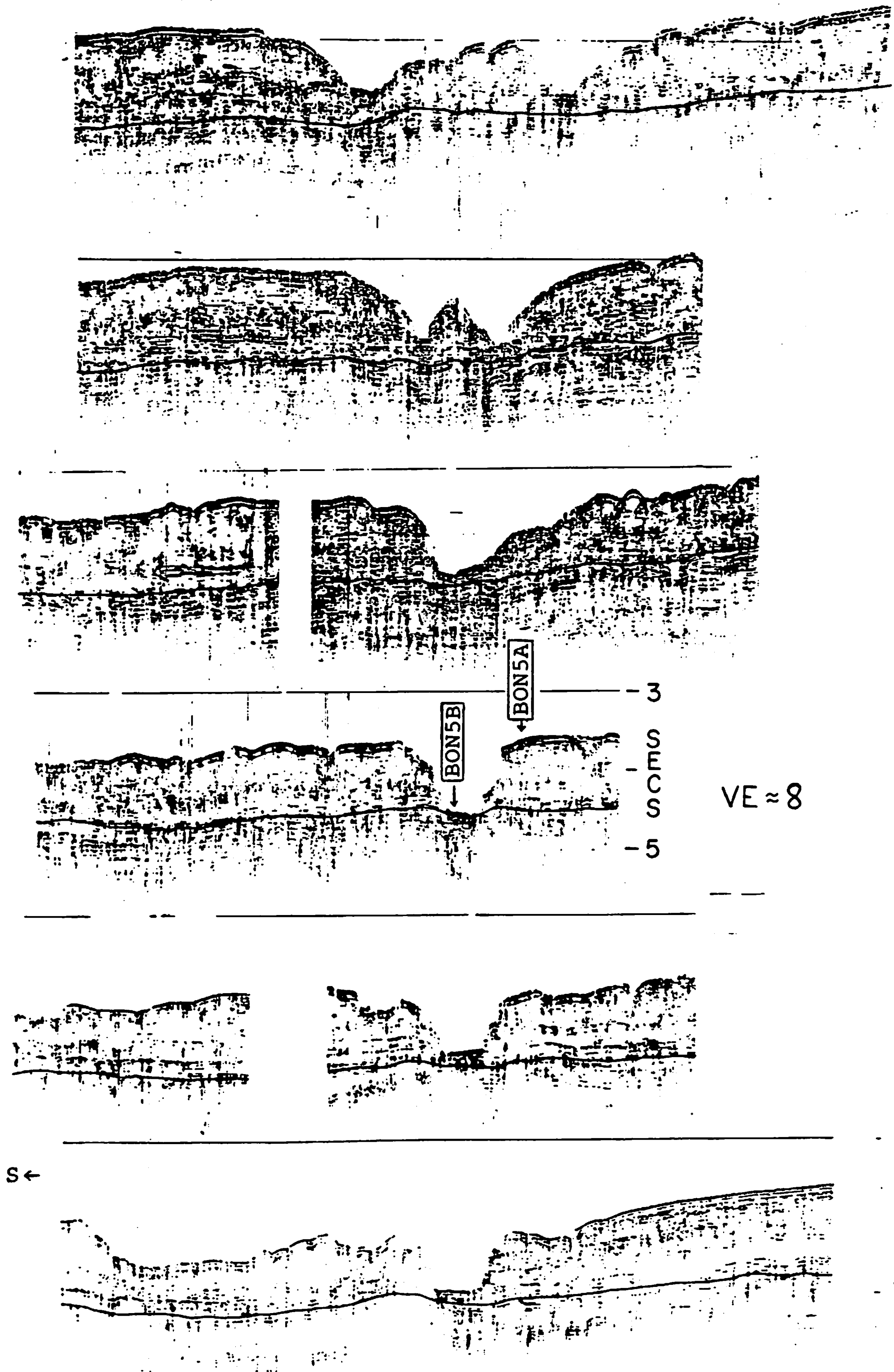


Figure 10. Sites BON 5A and 5B on HIG small volume, single channel seismic profiles (see Figure 6 for location). JNOC MCS line 78-A crosses these sites.

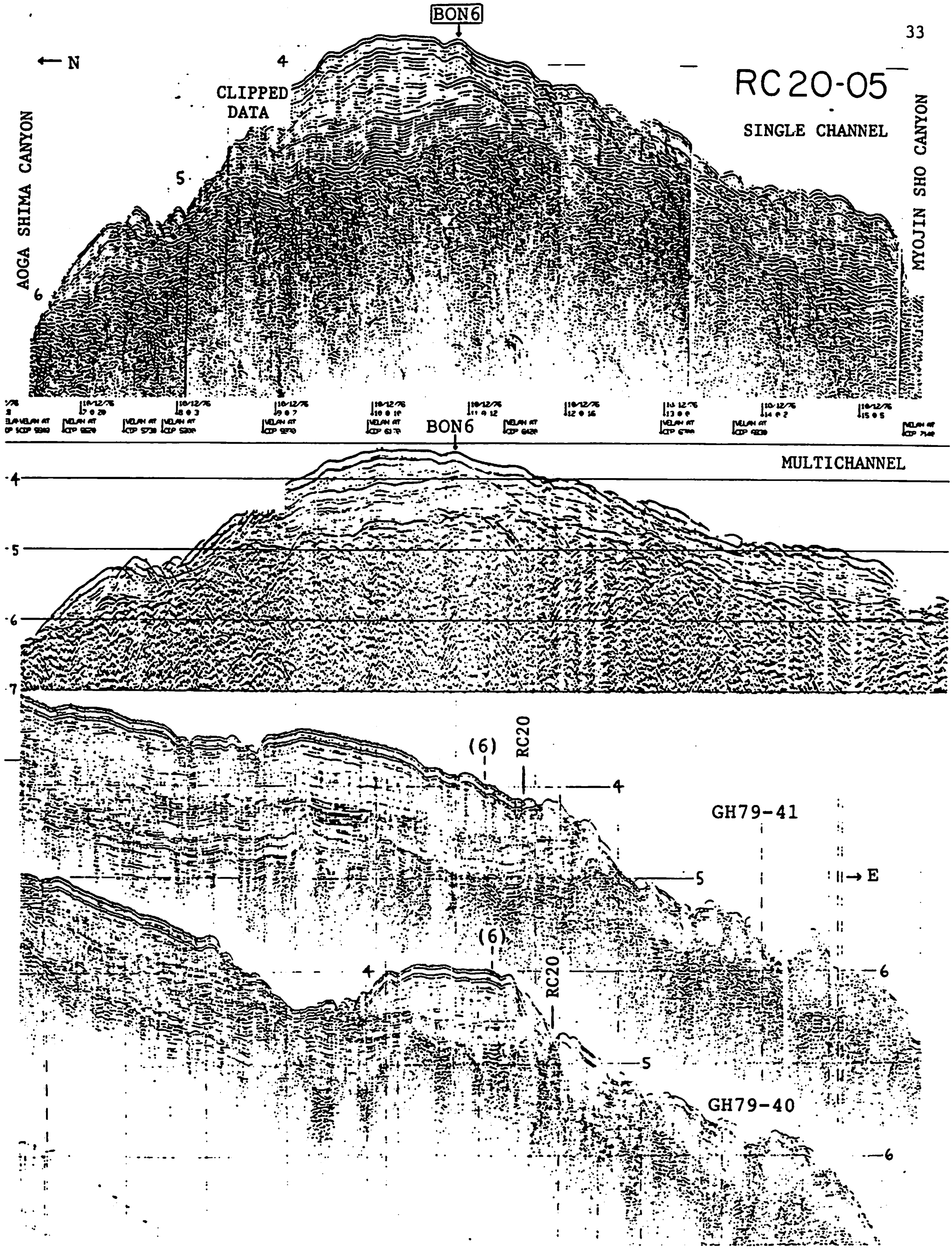


Figure 11. Site BON 6 on LDGO single and multichannel seismic profile RC20-05, and between GSJ single channel seismic profiles GH79-40 and 41.

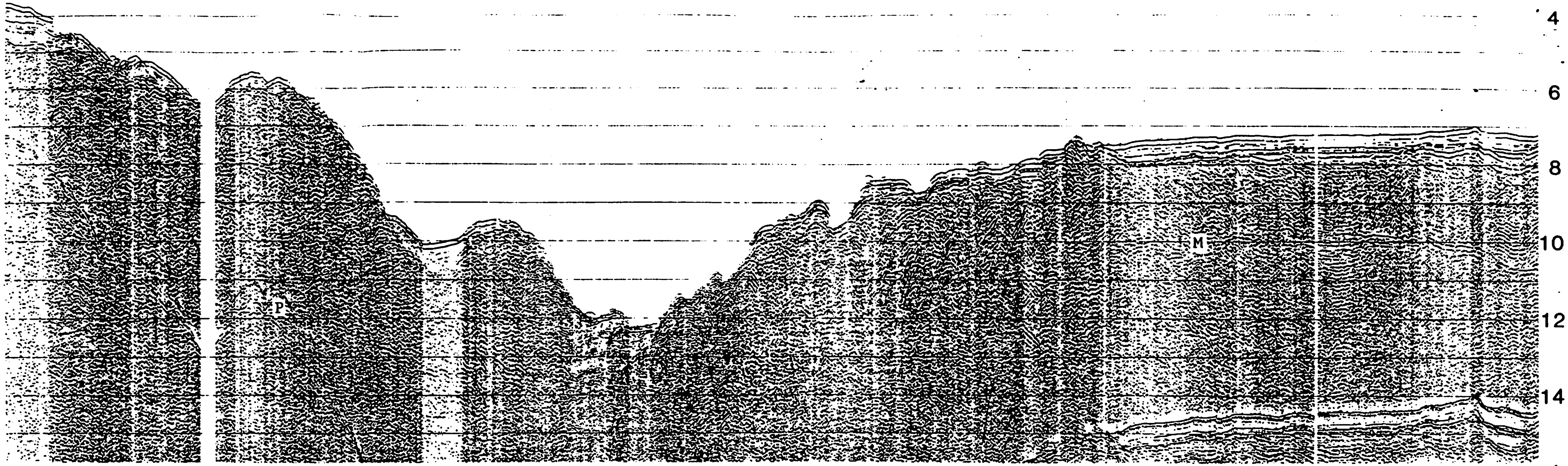
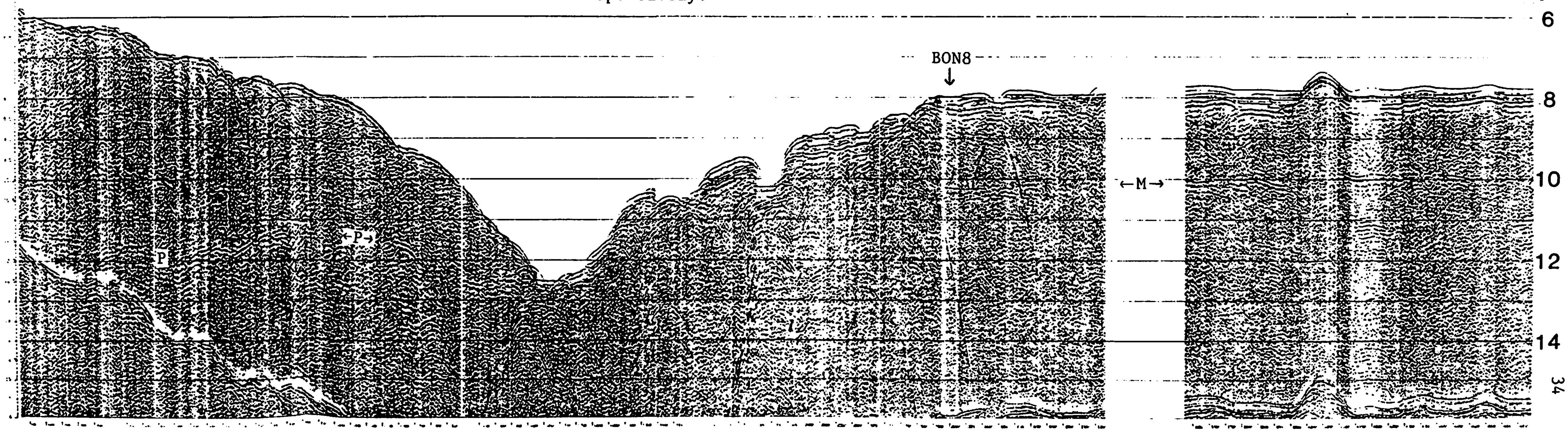


Figure 12. R/V CONRAD 2005, 24-fold stacked MCS profiles across the Bonin Trench (see Figure 5 for location). Unpublished data courtesy of Peter Buhl, LDGO. Reflections from Moho and the top of the subducting plate are labelled M and P respectively.



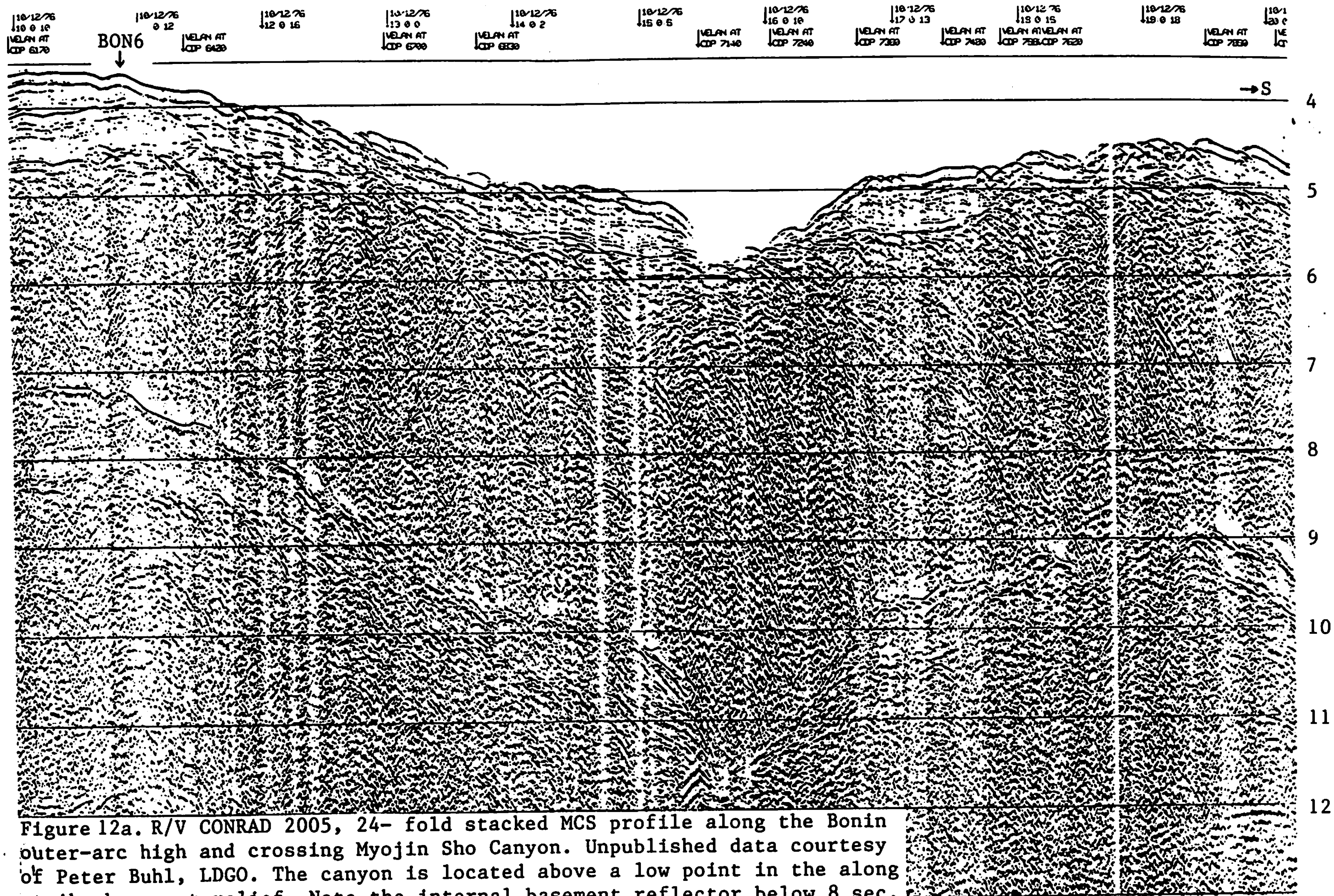


Figure 12a. R/V CONRAD 2005, 24- fold stacked MCS profile along the Bonin outer-arc high and crossing Myojin Sho Canyon. Unpublished data courtesy of Peter Buhl, LDGO. The canyon is located above a low point in the along strike basement relief. Note the internal basement reflector below 8 sec.

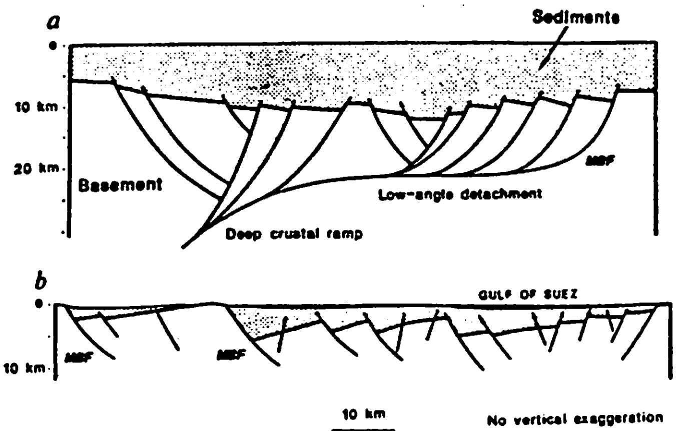


Fig. 1 Asymmetry of continental rifts in cross-section. Rifts commonly show half-graben-like forms in cross-sections taken normal to their long axes, with most basin relief generated by a single rift bounding fault (main bounding fault, MBF), or a system of a few main faults, which are inferred to bottom out to a low-angle detachment surface. *a*, Central Graben, North Sea, section (a submerged continental rift) is an approximate depth conversion of a time section presented by Gibbs[23]. *b*, Section crossing southern Gulf of Suez, constructed from industry well and seismic data.

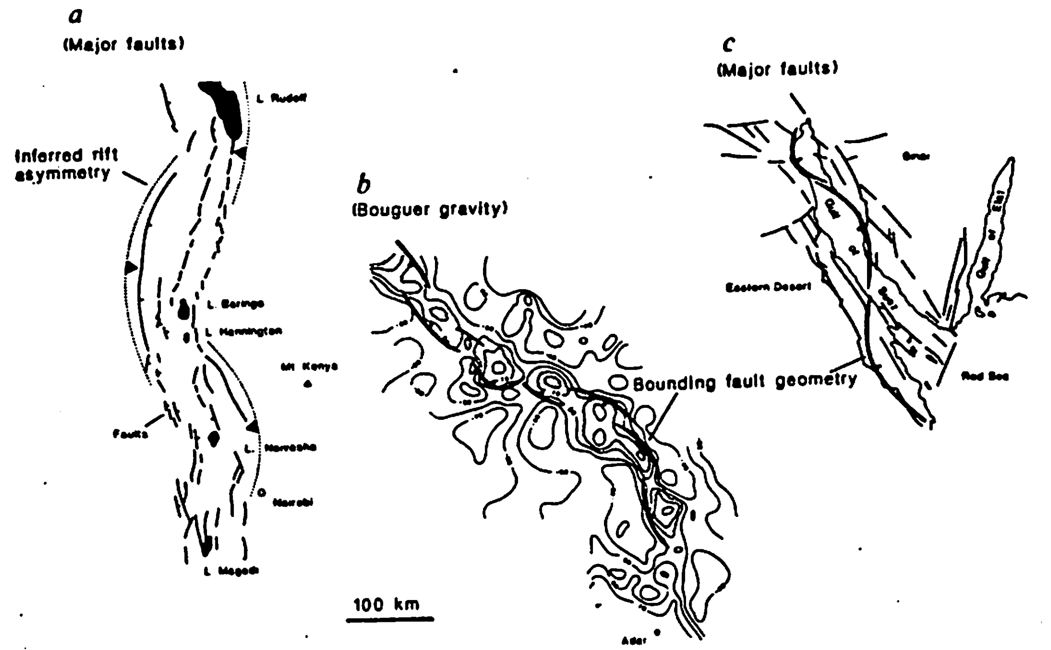


Fig. 2 Geometry of continental rifts in plan view. The major faults of continental rifts follow curvilinear patterns in map view, defining a sub-basin geometry that repeats generally every 50-150 km. Similar curvature is seen in the bounding faults of the Basin and Range Province[44]. The asymmetry of the rifts in cross-section commonly reverses at each successive sub-basin, although not in every case. *a*, Gregory Rift, Kenya. Surface traces of major faults are from ref. 45. *b*, White Nile Rift, Sudan. Gravity data are from ref. 19. *c*, Suez Rift, Middle East. Surface faulting from ref. 17. Sub-basin geometry in the Gregory Rift (*a*) is more complex than portrayed here.

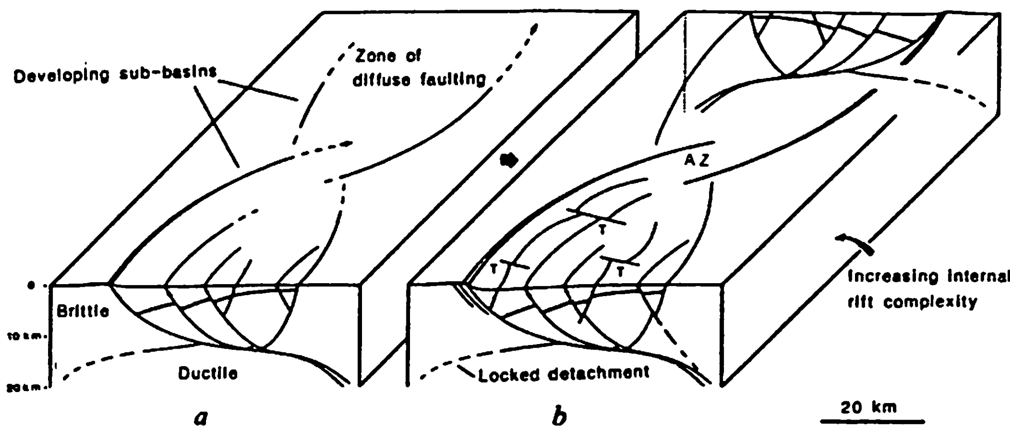


Fig. 4 Proposed model for the propagation of continental rifts. Upper crustal extension may initiate as a broad zone of diffuse faulting (*a*), but quickly evolves to a system composed of a few main listric faults (and perhaps in some cases planar fault-bounded blocks[35]) above two oppositely-directed detachments. For both detachments to remain operative, their deeper sections would need to be repeatedly recut, due to their mutually offsetting geometry. This rarely occurs, judging from the observed asymmetry of most continental rifts (Fig. 1), and one detachment locks. The active detachment propagates along the rift axis (towards the pole of opening), but curves inwards to form a large-scale scoop-like structure[44]. A theoretical treatment of this fault propagation would have to consider how this entire structure evolves—both the growth of the near-surface high-angle faults and the lateral propagation of the shallow-dipping detachments. Eventually the curving, active listric system departs enough from the overall rift trend to favour a new detachment system, which links to the old at a complex area referred to by Derksen and others[39] as an 'accommodation zone' (AZ). Again, opposing detachments may initially form, and the advantage may go to the detachment of opposite polarity. In this case, a reversal of rift asymmetry occurs, with greater down-faulting and sedimentation adjacent to the new main bounding fault (*b*). Detachment systems may overlap or merge at accommodation zones in a variety of configurations, but in the plan view shown here, a cross-section normal to the rift axis at the accommodation zone would actually appear to be a symmetric graben in form[39]. The important cross-faults in rifts referred to by Gibbs[23] as 'transfer faults' (T) are kinematically similar to accommodation zones, on a smaller scale.

Figure 13. Figures from Bosworth(1985) illustrating the three dimensional geometry of continental rifts inferred to have formed above detachment surfaces.

Figure 14a. Structural provinces and SeaMARCII bathymetry (100 m countours) of the Sumisu rift. The focal mechanism is of a 1976 M_b = 5.7 earthquake.

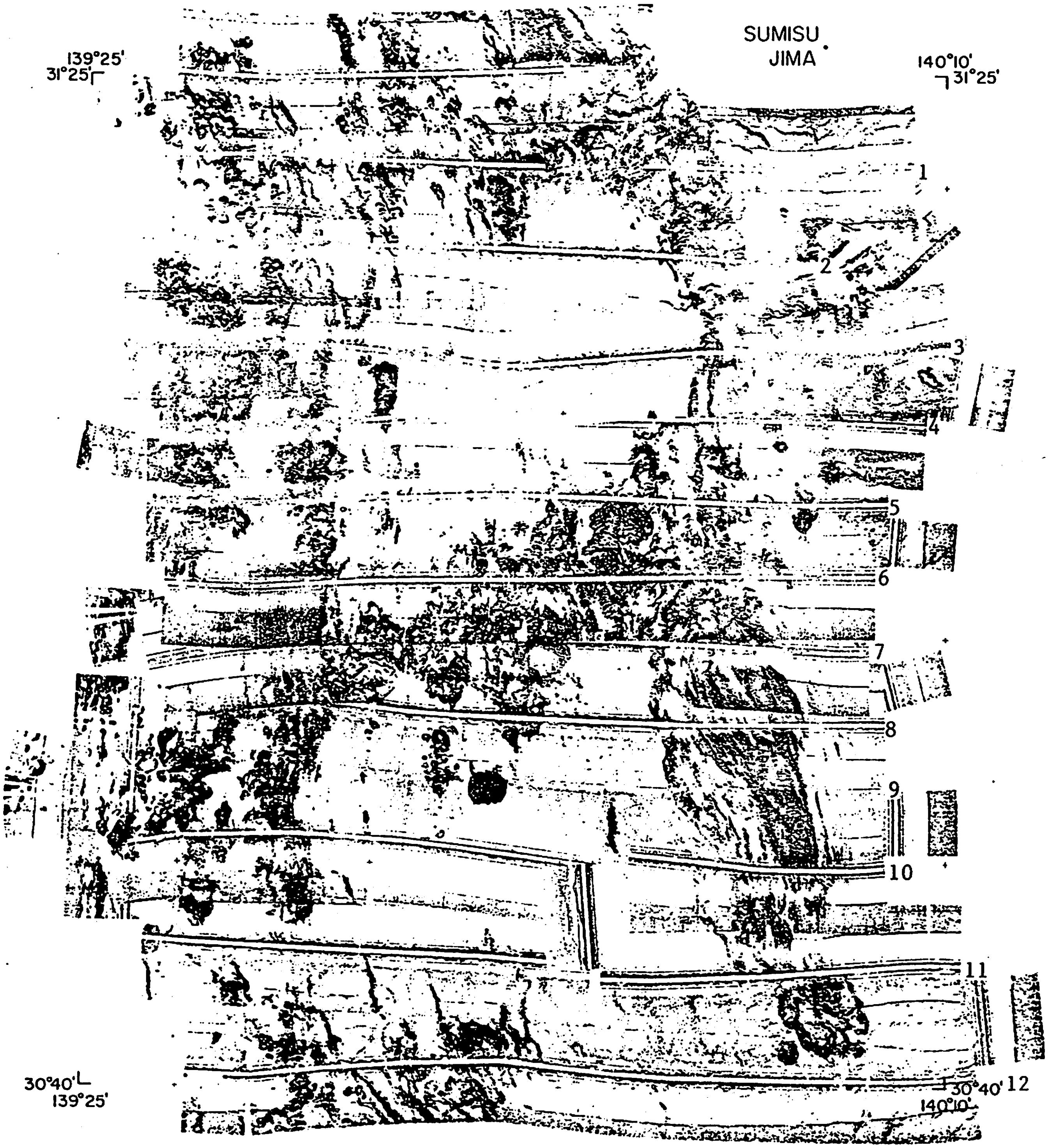


Figure 14b. SeaMARC II sidescan mosaic of the Sumisu Rift. Single-channel seismic profiles collected on track segments 1-12 are shown in Figure 15.

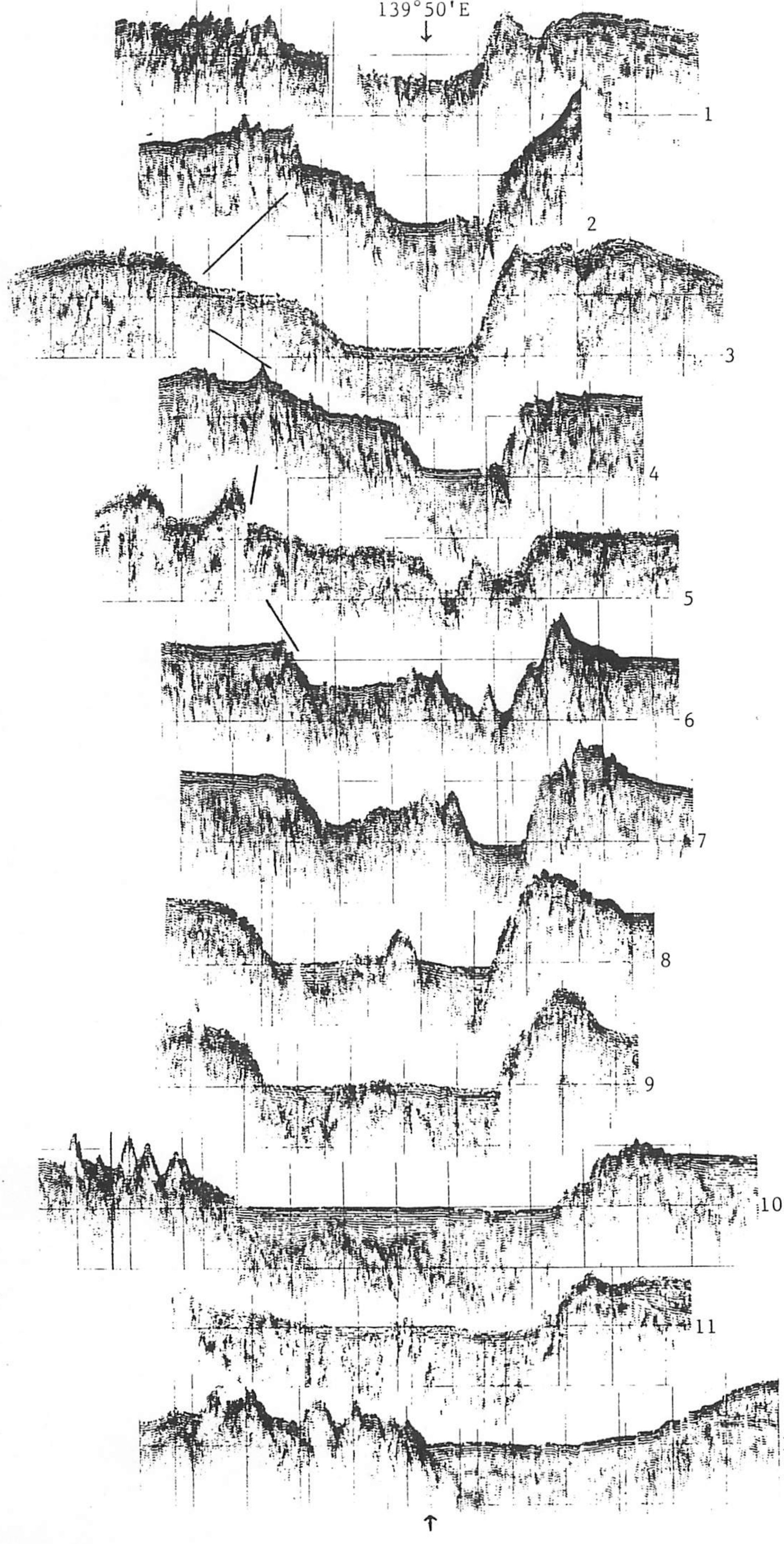


Figure 15. HIG single-channel seismic profiles across the Sumisu Rift. See Figure 14b for location. Each profile is aligned at 139°50'E and labelled by number at 3 seconds TWTT. Horizontal scale varies with ship speed variations due to currents (note apparent misalignment of western bounding fault on profiles 2-6). Vertical exaggeration varies between 8-12:1.

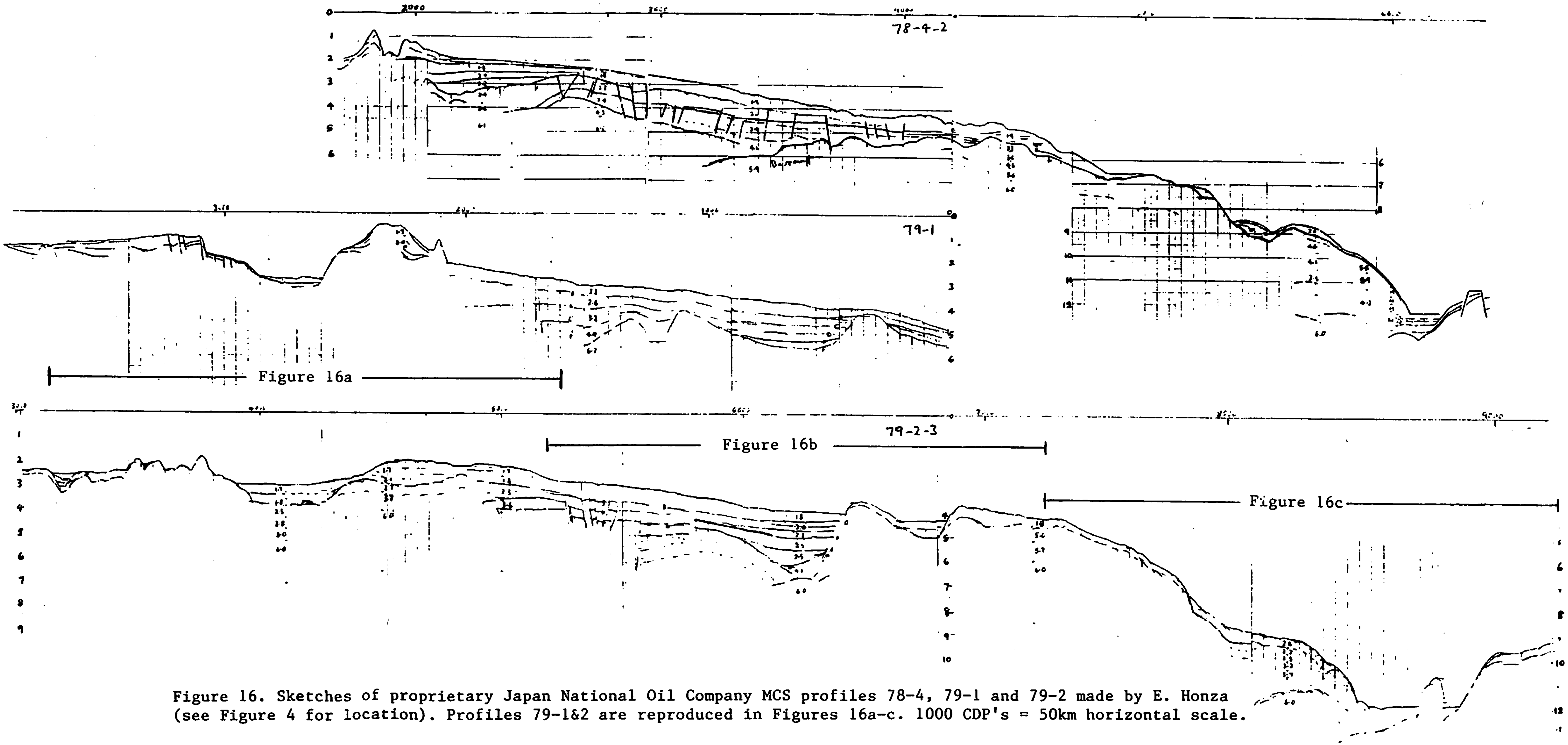


Figure 16. Sketches of proprietary Japan National Oil Company MCS profiles 78-4, 79-1 and 79-2 made by E. Honza (see Figure 4 for location). Profiles 79-1&2 are reproduced in Figures 16a-c. 1000 CDP's = 50km horizontal scale.

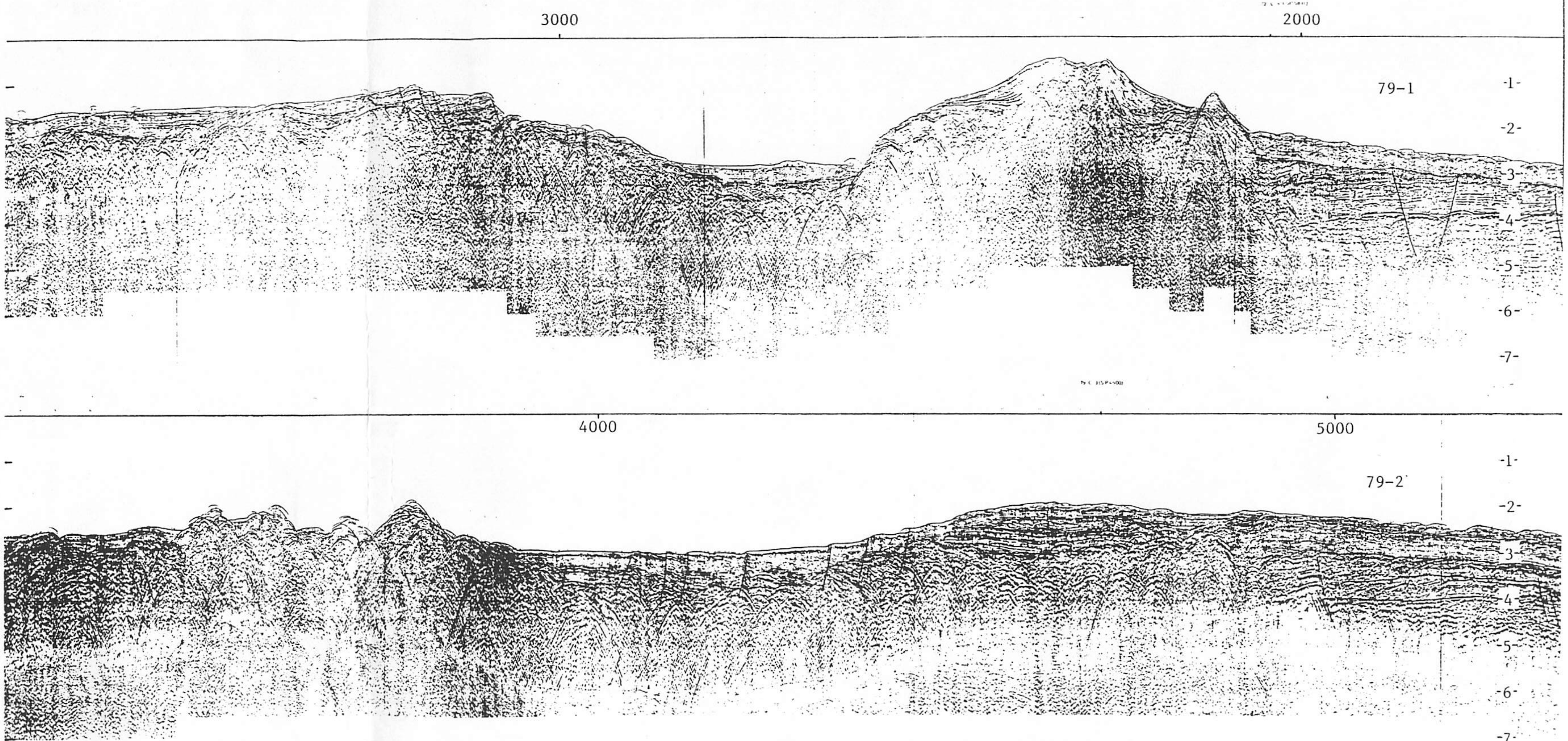


Figure 16a. Proprietary JNOC 24-fold stacked MCS profiles across the Sumisu Rift and Bonin arc.

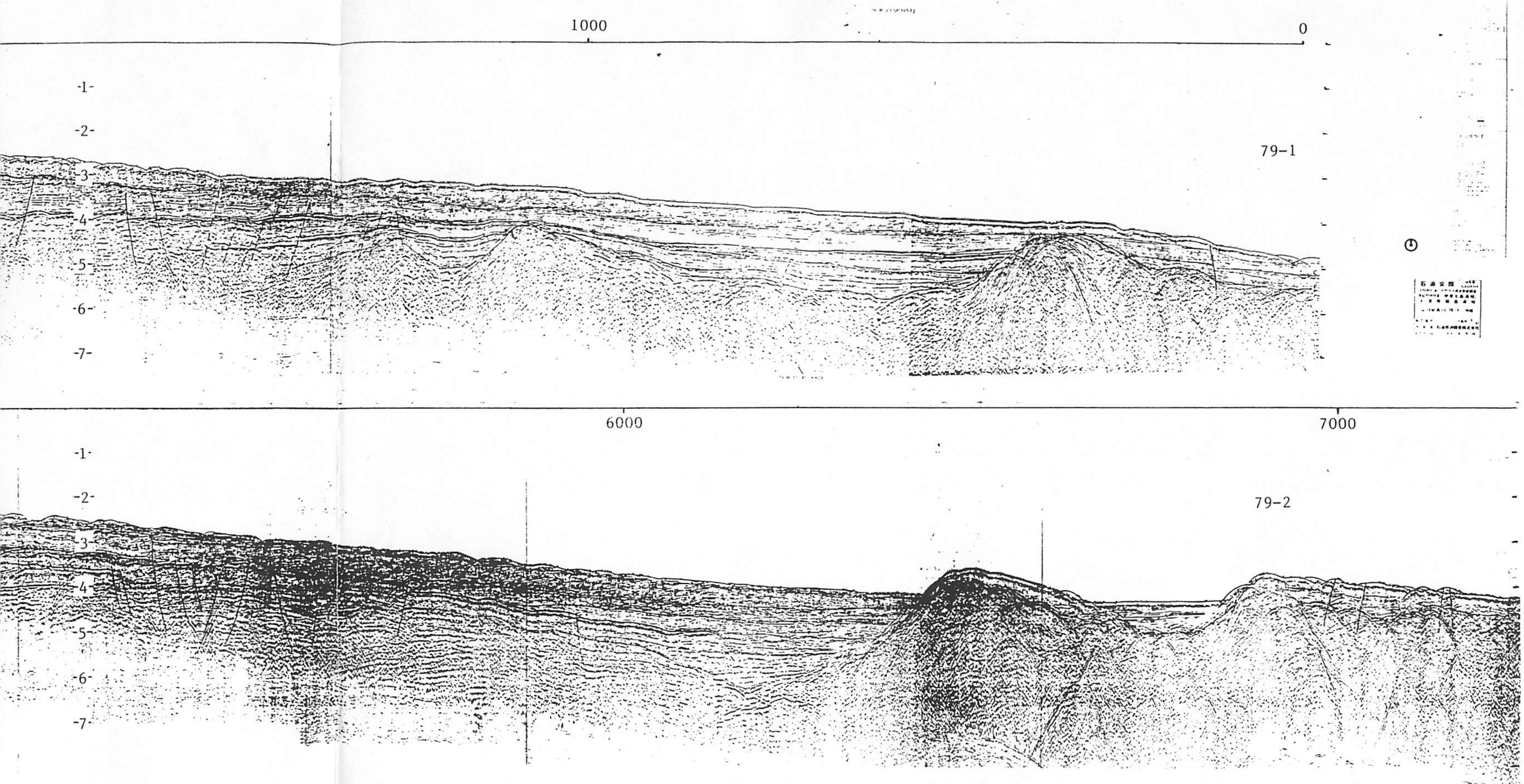


Figure 16b. Proprietary JNOC 24-fold stacked MCS profiles across the Bonin forearc and outer-arc high.

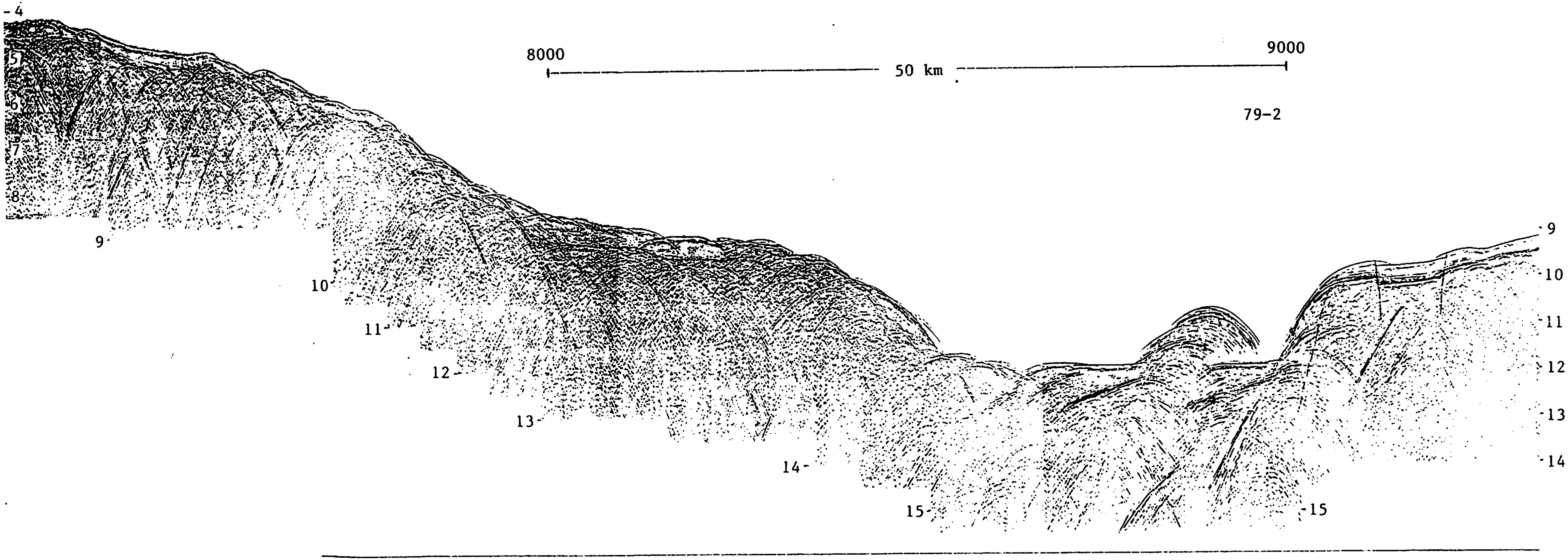


Figure 16c. Proprietary JNOC 24-fold stacked MCS profile across the Bonin trench.

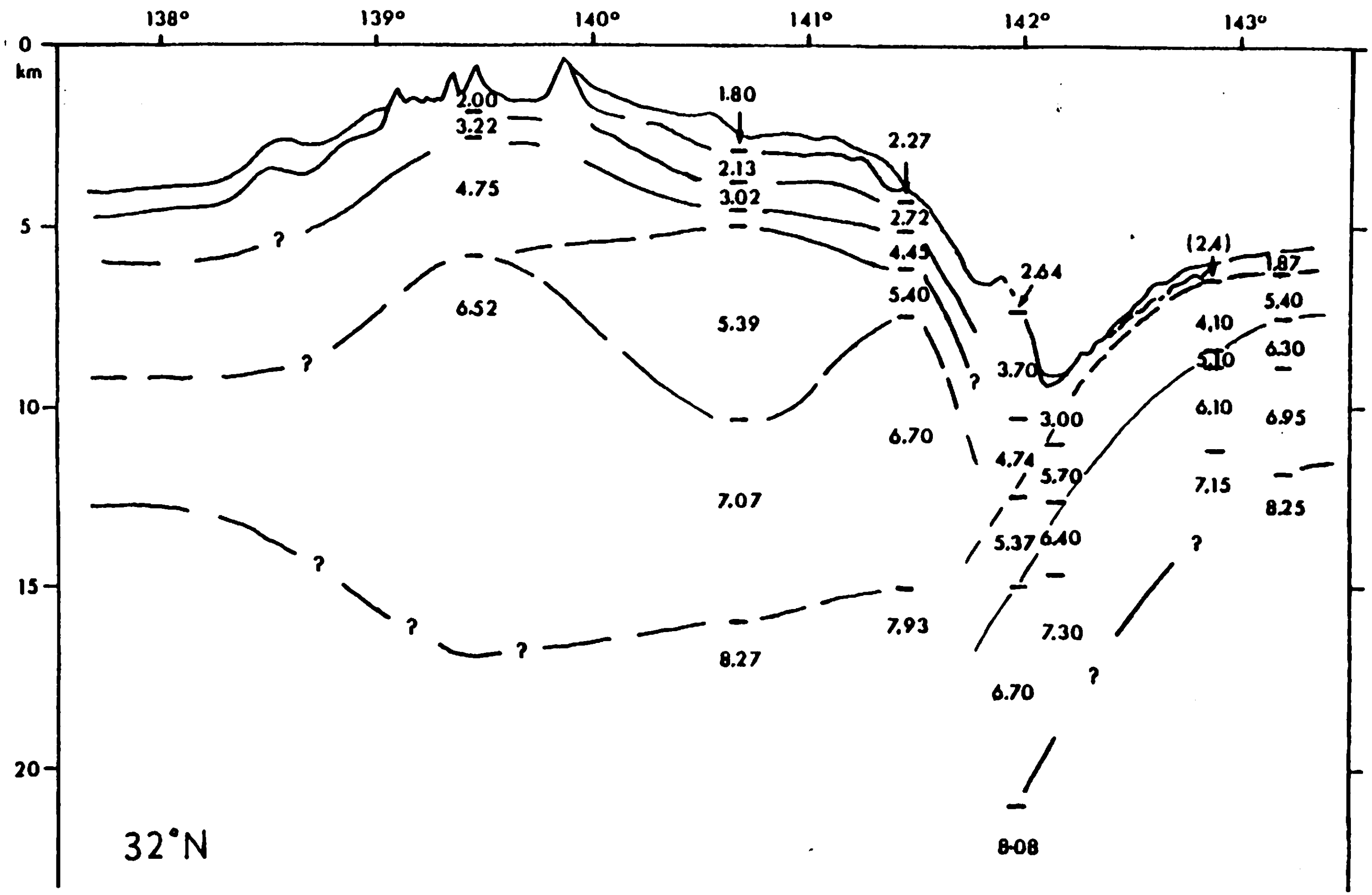
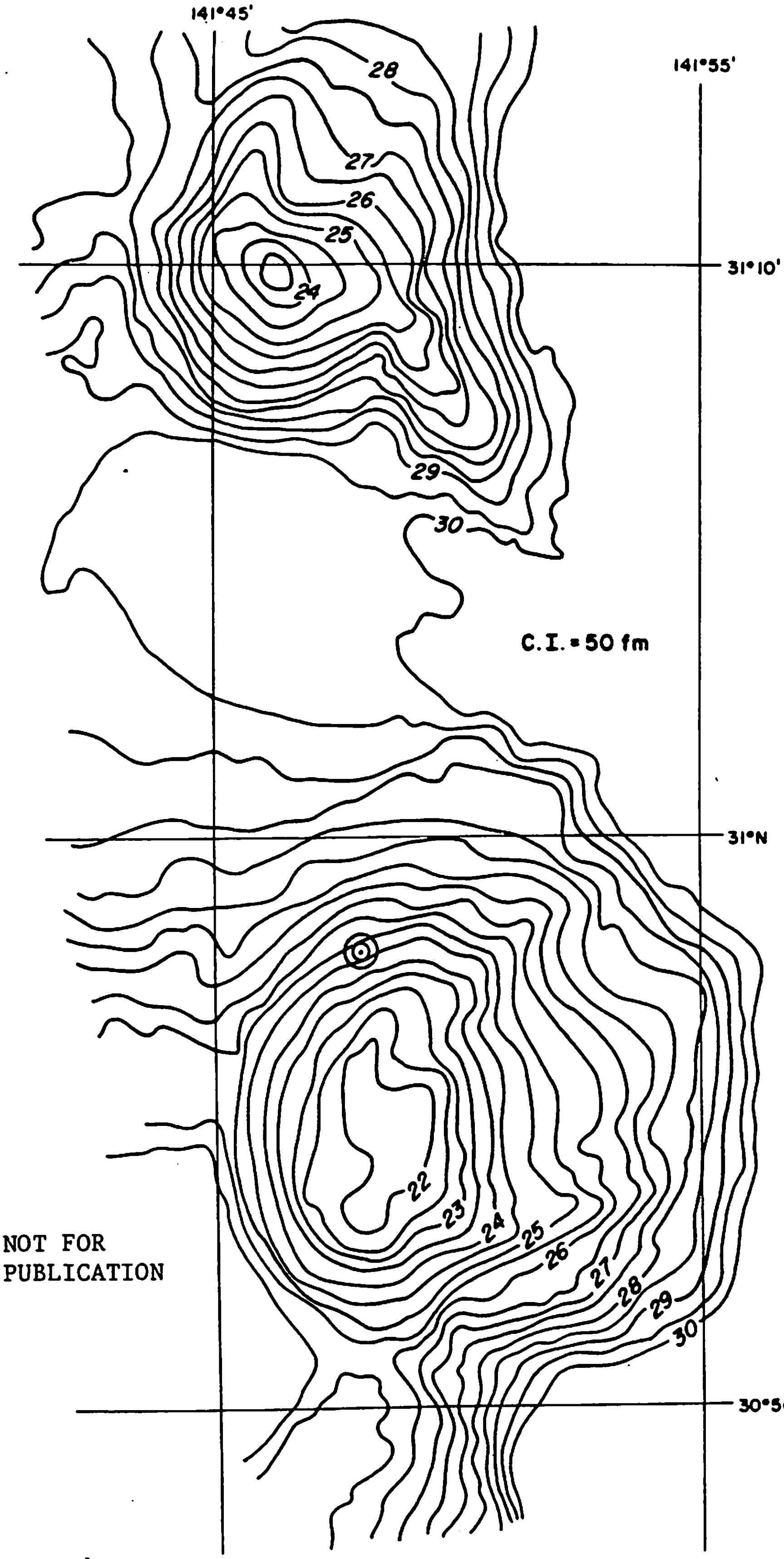


Figure 17. Crustal section across the Izu Arc-Bonin Trench along latitude 32°N from two-ship seismic refraction data summarized by Honza and Tamaki (1985).



NOT FOR
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Figure 18. 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.

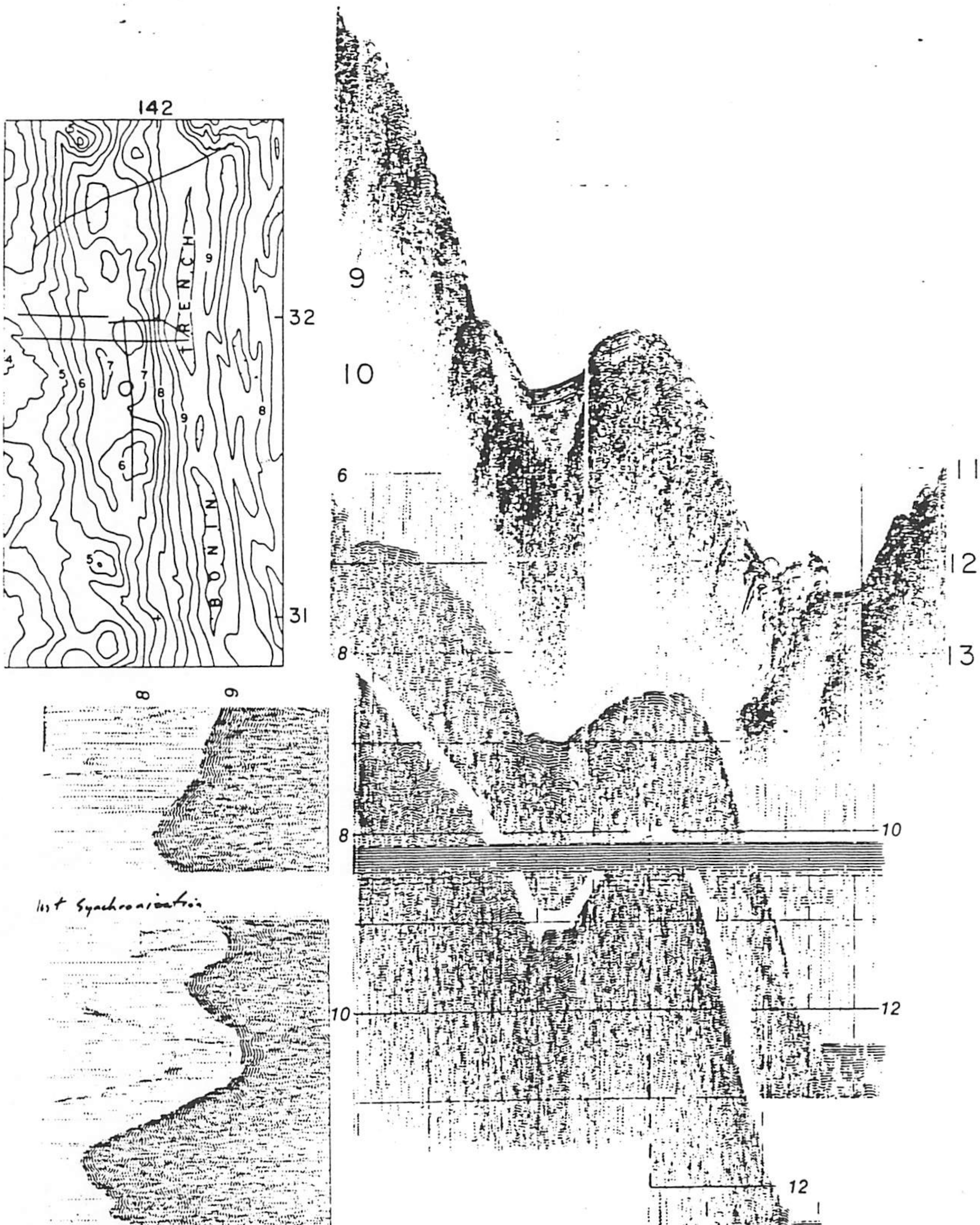


Figure 19. Single channel seismic profiles along and across the "domes" on the lower slope terrace of the Bonin Trench inner wall.

LITHOSPHERE PANEL MEETING

10-11 April 1986
University of Washington, Seattle

EXECUTIVE SUMMARY

(4) **WESTERN PACIFIC**

(a) The major thematic problems LITHP would like to see addressed in the Western Pacific are:

1) Geochemical evolution of back-arc basin crust.
2) History of arc magmatism.
3) Forearc basement composition and vertical tectonics.
4) Geochemical mass balances at convergent margins.
5) Ophiolite comparison.

- these problems must be addressed at more than one arc-trench system.

(b) A minimum of five legs are required to meet lithospheric objectives in the Western Pacific: 2 legs in the Mariana/Bonins (forearc), 1 leg in both the Lau Basin and Japan Sea (back-arc basins, marginal seas) and 1 leg devoted to drilling reference holes into basement seaward of the Mariana and Izu-Bonin trenches (geochemical mass balance).

"From the minutes"

Of particular interest in back-arc basins is the temporal and spatial relationship of MORB, back-arc basin and island arc basalts.
The Bonin Basin and possibly the Coriolos Trough are interesting as examples of the early stages of back-arc basin spreading.

Several important problems were identified in the forearc region that can only be attacked by drilling. These include the nature of igneous basement, the vertical tectonics of the forearc region, and the history of arc magmatism. Another attractive drilling objective is the large diapiric structures identified in both the Bonin and Mariana forearcs. Both the Bonin and Mariana forearcs offer important drilling targets and because of the variability in structure and tectonic history, LITHP strongly recommends both be drilled.

Another aspect of drilling at convergent margins championed by Charlie Langmuir is the establishment of reference holes on the incoming plate which include as complete recovery as possible of the entire sedimentary section and substantial penetration into basaltic basement (>100 m). Knowledge of the composition of subducted crust is critical for models of arc petrogenesis and for a general understanding of mantle and crustal evolution. For example, there are substantial chemical differences between recent lavas erupted in the Mariana and Izu-Bonin arcs that may be related to differences in the chemical composition of the sediments and crust being subducted. A reference hole seaward of each arc-trench system studied will provide the constraints needed to begin to examine this geochemical mass balance. LITHP strongly endorses this aspect of drilling at convergent margins.

THEMATIC OBJECTIVES IN THE WESTERN PACIFIC
JOIDES Tectonics Panel
May 1986

I. The Rationale for Island Arc Drilling in the Western Pacific

The origin and evolution of magma within the earth stand squarely at the heart of deciphering the evolution of Earth itself. Of all magmatic provinces, island arcs offer the best possible natural laboratory within which to decipher the physical and chemical evolution of magma. Unlike all other areas, the greatest depth of magma formation is limited to be at or above the subducting plate. Moreover, the source material is either normal mantle peridotite or subducted oceanic crust or mixtures thereof, and the thermal regime of the entire region is reflected in the heat transfer of magmatism itself. In addition, the timing of the events of subduction, incipient volcanism, volcanic-center migration, and magmatic flux provides truly fundamental constraints on the mechanics of separation and ascension of magma. Purely geochemical studies in the way of phase equilibria, bulk chemical composition, and isotopic signatures can only be understood when properly viewed through the context of the mechanics of magmatism. Island arcs offer our only hope of clearly understanding large scale magmatic processes. The arcs that are best suited to unravel such problems and that are accessible to drilling are in the western Pacific.

A detailed accounting through time of the mass and composition of all materials associated with arc evolution (magmatic flux, volatile flux, hydrothermal fluids in the forearc, and flux of downgoing oceanic crust and sediment) and also of the isostatic response of arcs on a regional basis provides the fundamental boundary conditions governing all arc processes. The most critical element of such a menu is time. Although old arcs span much time, their heavy blanket of sediments, pyroclastics, and lavas greatly obscures sampling this history. Arcs must be studied early in their evolution to answer most all of the important themes at issue.

Arcs of the critical age for analysis are Izu-Bonin, Mariana, Scotia, and Tonga-Kermadec. Accessibility and operating conditions essentially preclude Scotia, especially when considered in light of land-based follow-up studies. The overall Mariana-Bonin arc system is ideally suited to tackle nearly all of the essential problems, and Tonga covers what is left. Possibly only in studying the correlation between arc magma composition and downgoing plate composition does another arc, the Aleutians, offer a better perspective. What follows is a list of the principal thematic issues with a few words highlighting, where necessary, their importance and position within more global issues.

Themes in arcs and forearc regions

1) Arc evolution (structural, volcanic), beginning, timing, periodicity, magma transport
- Allows entire problem of magma production, mechanics of ascension, and wall rock chemical interaction to be assessed, and allows quantitative evolution of intimate coupling of downgoing plate and arc plate (i.e. segmentation, fracture zones, etc.).

2) Nature of arc igneous/metamorphic basement
- Are granodioritic plutons also characteristic of incipient volcanic fronts? Is the broad submarine arc ridge or welt of MORB type material produced during the initial breakoff and plumage of the lithosphere, or is it arc magma? What thermal regime is reflected in the metamorphic grade of these rocks?

3) Thermal regimes (isostatic response)

- The very major question of the deep thermal regime of subduction and magmatism can be largely answered by knowing the thermal regime of the forearc, and this couples with the visco-mechanical isostatic regime which further constrains the nature of the arc lithosphere.

4) Fluids, their budget and chemistry

- Do fluids from dehydration of the downgoing plate travel back up the oceanic crust and erupt in the forearc, carrying base metals stripped from the oceanic crust at high pressure? Are these the fluids that form forearc ore deposits?

5) Intra-arc structure (rotations, etc.)

- What are the timing and mechanics of major structural readjustments with the arc itself? Are these driven by regional or local forces?

6) Forearc dynamics, seamount offscraping, "cold volcanoes" (i.e. diapirs)

- Are cold forearc volcanoes a principal means of transporting and redistributing debris from the top side of the downgoing plate? What is the thermal-rheological regime associated with these features; what are the deformation rates; is the process selective of material type?

7) Boninites, relationship to ophiolites

- Are ophiolites sections shaved off in forearcs? Are boninites continually produced in the forearc region, or only early in arc development? Is there a progression from boninites to more typical arc magmas?

8) Relations of arc chemistry to plate chemistry

- Are regional variations in downgoing plate (oceanic crust ± sediment) chemical composition reflected in the composition of the lavas of the volcanic front?

9) Isostatic response of lithosphere to loading at different stages of arc/backarc evolution

- How thick is the arc lithosphere? Does it thin or thicken with time? Can the rates of isostatic adjustments of volcanic centers and arc crustal blocks be measured through sedimentation history and then be inverted to learn of lithosphere evolution?

III. The Rationale for Drilling in Western Pacific Back-arc Basins

The global thematic issue that might profitably be addressed by drilling in back arc basins is lithospheric extension. Like continental rift zones and passive continental margins, back-arc basins originate through lithospheric extensional processes. An immediately obvious question is whether the extension of island arc lithosphere (ultimately to form a back-arc basin) differs significantly from extension of continental lithosphere (which may lead ultimately to normal seafloor spreading). ODP has drilled, or will drill, holes at a number of passive continental margins (New Jersey, Galicia, Norway, Exmouth Plateau) to focus on lithospheric extension problems, so it seems that extension of arc lithosphere is a novel problem that can be addressed by drilling in back-arc basins of the Western Pacific.

The whole issue of lithospheric extension has been revitalized recently, with the recognition by Wernicke and other structural geologists that large scale extension in the Basin-and-Range province is mainly accommodated by normal slip on low-angle detachment surfaces rather than by wholesale stretching and thinning of the lithosphere, a concept popularized by McKenzie. We now have two schools of thought with their proponents: Lithospheric extension via a simple shear (detachment) mechanism, and extension via pure shear (stretching and thinning). The most important difference between the two concepts is that the location of maximum thinning of the mantle is laterally offset from the location of maximum crustal thinning in the detachment model. A likely result is the development of asymmetric patterns of structure, sedimentation, heat flow, and gravity anomalies over the extended lithosphere that would be difficult to explain using a stretching and thinning model unless special conditions are assumed.

The Western Pacific provides a wealth of opportunity for studying extension of arc lithosphere with ODP drilling. Drilling establishes boundary conditions (timing, kinematics, temperatures) that are essential for developing or testing models of extension. Best results are likely in the simplest tectonic situations. For this reason we advocate drilling extensional domains in demonstrably intra-oceanic arcs. We are therefore limited to the following locations:

1) Bonin arc
2) Coriolis trough
} active island arc rift zones

3) Lau basin
4) Mariana trough
} Rifted arc fragments with active back-arc spreading

To be properly effective, ODP drilling must be preceded, or accompanied by thorough deeply-penetrating MCS surveys in order to examine whether master detachment surfaces are present in these extensional domains. Gravity, heatflow, and SeaBeam/Seamarc surveys may also be required to properly locate drill sites.

The detachment model also predicts surface, or near surface exposure of deep-seated rocks, which is consistent with the recovery of metavolcanic rocks and gabbros in the Mariana trough, and upper amphibolite grade mafic mylonite from the Sorol Trough (east of Yap Island). Thus if extension of arc lithosphere occurs by slip on detachment surfaces, a window into the plutonic foundation of island arcs may be available for drilling without requiring large amounts of penetration.

Appendix B

R/V FRED H. MOORE
TECHNICAL CAPABILITIES
04 March 1986

R/V Fred H. Moore, originally a gift from Mobil Oil Corp. to The University of Texas Marine Science Institute, has been carrying out marine geophysical surveys for the University since 1978. Moore's data acquisition systems have been upgraded at various times through additional gifts of equipment and through investment in institutional funds. A recent donation of geophysical equipment from Chevron Oil Corporation, when fully implemented, will bring R/V Moore's MCS recording standards more in line with those of industry. Further effort to upgrade the sound sources with tuned sub-arrays of air guns is also underway. When completed, the vessel will be a more flexible platform capable of addressing a wider range of geological and geophysical research.

We expect R/V Moore's up-grade to be complete by early 1987. A description of the anticipated geophysical equipment is as follows:

Echo Sounding

3.5 and 12 kHz hull-mounted echo sounders. Raythron PTR transcievers and EPC flat-bed variable density plotters.

Magnetics

Dual (port and starboard) varian magnetometers.

Seismic Sound Sources

80 in^3 SSI Model S.80 water gun
2 X 2,000 in^3 Bolt 800c air guns
2 X 30m tuned sub-arrays of six guns each
60, 78, 108, 150, 240 and 429 cu. in. = 1065 in^3 per sub array[1]
1200scfm at 2000psi will fire 2130 in^3 source every 8 sec.

Seismic Receiving Array

Litton 96-trace, 3200 m LRS streamer with 33-1/3 or 16-2/3 m groups, 20 phones per 16-2/3 m group; 16 auxiliary channels for depth transducers, depth control, magnetic compasses, water break and quality control. Syntron depth control and compass system.[2]

Seismic Recording System

GUS 4200 marine system with 112 input channels, 1, 2, 4, ms sampling at 8, 16 or 32 sec records respectively. Data are demultiplexed in realtime and recorded on 9 track 1/2 in. tape at 6250 bpi in SEG-D format. System has full front-end quality control for streamer performance.

Sonobuoy System

Single channel receiver for VHF military buoys
Two-channel receiver for commercial (72 mHz) buoys
Sonobuoy data recorded on GUS auxiliary channels with full floating point gain ranging

Gravimeter

Bell BGM-2 marine gravimeter[3]

Navigation

Northstar 6600 Loran C
Magnavox 1107 dual channel transit satellite receiver
Global Positioning System
Flatbed plotter (3 X 4 feet)
Doppler speed log
Tail buoy tracking radar

Data Logging

PDP 11/34 based system recording 9-track, 1600 bpi on 1/2 in. tape. Logged data includes time, speed, air gun statistics, streamer depth and compass data, and all navigation including auxiliary shore-based systems as required. Parallel and serial interfaces available for other logging needs. Logged data also recorded on seismic tape headers. All data is displayed and printed as required. System also records magnetics and gravity.

Computer

PDP 11/34 general purpose computing system. Also used for seismic quality control.

Sediment Coring

Ewing piston corer and deep-sea trawl winch with 28,000 ft. 1/2 in. wire rope. Cores to 40ft. length.

Technical Support

It is anticipated that full MCS operations will require: UT party chief (if no UT science involvement in program), electronics engineer, computer engineer and 2 air gun technicians. Presently we do not receive technician support through NSF ship operations. Thus, the above support and appropriate travel are charged to each program.

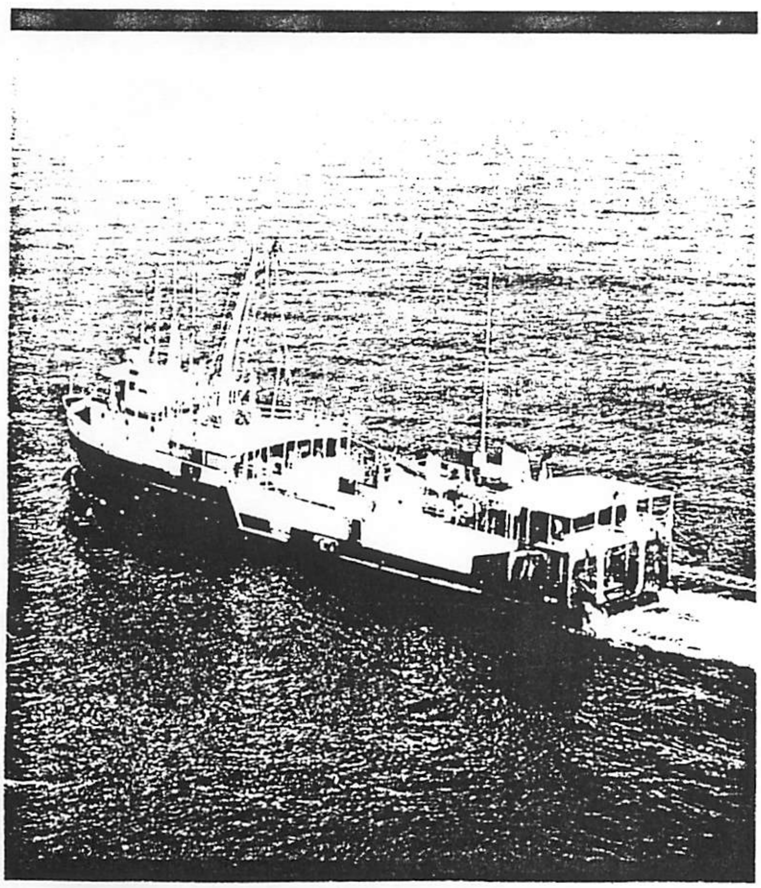
Notes

[1]429 and 240 in^3 guns will be requested from NSF. We presently rent them to fill the arrays.

[2]Compasses may be available only by rental from Syntron.

[3]Gravimeter is not presently scheduled for installation until required for a program.

THE R/V FRED H. MOORE



Length	165′
Beam	38′
Draft	11.4′
Height	79′
Gross Tonnage	297
Net Tonnage	202
Berths	
Crew	10
Scientists	23
Cruising Speed	10 kts.
Full Speed	11.5 kts.
Endurance	26 da.
Range	6,000 nm.
Fuel Capacity	62,200 gal.
Water Capacity	58,000 gal.

EQUIPMENT

- Main Engines
  Caterpillar D398C; 765 hp (2)
- Compressor System
  Two Gardner-Denver SP600 compressors (100 psi/600 cfm, each) feeding into two Gardner Denver MDY booster compressors (2000 psi/600 cfm, each)
- Generators
  100 kw capacity (2)
  50 kw capacity
- Communications
  Single sideband radio; 11 channels, 225 watts
  Single sideband radio; 40 channels, 150/1000 watts
  VHF Radio; 55 channels, 25 watts
  ATS-3 Satellite transceiver