Investigation of Upper Plate Response to Subducting Plate Morphology and Seamounts as Subduction Zone Asperities: Cooperative German, Costa Rican, and United States Project

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PROJECT SUMMARY

Observations of convergent margins worldwide suggest that the morphology and crustal thickness of a subducting plate may affect the mode of deformation, seismicity patterns, volcanic activity and composition, and elevation of the overriding plate. It has also been proposed that seamounts on the subducting plate may be earthquake nucleation sites or asperities. We propose to investigate the upper plate response to three different morphological segments of the Cocos plate that subduct beneath Costa Rica. We will investigate subduction of the smooth, seamount-dominated, and Cocos Ridge segments of the Cocos plate using a large marine airgun source, 20-30 ocean bottom instruments (seismometers and hydrophones), 30+ land instruments, and selected land shots to obtain wide aperture and near vertical seismic data along three regional transects. The wide aperture data will be used to establish crustal structure/velocity models across the arc and forearc areas, which are poorly known at present. The resulting models can also be used to process (i.e. migrate) near-vertical data recorded by the ocean bottom and land instruments to image the plate boundary zone reflections landward into the zone of seismogenic subduction and seaward to tie with existing seismic reflection data. Along all three transects a primary goal is to construct accurate velocity models so that the images of the plate boundary zone produced in this project can be tied to relocated earthquake hypocenters. Integration of these two data sets could provide a missing link in understanding the transition from aseismic to seismogenic plate motion.

In a particularly exciting part of this project, 30 ocean bottom instruments will be laid out in a grid pattern above a recent (1990) earthquake, which was located above the seamount-dominated segment of the Cocos Plate. Data collected from this grid will be processed with 3-D seismic reflection techniques, including pre-stack migration. Our goal is to reveal the detailed morphology of the plate boundary so as to identify any structural asperity, its relationship to the forearc backstop, and its relationship to the 1990 earthquake. This should directly test the hypothesis that subducting seamounts are earthquake nucleation sites as they collide with the forearc backstop.

The proposed transects are part of an international project called TICOSECT, which involves scientists from Costa Rica, the European Community, and the United States. This geophysical work will provide the framework for geological and geochemical aspects of the TICOSECT project that will further elucidate the effects of differing slab morphology and thickness on the upper plate.

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Thomas H. Shipley, Paul L. Stoffa, Kirk D. McIntosh

Three-dimensional Seismic Imaging of an Accretionary Wedge: Costa Rica

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The objective of this project was to image the accretionary structures in the sedimentary wedge of the Middle America Trench (MAT) where previous seismic reflection work had proved disappointing. It has long been believed that imaging problems on active margins are related to the fine scale of structure and its three dimensionality. Thus our purpose was to determine if we could improve structural images and then use these improvements to understand the tectonic processes and structural evolution of an active margin at seismic scales. In April of 1987, we collected over 6 million seismograms within a 8.5 km x 21.6 km area of the accretionary wedge offshore of Costa Rica, just landward of the MAT. This seismic data set included precise navigation collected from a shore based navigation system and ten streamer compasses, all crucial for the experiment.

We had originally proposed to process this data in a two pass 2D x 2D approximation to 3D migration. However, we obtained Geovecteur software which allowed us to eventually do a more correct one-pass 3D depth migration on a University of Texas Cray super computer. The process of developing a velocity field for depth migration took almost a year and consumed substantial efforts of data processors, students, and computational resources. We did not have independent velocity control. Therefore, starting with conventional semblance stacking velocities, we conducted a series of 2D and eventually 3D migration velocity tests of portions of the data volume.

The interpretation has been difficult because of the structural diversity observed in the 3D data volume. The resolution far exceeds what we would expect given simple Fresnel zone arguments, while the basic structures vary more along strike than we anticipated. At this stage, the story is one of structural diversity, yet the processes are fairly well understood at least in a temporal framework. Some basic results of the project include: structural diversity on a scale of hundreds of meters; large scale intra-prism fault reflections illustrate a whole-prism scale architecture previously undetected; sedimentary accretion is documented by offscraping at the same time as additional growth and thickening result from duplexing and out-of-sequence thrusting starting in the zone only a few kilometers from the trench axis; structures in the overlying slope cover demonstrate shortening of the whole wedge and overlying slope cover, from fault splays up from the prism, as well as broad shortening of the whole prism. Continued shortening is manifested in hundreds of small offset reverse faults that break the sea floor throughout the mapped area. Much of the structural diversity has its origin in subtle changes in relief of the oceanic crust, changing the location of faults and fault ramps, thereby changing the dimensions of the accreting fault blocks. The location of later out-of-sequence thrusting is also influenced by the basement structure.

Human Resource Development: Graduate students involved in this research include, Walter Kessinger (UT M.S. thesis), Kirk McIntosh (UC, Ph.D. thesis), George Coltrin (UT M.S. thesis), Hugh Winkler (UT), Paul Riherd (UT), Gina Miscovich (UC). Undergraduate support was provided for Kathleen Wall who worked as a research assistant. Data from this project has been and is being used in course work for both undergraduate and graduate classes given by Milo Backus and Paul Stoffa at the University of Texas.

List of papers:

Coltrin, G., Backus, M., Shipley, T.H., Cloos, M., 1989, Seismic reflection imaging problems resulting from a rough surface at the top of the accretionary prism at convergent margins, JGR, 94, 17485-17496.

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Stoffa, P.L., Shipley, T.H., Dean, D.F., Kessinger, W., Elde, R., Silver, E., Reed, D., Aguilar, A., 1991, Three-dimensional seismic imaging of the Costa Rica Accretionary Wedge: field program and migration examples, JGR, 95, 21693-21712.
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McIntosh, K., Silver, E., Shipley, T.H., 1993, Evidence and mechanisms for forearc extension at the accretionery Costa Rica convergent margin, Tectonics (in press).
McIntosh, K., Silver, E., Shipley, T.H., in review, Structure and growth processes of the accretionary prism off the Nicoya Peninsula, Costa Rica.

Abstracts (partial list):

Shipley, T.H., Stoffa, P.L., Cloos, M., Silver, E., Reed, D., Aguilar, A., Alvarado, F., Calvo, C., Rojas, F., 1987, Some preliminary observations of the Costa Rica three dimensional seismic data, Trans. AGU, 68, 1486.
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Shipley, T.H., McIntosh, K., Stoffa, P.L., Silver, E.A., 1990, Accretionary processes along the Middle America Trench off Costa Rica, AAPG Bulletin, 74, 1000-1001.
McIntosh, K., Silver, E.A., Shipley, T.H., 1990, Growth Processes and Volume constraints of the Accretionary Wedge off the southwestern margin of Costa Rica, Trans. AGU, 71, 1562.
Silver, E.A., Shipley, T.H., McIntosh, K., 1990, Effect of a depositional apron on accretion: Costa Rica 3D seismic reflection survey, Trans. AGU, 71, 1592.
McIntosh, K., Silver, E.A., Shipley, T.H., 1991, Forearc extension at the accretionary convergent margin of Costa Rica, Trans. AGU, 72, 487.

RESULTS FROM PRIOR NSF SUPPORT (1988-1993)

Yosio Nakamura

Yosio Nakamura has no prior direct support from NSF as a PI/PD. However, he had the primary responsibility in data acquisition using ocean-bottom seismographs (OBS) in each of the following NSF-funded projects:

1. EAR-8816928, Ocean Bottom Seismograph Study of the Structure and Dynamics of D'Entrecastaux Ridge Subduction, 1989, Cliff Frohlich, University of Texas at Austin, P.I.: Deployed 13 OBSs for 23 days and 29 days in two phases in cooperation with ORSTOM, a French overseas research organization, for microearthquake observations. All but one instrument recorded good data on each phase.
2. (grant number unavailable), EDGE-Alaska, 1989, Dale Sawyer, Rice University, P.I.: Deployed

four OBSs under adverse conditions for recording of air-gun shots from a commercial vessel, and recovered three, of which two had good data.

3. (grant number unavailable), Offshore Oregon, 1989, Anne Trehu, Oregon State University, P.I.: Deployed seven OBSs to record air-gun shots from a commercial vessel. All but one instrument recorded good data.
4. OCE-9102368, Three-Dimensional Survey of the Crust, Moho, and Mantle Near the East Pacific Rise, May 1993, Jan Garmany, University of Texas at Austin P.I.: This experiment encountered significant instrument losses (discussed in Field Program section), but 45 of the 46 instruments recovered recorded all the expected data.

OBS data acquisition was a supporting activity in each of the following NSF-funded projects:

5. OCE-9104100, Heat Flow/Basement Depth Relation for the Ocean Crust in the Western Gulf of Mexico: A Constraint on Thermal Models of the Oceanic Lithosphere?, 1992, Arthur E. Maxwell, University of Texas at Austin, P.I.: Deployed eight OBSs in support of a heat-flow experiment. All instruments recorded good data.
6. OCE-9116172, Three-Dimensional Seismic Reflection Investigation of Fluid Flow and Structural Evolution: Northern Barbados Ridge, 1992, Tom Shipley, University of Texas at Austin, P.I.: Deployed three OBSs in conjunction with a 3-D multichannel seismic survey. All instruments recorded good data.

Published Results and Meeting Abstracts:

Frohlich, C., R. Louat and Y. Nakamura, Earthquake activity in the southern Vanuatu arc recorded by the Texas digital OBS, *Mar. Geophys. Res.*, **12**, 253-267, 1990.

Louat, R., C. Frohlich, Y. Nakamura and Y. Hello, Etude d'un essaim de séismes de la partie centrale de l'arc insulaire des Nouvelles-Hébrides par un réseau d'OBS; mise en évidence d'une modification du mode de subduction en liaison avec la variation de la morphologie du bassin arriére-arc, *in* Geodynamique des Bassins Oceanique et de Marges Continentales, Réunion extraordinaire de la Société Geologique de France, 1990.

Trehu, A., T. Holt, J. Shi, Y. Nakamura, T. Brocher, and M. Moses, Preliminary results from the 1989 Oregon onshore-offshore seismic imaging experiment, *EOS Trans. Am. Geophys. Union*, 71, 1588, 1990.

Olson, D. R., C. Frohlich, Y. Nakamura, R. Louat, and Y. Hello, Earthquake locations from OBS and local network records, near Efate, New Hebrides trench, Vanuatu., *EOS Trans. Am. Geophys. Union*, 72 (44) suppl., 348, 1991.

Trehu, A. M., J. N. Nabelek, S. Azevedo, T. M. Brocher, J. Luetgert, W. D. Mooney, I. Asudeh, R. Clowes, G. R. Keller, K. Miller, and Y. Nakamura, Crustal structure of the Cascadia subduction zone beneath western Oregon, *Geol. Soc. Am. Abstracts and Programs*, 24 (5), 87, 1992.

Shipley, T. H., G. F. Moore, J. C. Moore, G. Zwart, N. L. Bangs, R. L. Stoffa, V. Sen, Y. Nakamura, and S. Kuramoto, Three-dimensional seismic survey at the toe of the Barbados Trench: Some first observations, *EOS Trans. Am. Geophys. Union*, 73 (43) suppl., 356, 1992.

Sen, V., Y. Nakamura, P. L. Stoffa, Y. Hello, T. H. Shipley, and N. L. Bangs, Preliminary results from an ocean bottom seismograph experiment at the toe of the Barbados trench., *EOS Trans. Am. Geophys. Union*, 73 (43) suppl., 356, 1992.

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Nakamura, Y., J. D. Garmany, L. K. Könnecke, and Y. Hello, Deep crustal structure and anisotropy in the central Gulf of Mexico basin — A seismic investigation with upgraded Texas ocean-bottom seismographs, *EOS Trans. Am. Geophys. Union*, 73 (43) suppl., 490, 1992.

Introduction

The Pacific margin of Costa Rica is a 575 km part of the Middle America Trench (MAT) along which three distinct segments of the Cocos plate subduct [von Huene et al., in review] (Figure 1). The Cocos Ridge segment in the south, the seamount dominated segment off central Costa Rica, and the relatively smooth segment off the Nicoya Peninsula are morphologically and genetically distinct and have correspondingly different effects on the overriding Caribbean plate. We propose to explore the relationships between subducting plate morphology, upper plate evolution, and the seismogenic zone. Costa Rica is a good place to examine these problems because of the differing segments of the Cocos plate, including the Cocos Ridge, subducting along the same active margin.

The area of Cocos Ridge subduction exhibits many of the features observed in other aseismic ridge-trench intersections including a gap in the volcanic arc [McGeary et al., 1985] and rapid uplift of the arc and forearc [Corrigan et al., 1990]. The northern segment displays many features of "normal" subduction zones such as a well defined Wadati-Benioff zone and active andesitic volcanism. However, little is known about the deep structure of the arc and forearc in either of these areas or the intervening central segment, and the geometry of the subducting plate boundary, though reasonably well constrained by seismicity in the north, is undefined beneath southern Costa Rica [Burbach et al., 1984; Güendel, 1986; Protti et al., in review]. Offsets in the trend of the volcanic arc, a change to more alkalic volcanic composition at the southernmost part of the active arc, and a change from extensional backarc deformation (especially in Nicaragua)[Plafker, 1976; Mann et al., 1990] to backarc thrusting, documented by the 1991 Limon earthquake (M=7.5)[Plafker and Ward, 1992; Goes et al., 1993], have also been reported.

We also propose to investigate in Costa Rica the effect of subducting seamounts and their possible relationship to subduction zone earthquakes; as proposed by Cloos [1992] some subduction zone earthquakes may nucleate where underthrust seamounts collide with the crystalline or otherwise strong backstop of the overriding plate. The distribution, dimensions, and some effects of subducting seamounts in this area are now defined by Hydrosweep bathymetry, high quality seismic reflection data, and marine-land refraction profiles recently acquired in the seamount domain off central Costa Rica [Hinz et al., 1992; von Huene et al., in review]. These data suggest a seamount relationship to the 1990 Cobano (Ms=7.0) earthquake (Figure 1) [von Huene, personal communication, 1993].

Because of great international interest in this area, an inter-disciplinary geological-geophysical transect project, known as TICOSECT, is now being organized and has been endorsed by the Global Geoscience Transects program (GGT). The GGT Project is part of the International Lithosphere Program under the sponsorship of the International Council of Scientific Unions program. As a primary geophysical component of the TICOSECT project, one purpose of the work in this proposal is to collect wide aperture seismic data along three corridors across Costa Rica using up to 30 ocean bottom seismic instruments (seismometers and hydrophones), 30+ seismic land stations, and an onshore DFS V (Digital Field System) recording system to record signals from a large, marine air gun source (>10,000 cu. in.) and from selected land shots. In addition, near vertical incidence data recorded by these instruments will be processed to obtain reflection images of the plate boundary. Multi-channel seismic (MCS) acquisition is not included in this proposal because the proposed transects coincide with existing MCS data. In this cooperative effort U.S. scientists (this proposal) will have primary responsibility for marine activities (supply the ship and energy source and deploy instruments). German (E. Flueh and R. von Huene, GEOMAR) and Costa Rican (G. Leandro, ICE, the national electric company) groups will have primary responsibility for land operations (operate land stations and provide land shots), and GEOMAR will also supply and service 10 ocean bottom hydrophones (OBH).

The results of the proposed experiments will allow us to delineate the configuration of the plate boundary and crustal structure from the trench axis to the volcanic arc in relation to the three different crustal segments entering the subduction zone along the MAT. We will also investigate the nature of shallow, subduction zone seismicity with respect to the variable topography of the subducting plate. A particularly novel aspect of the proposed work is to use the ocean bottom and land instruments in a grid configuration above a likely seamount-asperity (the Cobano epicenter). These data will be processed with seismic reflection techniques, including 3-D, pre-stack depth migration, to image the underlying seismic asperity.

Geologic and Tectonic Setting

From northwest to southeast along the MAT off Costa Rica, the trench bathymetry changes from greater than 4000 m to less than 2000 m, the predicted Cocos-Caribbean plate convergence velocity increases from 86 to 95 mm/yr (calculated using NUVEL-1 [table 2a of DeMets et al., 1990]), and three distinct segments of the Cocos plate subduct (smooth, seamount-dominated, and Cocos Ridge; Figure 1). In addition to different morphology the subducting segments also have different ages and origins. The oldest lithosphere, subducting off northern Costa Rica, is late Oligocene in age and formed as part of the Farallon plate or as part of a newly formed Cocos plate (after about 25 Ma)[Klitgord and Mammerickx, 1982; Hey, 1977]. To the southeast, the subducting plate is apparently younger, early-middle Miocene (15-20 Ma) in age, and formed along a ≈ east-west trending Cocos-Nazca spreading center [Hey, 1977; Protti et al., in review].

Possibly the most important event in the Pliocene-Recent tectonic history of Costa Rica is the subduction of the Cocos Ridge, although its timing and effects are controversial. Based on magnetic anomalies in the Panama Basin, Hey [1977] and Lonsdale and Klitgord [1978] interpret that the Cocos Ridge intersected the MAT at about 1 Ma. Despite the recent timing inferred for this event, several features of the volcanic arc appear to be affected by it. The most obvious is a 175 km wide gap in recent volcanism landward of the ridge (Figure 1). Interestingly, adjacent to the gap on the northwest, the eruptive flux is very high, approximately 3-7 times greater than other sites measured along the active arc [Carr and Stoiber, 1990; Leeman and Carr, in review] and the volcanic chain is nearly E-W oriented rather than NW-SE. Uplift and compression in the arc and forearc [Corrigan et al., 1990; Collins et al., in review; Kolarsky et al., in review], and backarc compressional deformation in the Limon Basin [Plafker and Ward, 1992], have also been linked to the subducting ridge. A difficulty in these interpretations is that the tip of the ridge would only recently have passed beneath the Osa and Burica Peninsulas if ridge subduction started after 1 Ma. Two different explanations for this timing problem are that the effects listed above are largely caused by subduction of younger lithoshpere, unrelated to the Cocos Ridge [Protti et al., in review], or that subduction of the Cocos Ridge has been misinterpreted and actually began before 3 Ma, thus allowing it to penetrate beneath most of the isthmus [Collins et al., in review]. Independent data that could indicate the amount of ridge penetration, such as the crustal thickness of the subducted plate, are not available.

The Central American volcanic arc is generally believed to be built on altered Mesozoic age oceanic crust related to the Caribbean plate. However, island arc volcanism occurring throughout the Tertiary has covered much of the basement except terranes, including the Nicoya Complex [Dengo, 1962], that are exposed along the Pacific coast of southern Central America and Colombia. Two general interpretations for these units are that they are the uplifted and exposed edge of the Caribbean plate [Bowland and Rosencrantz, 1988], and thus represent the arc basement, or that they are exotic, arc and seamount terranes that have docked with the Caribbean plate during plate convergence [Baumgartner et al., 1989]. The Nicoya Complex of the Nicoya Peninsula, the best studied of the basement terranes, has a basal unit interpreted as latest Jurassic oceanic crust [De Boer, 1979; Kuijpers, 1980; Galli-Olivier, 1979], and an upper unit composed of basalt flows, pillows, and volcanic agglomerate, interbedded with volcanogenic turbidites and pelagics, and intruded by gabbro and diorite [De Boer, 1979; Schmidt-Effing, 1979; Kuijpers, 1980]. The upper unit, which may include material as young as latest Cretaceous [Schmidt-Effing, 1979], has been interpreted as an oceanic plateau [Schmidt-Effing, 1979; Duncan and Hargraves, 1984; Bowland and Rosencrantz, 1988] or as an early island arc [De Boer, 1979] built on oceanic crust (the lower unit). Whereas these interpretations imply that the ophiolitic basement rocks are autochthonous with respect to the Caribbean plate, Berrangé and Thorpe [1988], Baumgartner et al. [1989], and Di Marco et al. [in review] infer from stratigraphy and paleomagnetics that they are exotic terranes that have docked to the Caribbean plate following convergent margin development.

Crustal Structure of Costa Rica and Available Data

The crustal structure is best known in the forearc area of Costa Rica based on MCS reflection data. Profiles acquired by the University of Texas in 1977-78 showed reflections from the top of the subducting Cocos plate from the trench axis to the shelf edge or near it in several areas [Crowe and Buffler, 1983]. MCS data acquired by Shell and presented by Kolarsky et al. [in review] show a clear plate boundary reflection in the Experiment 3 corridor (Figures 1 and 2). More recent data off the central Nicoya Peninsula, including a 8.5 x 22 km 3-Dimensional survey (Figure 2), confirmed the earlier results and provided significantly improved images of the interior of the accretionary prism [Stoffa et al., 1991; Shipley et al., 1992; McIntosh, 1992]. These 3-D data provide spectacular views of the prism interior, but their full potential remains unfulfilled in part due to the absence of a well constrained velocity structure that could both facilitate accurate depth conversion and yield a sharper subsurface image (upon re-migration).

In 1992, German and Costa Rican teams acquired ≈1860 km of multi-channel seismic reflection data concentrated in the area from the southern Nicoya Peninsula to the Osa Peninsula (Figure 2) [Hinz et al., 1992]. In addition, wide angle seismic profiles were recorded using new German ocean bottom instruments (OBH, equipped with a hydrophone), assorted land instruments, and either a 2380 cu. in. or a 4000 cu. in. airgun array. These data, acquired in two cruises from late 1991 to Sept. 1992, are in the interpretation stage. Several problems affected the first OBH program, essentially a test cruise, so only 2 OBHs operated fully on each line. In contrast, all OBHs worked during the second cruise and the results are good. Reflection and refraction arrivals clearly mark the top and base of the subducting Cocos plate crust, and, even with the relatively modest air gun source, some arrivals are identifiable to ranges of over 117 km. These data provide important upper plate velocity information that can be eventually combined with the data from the proposed work for a regional velocity model.

Knowledge of the velocity structure beneath the Costa Rican landmass remains extremely limited. The recent (German-Costa Rican) seismic work covered parts of the forearc, but limited source energy and station coverage (only two land stations, both near the coast) precluded measurement of the arc's crustal velocity structure. Currently the primary information regarding the deep structure is from Matumoto et al. [1977], based on local network records of earthquake arrivals and four explosive shots in northwestern Costa Rica and southern Nicaragua. This model indicates a 43 km thick crustal section, which is relatively thick for an intra-oceanic arc built on oceanic crust, but may further support the oceanic plateau origin described above. In the absence of a better defined model, this is still the standard for earthquake relocation in Costa Rica. The cross section by Buffler et al. [1985] incorporated the Matumoto et al. model, results from a NW-SE oriented refraction profile recorded by two earthquake seismograph stations, and a velocity model derived by Liaw [1981] from between the Nicoya Peninsula and the volcanic arc (Figure 3). These independent velocity determinations are comparable and show landward thickening upper plate crust, but they fail to adequately locate the Cocos-Caribbean interface.

One of the critical aspects of Costa Rican crustal structure that remains unknown is the seaward extent and external geometry of Nicoya Complex-type ophiolitic rocks and their variation along the margin. In particular, is the forearc region primarily ophiolite, such as off Guatemala [Aubouin and von Huene, 1985], or is it primarily accreted sediment? Buffler et al. [1985] interpreted the forearc off Nicoya as an accretionary complex (Figure 3), and the recent work by Baumgartner et al. [1989] and Di Marco et al. [in review] indicates that the outer Osa Peninsula and nearby Caño Island are composed of sedimentary melange accreted in post-Eocene times. In contrast, Corrigan et al. [1990] indicate a primarily ophiolitic forearc composition (Figure 4). Information about the forearc structure and composition is essential for accurate mass flux estimates, which are in turn useful for understanding both convergent margin mechanics and the geochemistry of volcanic arcs. This information may also help clarify the mode of ophiolite emplacement (i.e. geometry and continuity may suggest discrete seamount terranes vs. coherent oceanic crust, as discussed above). Clearly, the work of Liaw [1981] and Matumoto et al. [1977] do not indicate the ophiolite limits. Ponce and Case [1987] demonstrated that a vertical sediment-ophiolite contact near the shelf edge off the Nicoya Peninsula is a permissible interpretation of gravity data (Figure 5); however, this is a non-unique solution of the Nicoya Complex external geometry.

Seismicity

Seismicity in Costa Rica occurs to a large extent as Cocos-Caribbean subduction zone activity, but there is also a substantial component associated with Caribbean intraplate deformation. The primary feature of the subduction zone seismicity, documented by many authors [Burbach et al., 1984; Güendel, 1986; Protti et al., in review], is the progressive shallowing of dip and depth of the Wadati-Benioff zone from NW to SE (Figure 6). In northern Costa Rica the Wadati-Benioff zone is well defined to depths of 200 km with a steep, 80 degree dip (at depths greater than 100 km), whereas in southern Costa Rica the slab is seismically undefined and seismicity is primarily restricted to the upper 50-70 km. Previous workers interpreted that tears in the slab may lead to observed changes in orientation and position of the volcanic chain [e.g. Stoiber and Carr, 1973; Burbach et al., 1984]. More recently, Güendel [1986] interpreted local network seismicity and found that a coherent, but smoothly contorted, slab may exist under Costa Rica, and Protti et al. [in review] found evidence for a single tear in the slab under central Costa Rica, the Quesada sharp contortion, based on a more extensive record of local network data.

The local network data also demonstrate distinct clusters of interplate earthquakes, primarily in the seamount-dominated (central) segment of the subducting Cocos Plate (Figure 7). One cluster is apparently associated with the moderate size, 1990 Cobano (M_S=7.0) earthquake. This configuration is intriguingly similar to that predicted by the model of subduction zone seismicity proposed by Cloos [1992] in which seamounts act as earthquake asperities when they collide with a strong, crystalline-rock backstop (Figure 8). von Huene et al. [in review] suggest that the 1990 earthquake, as well as a similar one in 1952, may have nucleated about the same asperity. Protti et al. [in review] also indicate that seamounts in this area may act as asperities, and due to their limited area of interplate coupling may explain the relatively moderate earthquake magnitudes ($\leq$7.0) historically observed in this central segment.

The significance of intraplate seismicity in Costa Rica became much more evident with the 1991, Ms=7.5 Limon area earthquake (Figure 1). Plafker and Ward [1992] characterize this event as backarc thrusting, as do Suárez et al. [in review], who directly attribute this style of deformation to Cocos Ridge subduction. An aftershock study following the 1991 event by Fan et al. [1993] shows that these events are spatially segregated with primarily thrust mechanisms to the south and east of the main shock and dominantly strike-slip mechanisms to the north and west. These data and similar strike-slip mechanisms following the 1983 Golfo Dolce (Ms=7.3) subduction zone earthquake suggest to Fan et al. [1993] that a diffuse, left-lateral tectonic boundary is developing across south-central Costa Rica.

Research Objectives

The primary objective is to delineate the configuration of the plate boundary and crustal structure from the trench axis to the volcanic arc in relation to the three differing types of oceanic crust (smooth, seamount-dominated, and Cocos Ridge segments) that are subducting. These results will allow a much improved assessment of regional seismotectonics, enable mass flux analysis, and improve ideas of the origin and history of the Central American convergent margin.

Seismic Front. A specific objective is to investigate the nature of the seismic front, which is defined by Byrne et al. [1988] as the trenchward limit of seismicity within the overriding plate and along the plate interface (Figure 9). Mechanisms recently proposed for the transition to seismogenic subduction are (1) increased strength of the decollement zone or subducting sediments, [Vrolijk, 1990], (2) landward increase in strength of the over-riding plate (at the "backstop") as well as the decollement zone material [Byrne et al., 1988], and (3) the seamount-asperity hypothesis, involving interaction of seafloor irregularities, i.e., seamounts, with a crystalline rock backstop (Figure 8) [Cloos, 1992]. This transition zone is a missing link between seismic reflection and earthquake seismological studies of subduction zones.

Seamount Asperity Hypothesis. We believe that the seamount dominated segment of the subducting Cocos plate is an excellent place to test the seamount-asperity hypothesis. Hydrosweep bathymetry (Figure 10) shows numerous seamounts seaward of the MAT, and it also clearly shows linear furrows in the trench slope marking the paths of several recently underthrust seamounts (labeled seamount furrows). The furrows, which are aligned with the Cocos-Caribbean convergence vector, vary in length and thus indicate their respective distance of underthrusting [von Huene et al., 1993 (in review)]. A furrow similar to these is present along the Experiment 2 transect (Figures 1 and 10), although its seaward portion has been modified by another seamount that is now beneath the lower trench slope (beneath the -2000 label between the extended dip lines). Because trench slopes can rapidly re-establish their original morphology [Lallemand and Le Pichon, 1987; Collot and Fisher, 1989], the presence of the furrow indicates very recent seamount subduction. The existing data (UTIG and German, reflection and refraction) are insufficient to prove that the seamount that caused this furrow is now present beneath the proposed 3D OBS grid; however there is an asperity there that has repeatedly nucleated large earthquakes (1990 and 1952). Due to the observable furrow, the nearly linear trail of seamounts farther seaward on the Cocos plate, and the tight cluster of aftershocks (figure 7), we believe that the asperity is likely to be a seamount. As described in the following section, the 3D OBS experiment is designed to obtain a detailed image of the top of the subducting slab. A seamount or other significant structural feature identified beneath the Cobano epicenter will be a powerful confirmation of the seamount-asperity hypothesis. In the absence of a structural asperity, this 3D data volume should indicate alternative mechanisms for the observed seismicity by reflection configuration, reflection/refraction amplitudes, and velocity distribution.

Smooth Segment Seismicity. We can also investigate the seismic front in a contrasting environment, the central Nicoya Peninsula, where the subducting Cocos plate is comparatively smooth (Experiment 1; Figure 1). We expect to delineate the velocity structure from the trench to beneath the Nicoya Peninsula, which will allow a close comparison of the Cocos-Caribbean plate boundary as defined by seismic reflection and refraction data versus its location from shallow thrust earthquakes. On existing seismic profiles, reflections from the plate boundary zone are commonly visible from the trench to near the shelf edge [Crowe and Buffler, 1983; Shipley et al., 1992], and large thrust earthquakes have occurred only 10-15 km landward of the shelf edge (e.g. 1978 Ms=7.0). Preliminary investigation, based on these data, suggests that the earthquakes may be deeper than the projected seismic reflection decollement. If this geometry holds true after revised hypocenter location and seismic reflection depth conversion, both performed using the same velocity model derived from our proposed wide angle profiles, then deep crustal accretion (of oceanic crust?) may be implied as a seismogenic process. Alternatively, if the revised hypocenter and decollement positions appear to coincide, then changes in the decollement zone physical properties and/or the increased strength of the overriding backstop likely account for the seismic front in this smooth segment of subducting crust. A particularly favorable aspect of this entire margin is that, based on existing MCS and OBH data, we confidently expect to acquire reflection images of the plate boundary (from OBS and land stations) within the seismogenic zone of interplate motion.

Cocos Ridge. An objective of the southernmost transect is to reveal the crustal structure in the vicinity of the subducting Cocos Ridge (Experiment 3; Figure 1). Here it is unknown whether the ridge tends to promote net accretion or erosion of the upper plate, and the magnitude of compressional deformation it induces in the forearc is controversial [Corrigan et al., 1990; Gardner et al., 1992; Heywood and Silver, 1983; Kolarsky et al., in review]. We also expect to establish the position of the subducting plate and its dip in this area, where the slab is not defined by Wadati-Benioff zone seismicity. Existing MCS data along the offshore portion of this transect suggest a very shallow subduction angle of $\approx 3^\circ$ [Kolarsky et al., in review]. It is possible that the buoyancy of the thickened crustal section of the ridge ($\approx$ 17 km thick as measured by Bentley [1974]) as well as probable younger age of the Cocos plate in this area causes the plate boundary to lie along the base of the crust of the overlying Caribbean plate [Protti et al., in review; McGeary et al., 1985]. By establishing the position of the plate boundary and measuring the crustal thickness of the subducting plate we may be able to identify thickened crust of the subducting Cocos Ridge. The expected shallow subduction angle [Kolarsky et al., in review] should help with this part of the experiment, and any evidence of landward ridge penetration beyond the coast will advance current understanding of regional plate motions, structural history, and arc volcanism.

Nicoya Complex Limits. A general objective is to differentiate crystalline basement (the backstop) and accreted sedimentary material in the forearc regions of all three transects. In the north, this boundary will occur seaward of the Nicoya Peninsula. The southern transect is close to Caño Island, so we can test the boundary location indicated by Baumgartner et al. [1989] and Di Marco et al. [in review] as discussed above (see Figure 1). Successful determination of this boundary will lead to improved estimates of the volume of accreted material and constrain interpretations of accretionary processes and prism development. Such information is also useful for studies of global mass flux [Reymer and Schubert, 1984; von Huene and Scholl, 1991] and volcanic geochemistry [Morris et al., 1990; Stern, 1991; Plank and Langmuir, 1993].

Field Program

Three geological and geophysical corridors across Costa Rica have been identified as part of the Global Geoscience Transects program (GGT), to study the nucleation of large subduction zone earthquakes, the controls on modern volcanism, and to document deep crustal structure (Figure 1). Several crustal geophysical experiments are planned beginning with a first phase, based on a marine seismic source and selected land explosive shots (the basis of this proposal, TICOSECT Phase I) and followed by a second phase using land sources, that will be designed using the results obtained from Phase I. Phase II, employing on-land sources, will likely encompass two 'high-density' wide-angle profiles. Phase I and Phase II geophysical experiments will provide detailed crustal structure and velocity information for the Costa Rican forearc and arc and thus provide the backbone for the other elements of the Global Geosciences Transects.

The focus of this proposal is TICOSECT Phase I, consisting of three onshore/offshore seismic experiments using a powerful marine airgun source array along the Pacific coast of Costa Rica. This work is a reflection/refraction and 3-D imaging program using ocean bottom and land instruments. The R.V. Maurice Ewing with its sound source of 20 air guns is proposed as the shooting ship. The source capacity will be about 11,450 cubic inches (188 liter) fired as often as every 27 seconds (50 m at 4.5 knots). The source capacity obtained with minor changes to the standard Ewing array is about three times that of the latest M/V Sonne (German research vessel) refraction work in this area. We also plan to obtain wide aperture, reversed profiles with land explosive shots along each transect. Costa Ricans (ICE) have volunteered to provide these land shots; they are capable and experienced in this work, having provided shots during the recent German/Costa Rican acquisition program. To improve signal-to-noise ratios we will re-occupy some marine shot locations for subsequent vertical stacking. This will require precise navigation of shot locations using a real-time differential GPS system. The 3-D imaging program also requires precise navigation. With an established reference station in Panama (600 km baseline) navigation updates can be obtained about every three seconds relayed through the INMARSAT data channel. Our previous experience with a similar navigation system offshore Barbados (300 km baseline) indicates we should expect relative locations to within about 10 m at all times.

The three experiments will acquire reflection and refraction data at sea using a combination of the GEOMAR OBH (ocean bottom hydrophone) and the UTIG OBS (ocean bottom seismometer). The UTIG instruments, designed and built by UTIG, have been recently upgraded; Table 1 gives the main OBS characteristics. For this experiment 20 UTIG OBSs and 10 GEOMAR OBHs will be available. Data will be acquired at a 5 ms sample rate in all the OBHs and at 8 ms sample rate on all the UTIG OBSs to allow 3 component data recording. The 3 component data provide redundancy for picking arrivals, record shear waves for identification of shear converted phases and additional lithologic discrimination, and allow for improved OBS location determination.

Instrument reliability. Questions of the reliability of the UTIG OBS instruments were raised by a recent experiment along the East Pacific Rise in which 13 OBSs were lost. In this experiment, we used anchor frames of a new design without in situ pre-testing. This was clearly a mistake; apparently half of the 20 instruments we deployed on the first array flipped over upon landing on the rough terrain and were unable to return to the surface after being released from their anchors. After this incident, during the same cruise, we modified the anchor frame and solved the problem. Overall, the experiment was successfully completed and 45 of 46 recovered instruments returned full data. We plan to use anchor frames of an earlier, proven design for the proposed project, so the problem experienced in this cruise will not be repeated. We are currently in the process of replacing the OBSs lost during the East Pacific Rise experiment, and expect to bring the number of available instruments in the UTIG/ORSTOM instrument pool up to the original 30 by early 1994. The GEOMAR OBH instruments have now been used successfully in many projects including the summer 1992 Costa Rica survey (SO81). Most recently GEOMAR completed an OBH survey in the Mediterranean Sea with 21 deployments and 100% instrument and data recovery. These instruments should now be considered robust and reliable.

Onshore instrumentation will require 30 seismographs that can record continuously for several days. Such instruments are available at the GFZ (Geologisches Forschungszentrum), Potsdam, Germany and from the IRIS/PASSCAL instrument pool. The time of the experiment is not yet fixed (December 1994 is preferred), so we are applying for the instruments from both pools to assure availability. GEOMAR will apply to GFZ and UTIG to IRIS. Financial support for instrument transportation to Costa Rica, for expendables, three field operators (technicians), and later data reduction was applied for in the GEOMAR proposal to the Deutsche Forschungsgemeinschaft.

Ground transportation, field assistance (5 cars with drivers and some additional personnel), and explosive shots (for reversed refraction profiles) will be provided by the Costa Rican institutes under the leadership of ICE (the electric utility company). ICE has an extensive radio communication system to its mobile units, which we will extend to the ship. In addition, ICE and RECOPE (the national oil company) will operate their 120-channel DFS V instrument (7.2 km cable length) and also record all shots. UTIG will work with ICE to refurbish the DFS and provide technical assistance during the experiment. UTIG will also provide technical help to assure reliable ship to shore communication and trigger pulses for the DFS instrument.

Existing MCS data preclude the need for MCS acquisition during this project (Figure 2). MCS profiles along Experiment 1 and 3 transects reveal the shallow structure and show the plate boundary position from the trench to at least the shelf edge. Lower quality data and more complicated structure obscure the plate boundary on the Experiment 2 MCS line, but the concentrated shooting and instrumentation (described below) combined with orthogonal refraction profiles and single channel seismic (for reference) should provide excellent coverage for this experiment.

Experiment 1. The land instruments will first be installed along the profile between Garza (Nicoya peninsula) and Los Chiles (close to the Nicaraguan Border; Figure 1). The first 20 instruments will be separated by 3 km each (Garza to Rio Tempisque), while the remaining 10 instruments will be separated by 6 to 8 km each. With this spacing instruments will be placed a maximum distance of 140 km NE of the coast, extending 30 km past the volcanic arc. Based on earlier experiences, this setup will allow a detailed investigation of the crustal structure from the trench into the Tempisque Basin. Energy transmission across the Tempisque Basin and the volcanic arc is yet unknown, but the results of this experiment will provide valuable help for the land profile in the second phase of TICOSECT. The DFS V will be located close to the coast and record 120 channels on a 7.2 km geophone array.

Offshore, 10 OBSs and 10 OBHs will be deployed along the transect (Figure 12). Ten instruments will be deployed at 5 km spacing starting from 10 km seaward of the trench axis, and the remaining 10 instruments will be deployed every 2.5 km to near the coast. The denser spacing on the landward end of the profile is designed to permit direct imaging of the recorded data using pre-stack migration techniques.

The 100 km dip line will be shot two times. The ship's speed will be reduced to the minimum, e.g., 3.5 to 4.0 knots. On the first pass, shots will be fired every 40 seconds (a shot spacing of 70-80 m). The re-shoot of the line will be done at a 2 minute shot interval (about 210-240 m) to guarantee that reverberations from previous shots are kept to an acceptable level. If source generated noise is not a problem, data from both lines can be combined. In addition to the primary dip line, one or two 20 km strike lines will be shot at the landward end of the dip line.

The OBS and OBH instruments will be made ready for deployment prior to arrival at the first transect study area. Their deployment will require one day and shooting will require 2 days. Instrument recovery can be accomplished in 1 day, and we are allowing one day for contingency and transit, so the time required for Experiment 1 is 5 days. During the Experiment 1 shooting, another 10 UTIG OBSs will be prepared for Experiment 2 deployment. As the 10 GEOMAR and 10 UTIG instruments are recovered from Experiment 1, they will be refurbished for deployment in the second study area.

Experiment 2. The second experiment includes wide angle profiles and a 3-D ocean bottom receiver experiment designed to identify and map the asperity at the site of the 1990 Cobano (Ms=7.0) earthquake (Figure 1). Based on an expected size of about 10-20 km diameter (from Cloos [1992] table 1) at a depth of about 12 km, the 3-D survey will consist of 36 dip lines spaced every 250 m and covering a 35 km by 9 km area (Figures 10 and 13). Two lines will be extended seaward and landward for a total length of 100 km, and five 40 km strike lines will be acquired. The shot interval is expected to be 50 m along the lines unless reverberation levels are too high. In that case, the shot interval may be increased to as much as 250 m, because ship speed of 4.5-5.0 knots is necessary to acquire the required number of lines in a 6 day period. To test the reverberation level, we will recover one of the initially deployed GEOMAR OBHs after several hours of shooting a test pattern at shot intervals of 50 m, 100 m, 150 m, 200 m, and 250 m. The optimum shooting schedule will then be chosen so that reverberations are at an acceptable level yet the shooting rate is as often as possible. A longer shot interval will reduce the imaging fold, but, as discussed below, each shot-receiver pair contributes so the fold should remain acceptably high.

The offshore receivers will be deployed in a rectangular grid separated by 5.0 km along the inline (shooting) direction and 1.0 km in the cross line direction (Figures 10 and 13). Based on the 50 m shooting schedule, each of the 3-D grid lines will consist of 700 shots. Assuming all instruments record and return successfully, 21000 pressure or vertical component traces will be recorded per shooting line. Nominal imaging fold will be determined by the number of source-receiver pairs that can be coherently imaged into each subsurface point. Any instrument failure would, to a first approximation, reduce this fold linearly. Consequently, reduction of the brute signal to noise level is not likely to be a significant problem for reasonable instrument failure, e.g., <20%, because the nominal fold is 7.56×10^7% (21000 shots/line x 36 lines). Thus, failure of widely separated instruments is not considered significant; only failure of several nearby instruments would significantly limit subsurface illumination in the vicinity of these instruments. Several of the UTIG OBSs will be equipped with hydrophones from GEOMAR so that instrument responses can be compared. Later, during processing, a filter will be designed so that data from both instruments can be used in the imaging.

The land instruments will be split into two groups. One group of 15 instruments will be placed near the southeastern coast of Nicoya peninsula, similar to the OBS deployment offshore. These instruments will record all shots without being moved. The other 15 instruments will be used to observe a wide-angle profile from Puntarenas across the central valley. They can be deployed three times each, and record for about 48 hours each time. If the shot interval is one minute, each instrument will record 12 to 14 shots for any 200 m wide offset bin, which allows later stacking and should provide a good signal to noise ratio, despite the expected high cultural noise level. With an average spacing of 2 km between instruments, a 90 km long profile will extend from Caldera to Puerto Viejo across the volcanic arc. During this experiment the DFS V instrument will be setup twice, first along the Montezuma-Cobano road, and later farther northeast near Pochote. The two DFS V lines will examine volcanic vs. sedimentary sections of the Nicoya Peninsula. Because the shooting will be done in a pattern that traverses the entire grid, both deployments will record shots from throughout the 3-D grid; one setup will also record a colinear strike profile.

To acquire the 3-D OBS/OBH data will require 6 days. To extend the survey with the two 100 km dip and the five 40 km strike lines will require an additional 2 days. Thus, the bottom instruments will record a total of 8 days, their maximum capacity. We are budgeting two days for instrument deployment and two days for retrieval. One day of transit is scheduled during which all 10 GEOMAR instruments and 10 of the UTIG instruments will be refurbished for Experiment 3.

Experiment 3. The offshore setup and shooting plan for this transect is identical to Experiment 1, and the onshore corridor is between Dominical and Limon. The 25 land instruments will be placed from the coast into the Cordillera de Talamanca along the 50 km long road entering the mountains. The remaining 5 stations will be deployed east of Turrialba volcano, on the eastern flank of the Cordillera. The earlier experiments by the German groups indicate that good energy transmission is expected along the western part, but we have no experience across the Cordillera. Again, this will provide valuable information for the second phase, when land shots are to be observed across the Cordillera. As in the first experiment, the DFS V will be located close to the coast.

Summary. The field program consists of three experiments with eight days of transit from San Diego to Costa Rica. Experiments 1 and 3 will each take one day to deploy instruments, two days to shoot and one day to recover the instruments. Experiment 2 will take two days to deploy, eight days to shoot, and two days to recover. Thus a total of 20 days on location. We allowed an additional four days total for transit between experiment sites, for contingency, and for a quick port-stop to pick up scientists in Costa Rica. These four days "contingency" are not excessive considering the necessity to coordinate the onshore work with the offshore work. The total cruise time requested is 32 days. The extensive land network requires the work to be scheduled during the dry season (mid-November to April), so we tentatively request ship time in December 1994.

OBS Imaging Evaluation

To evaluate the feasibility of obtaining detailed images of the subducting Cocos plate using OBS data, we constructed three simple velocity models and generated finite difference synthetic data. The models (Figure 14) are based on preliminary interpretations of the recently acquired German /Costa Rican refraction data [von Huene, pers. commun.] off the Nicoya Peninsula. We modeled the portion of the forearc where the plate boundary is 10-20 km deep (Figure 14, a), which includes the interplate seismic front. The first model has horizontally stratified velocity layers in the upper plate above a smooth, gently dipping subducting plate (Figure 14, b). This is used primarily as a control model, but it should apply to the smooth segment of the subducting Cocos plate off the Nicoya Peninsula. The second model has an identical upper plate velocity structure but includes a 2 km high, flat-topped seamount on the subducting plate (Figure 14, c). Many of the seamounts currently approaching the MAT are comparable in relief and exhibit relatively flat profiles due to elongation in the dip direction. The third model has identical morphology on the subducting plate (flat-topped seamount) but has a more complicated upper plate structure (Figure 14, d). In this case the seamount is intersecting a landward dipping backstop of crystalline rock (Vp=6.2 km/s) and the material seaward of the backstop (Vp=5.5 km/s) is weaker accretionary prism material. The purpose of the second and third models was to see if OBS data are capable of resolving a subducted seamount at seismogenic depths and therefore able to test the seamount-asperity seismogenic model.

The finite difference modeling results are quite promising, with clear reflection arrivals from the top of the slab, a mid-crustal (oceanic) reflector (except where excluded in model 3), and Moho. Figure 15 shows synthetic records (pressure) from each of the three different input models. The display is limited to a 5 s-9 s time window that includes the three important reflections. There are five separate records for each velocity model that consist of 500 shots recorded by the individual OBSs (originally 600 shots/record with 50 shots trimmed from each side). Several high phase velocity events in the records are reflections from the edge of the finite difference model. Two of these events are labeled "edge effect" in OBS record 3, model 1, but they are apparent in most of the records. Because this noise is a result only of the modeling technique and parameters used, similar events will not contaminate the field data (We do, however, expect other low phase velocity coherent energy as seen in the modeling, which will necessitate f-k filtering either prior to or as part of the migration of the data). The most significant events relative to this analysis are reflections from the side of the seamount (recorded by OBSs at 5, 10, and 15 km) and from its top (recorded by OBSs at 15, 20, and 25 km). These events are visible in both model 2 and 3 results, so seamount detection appears likely even with variation in the forearc structure.

The results of the recent German-Costa Rican projects also point toward the likely success of imaging the plate boundary structure. Figure 16 (upper portion) shows an OBH record from SO81 profile 200 (see Figure 3 for location) about 40 km landward of the trench (from Flueh [personal communication, 1993]). A high amplitude reflection arrival from the top of the subducting Cocos plate is visible on this record and on the coincident (conventional) seismic reflection profile (Figure 16, lower portion; from Hinz et al.[1992]). Other important arrivals have been interpreted on the OBH record shown in Figure 16 and on the other five OBH records and two land records collected along this profile. The resulting interpretation for SO81 profile 200 is shown in Figure 17 (from Flueh [personal communication, 1993]). We expect to make similar but significantly more detailed structure/velocity interpretations along our transects, which will also extend up to 100 km farther onshore.

Data Reduction and Analysis

The basic data reduction encompasses a variety of instruments and data. The reduction of the onshore instruments, including the DFS V data will be the responsibility of GEOMAR along with their OBHs. UT will be responsible for primary data reduction of the UT OBSs. All of these data will be processed to SEG-Y format to allow integration and exchange between UTIG and GEOMAR. The basic OBS pre-processing includes demultiplexing, as required, precise location and orientation of each instrument using water-wave arrivals (c.f. Nakamura et al., 1987), horizontal component rotation to radial and tangential directions, clock-drift corrections, merging with navigation data, and reformatting to SEG-Y, the industry and IRIS/PASSCAL standard format. Some initial bandpass filtering and f-k filtering will be applied as necessary. The instrument transfer function between German and UT ocean instruments will be determined at this stage from GEOMAR hydrophones deployed in a few UT OBSs. Once the basic data reduction is concluded, data will be exchanged between groups and provided to national archiving schemes. As illustrated in the tentative project schedule (Figure 18), we plan to cooperate fully during the data analysis and interpretation phases, including personnel exchanges, rather than duplicating efforts.

<u>2-D Data Processing</u>. The first personnel exchange will occur during the processing of the Experiment 2 extended dip lines and strike profiles (Figure 18). K. McIntosh will travel to Kiel and work with E. Flueh and others to develop 2-D crustal models by iterative ray tracing and amplitude modeling. This work will combine results from the OBSs, OBHs, and land stations. The objectives of this first stage are to establish the velocity and crustal structure along this transect, develop the velocity model that will be used for the 3-D processing, and establish consistent modeling procedures to process the data sets from Experiments 1 and 3. For efficient use of personnel the Experiment 1 data will then be analyzed at UTIG and the Experiment 3 data analyzed at GEOMAR. After these initial velocity and crustal structure interpretations are made, selective 2-D migrations of the crustal transects, including ocean bottom and land data, will be performed at UTIG (Figure 18). This will extend the seismic reflection image of the plate boundary beneath the Costa Rican landmass, well into the seismogenic zone of the plate boundary, and also extend seaward to tie in with the existing reflection data.

<u>3-D Data Processing</u>. The 3-D imaging experiment will be processed at UTIG. The University of Texas System Center for High Performance Computing's (CHPC) Cray Y-MP8/864 will be used for this processing, and the work will be carried out by S. Saustrup, K. McIntosh, and the graduate research assistant, under the supervision of P. Stoffa. We expect that GEOMAR will send one team member to Austin during the analysis phase to help with this effort. Processing of the 3-D OBS data will be done using pre-stack depth migration. Prior to migration, muting and f-k filtering will be applied to eliminate coherent noise and enhance the reflections of interest. Two migration approaches will be considered: Kirchhoff migration [Schneider, 1978] and split step Fourier migration [Stoffa et al., 1990; Tanis, 1993]. A 3-D Kirchhoff approach can be employed for arbitrary source-receiver positions. Ideally, we could use a 3-D finite difference solution of the eikonal equation [Vidale, 1991; Faria and Stoffa, 1993] to generate for each source and receiver position direct wave travel times into the subsurface image volume. Stacking the data along the travel time trajectories predicted by summing the source and receiver times would result in the migrated image. Initially, however, a computationally less intensive approach will be to idealize the subsurface 3-D velocity function based on simple layers with gradients as determined from iterative ray tracing that models the reflection events of interest. These travel times can be quickly generated for the pre-stack migration and the resulting images will be used to refine the 3-D velocity function. This process will be repeated using a subset of the receivers until the images are in agreement where overlap in illumination occurs.

Alternatively, we can employ the split-step Fourier method to generate the migrated images. In this case, the data have to be regularized onto an equi-spaced x and y grid. This can be accomplished by trace interpolation. We currently use CGG's Geovecteur on the CHPC Cray Y-MP for all basic seismic data processing, such as f-k filtering and trace interpolation. After interpolation, we propose to migrate the source and receiver wavefields in one step directly to the depth just above the first reflection of interest using a replacement medium velocity. At this point, migration will proceed to deeper depths, possibly at 50 m intervals, and the image will be constructed by correlating the source and receiver wavefields at each depth. Optimized Cray code that runs in parallel on all 8 processors of the CHPC Cray Y-MP8/864 is available for this task. The assumption of small lateral velocity variations limits the accuracy of this method, but experience has shown that lateral variations of less than 50% in each depth interval gives good results [Tanis, 1993]. This is a very efficient migration algorithm and may be adequate for the imaging required.

Earthquake Relocation. By the third year we expect to have the regional velocity structure of the upper plate determined using the data from this project and the previously acquired German and Costa Rican data. At that time an earthquake seismologist from Costa Rica will visit UTIG to work with our seismology group on an earthquake relocation project. Using the improved upper plate velocity structure the great number of earthquakes recorded by local networks in Costa Rica may be accurately relocated. This should immediately improve seismo-tectonic interpretations of Costa Rica, and, in the long term, the better upper plate velocity structure will continue to be useful for data collected by the extensive local area networks supported by the National University and U.C. Santa Cruz (F. Güendel and K. McNally) and ICE.

Significance of the Proposed Research

The proposed work is both scientifically and logistically difficult, but the basic results, three velocity/structure cross-sections from the trench to the arc and a 3-D image of a portion of the downgoing slab, provide unique data to examine many basic questions of accretionary prism to seismogenic zone relationships.

1. In the vicinity of the Cobano earthquake, the 3-D images will reveal whether the morphology of the downgoing plate is consistent with a seamount asperity. The work should show the size of any existing feature and possibly its relationship to a crystalline rock (high velocity) backstop.
2. Supplemented with existing German and UT multichannel data, the proposed transects should bring to light the spatial relationship between the seismic reflection decollement and the position of shallow, subduction zone thrust earthquakes. Thus questions about the nature of the seismic front (changes in fault zone properties?, oceanic basement accretion?, upper plate tectonic erosion?) and the geologic significance of deep reflection patterns can then be addressed.
3. This leads to questions of mass-balance. The evolution of accretionary prisms remains controversial with conflicting ideas about whether sediment accretion is the norm or the exception and why. Delineation of the detachment fault morphology (i.e. ramps, flats, etc.), traced from the trench to the seismogenic zone should provide good first order constraints on amount of accretion, underplating, and bypassing beneath the prism.
4. The velocity structure will also be useful in mass balance calculation and porosity reduction estimates for the three different transects, providing estimates of the geometry of the backstop and nature of the material comprising much of the accretionary prism (is it Nicoya-like or accreted sediments?). The volume of the accretionary prism may be significantly different between the northern (smooth crust, accretionary?), central (rough crust, erosional?) and southern (ridge effects, erosion?) areas due to variations in the geometry and topography of the incoming plate.
5. The velocity structure should allow seismologists to relocate local network earthquakes to refine models of the tectonics, from source mechanism, to major seismotectonic questions related to the Wadati-Benioff zone and cross-structures in Costa Rica.
6. We may be able to place limits on the amount of penetration of the Cocos ridge beneath Costa Rica and therefore refine timing estimates of its initial subduction. This is important for documenting plate motions, demonstrating its affect on the arc and forearc structure, and for understanding its affect on arc volcanism.

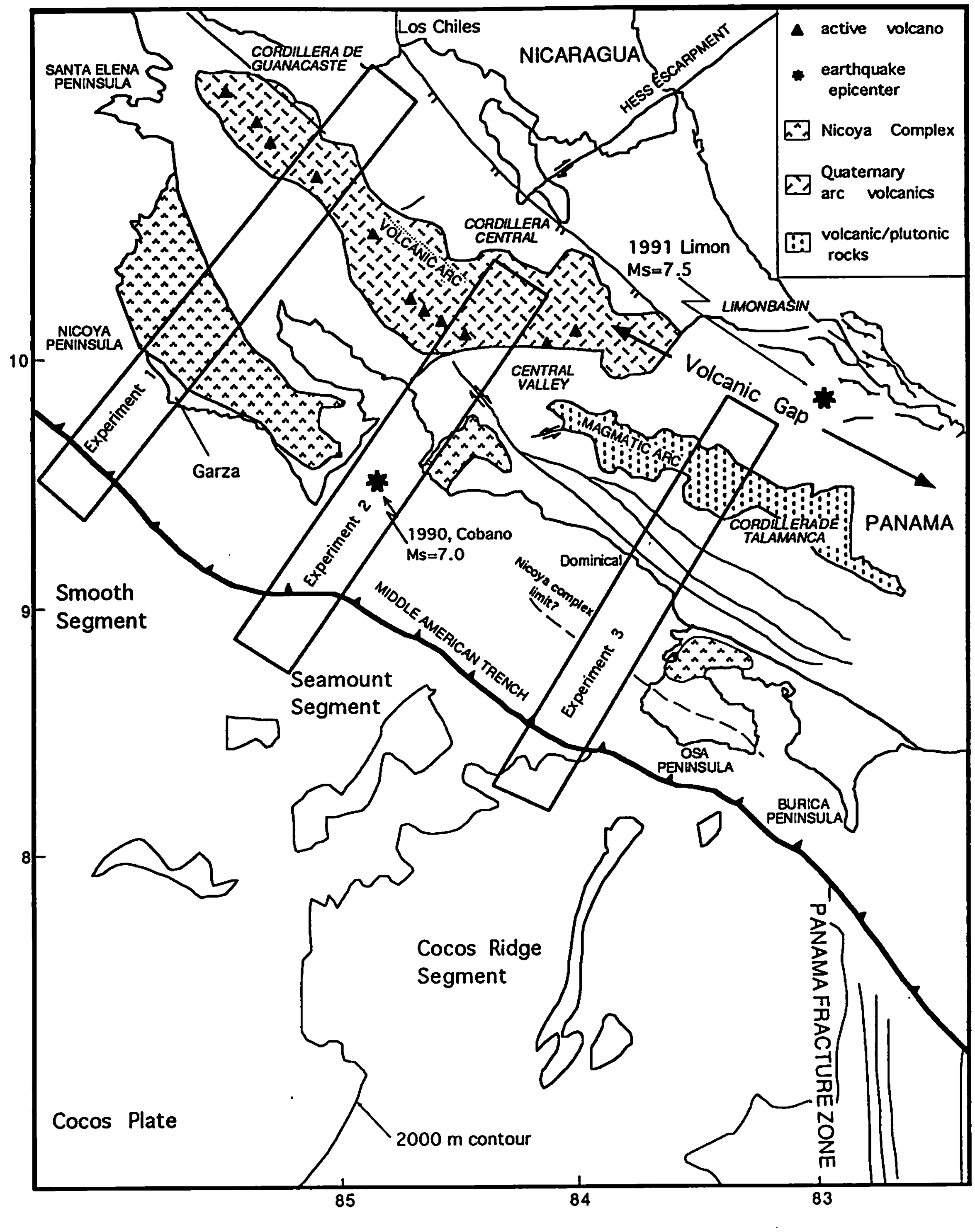


Figure 1. Map of Costa Rica showing the three transects containing TICOSECT Phase I geophysical experiments proposed in this project. Note the varying morphology of the subducting Cocos plate: from NW to SE, smooth, seamount dominated, and Cocos Ridge segments. The 1990, Cobano epicenter is located in the Experiment 2 corridor. The trends of the volcanic centers are deflected eastward in central Costa Rica adjacent to the volcanic gap. The volcanic gap is aligned with the projection of the Cocos Ridge, as is the 1991 Limon epicenter near the Caribbean coast. The dashed line crossing the Experiment 3 corridor and Osa Peninsula is the seaward limit of Nicoya complex ophiolitic rock interpreted by Baumgartner et al. [1989]. Experiment 3 will be a direct test of this interpretation.

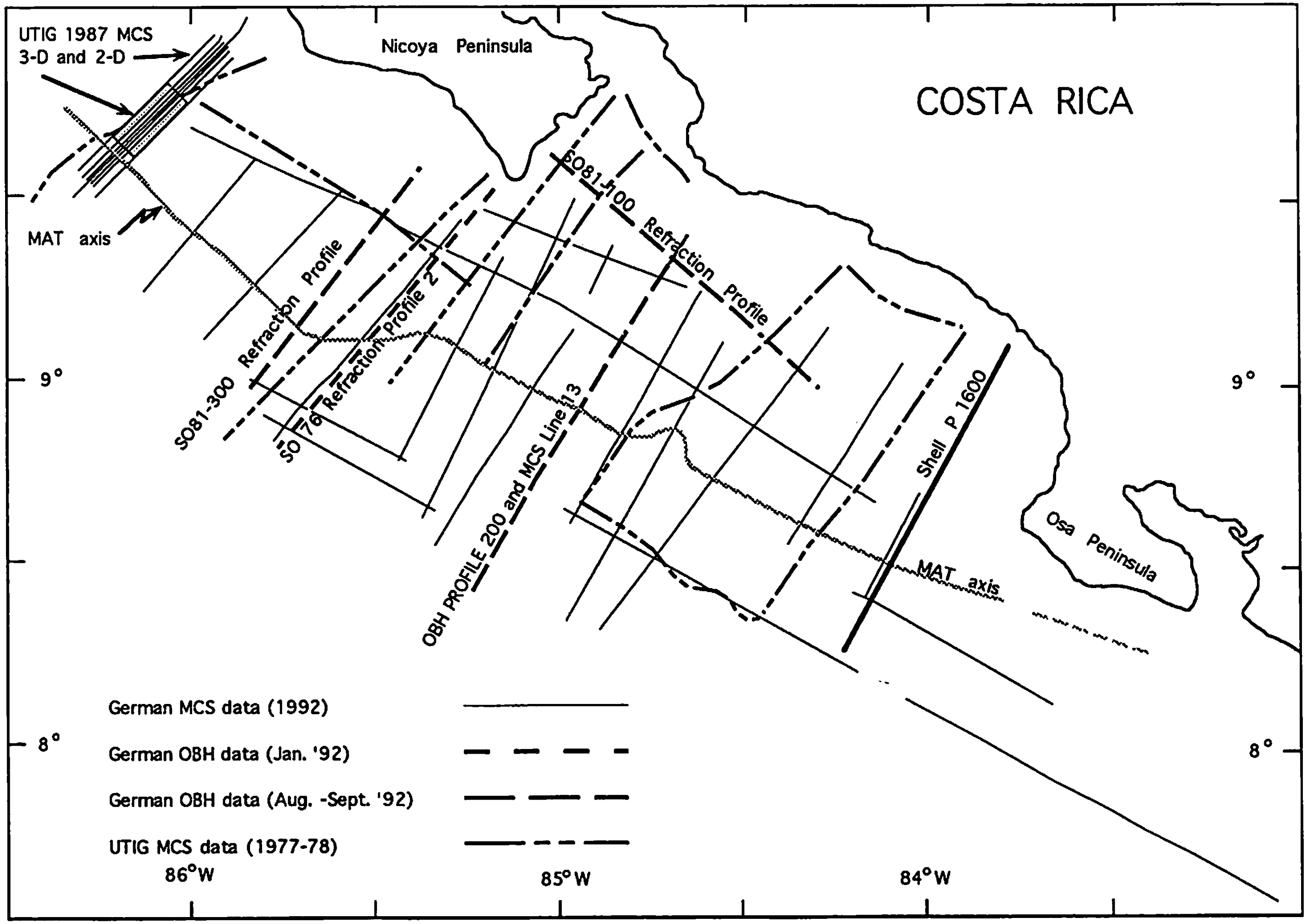


Figure 2. Map of offshore portion of study area showing multi-channel seismic reflection (MCS) data and German ocean bottom hydrophone (OBH) profiles. The first German cruise, SO 76, resulted in only 2 OBH fully working on each of three lines. Only Profile 2 of this test cruise is shown here. The German MCS data are of high quality and provide good regional coverage when combined with the UTIG and Shell data. The OBH data from the second cruise, SO 81, were acquired with 6 or 7 OBHs and two or three land instruments on each of three profiles (SO81-100,200,300).

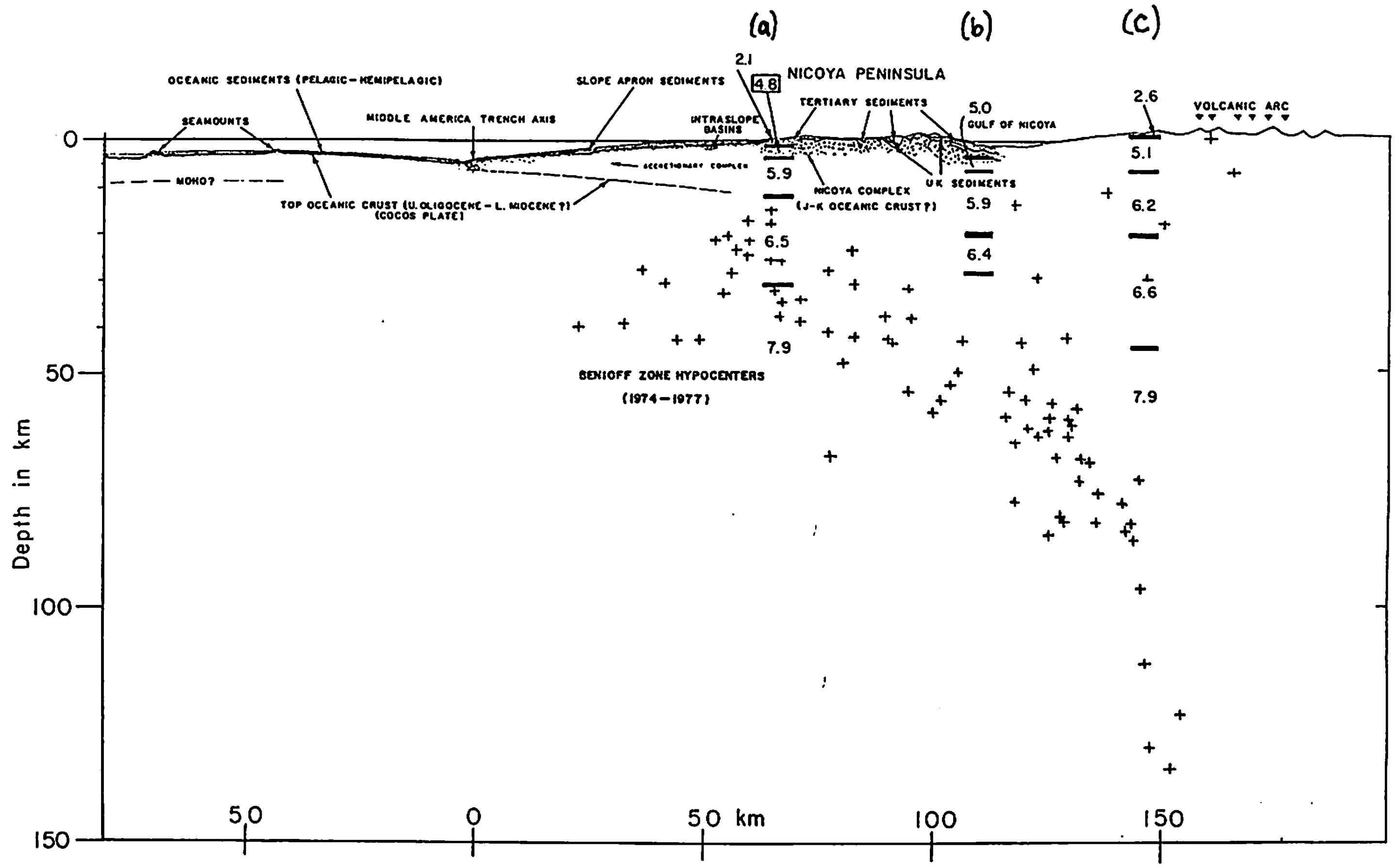


Figure 3. Crustal section across the Nicoya Peninsula and volcanic arc from Buffler et al. [1985]. Velocity model (a) was derived from an offshore-onshore seismic refraction profile recorded by two stations on the Nicoya Peninsula. Models (b) and (c) were derived by Liaw [1981] and Matumoto et al. [1977], respectively, using earthquake arrival times. The plate boundary is not clearly defined by these models (compare velocities and hypocenters). Note the 43 km crustal thickness interpreted in model (c) near the volcanic arc.

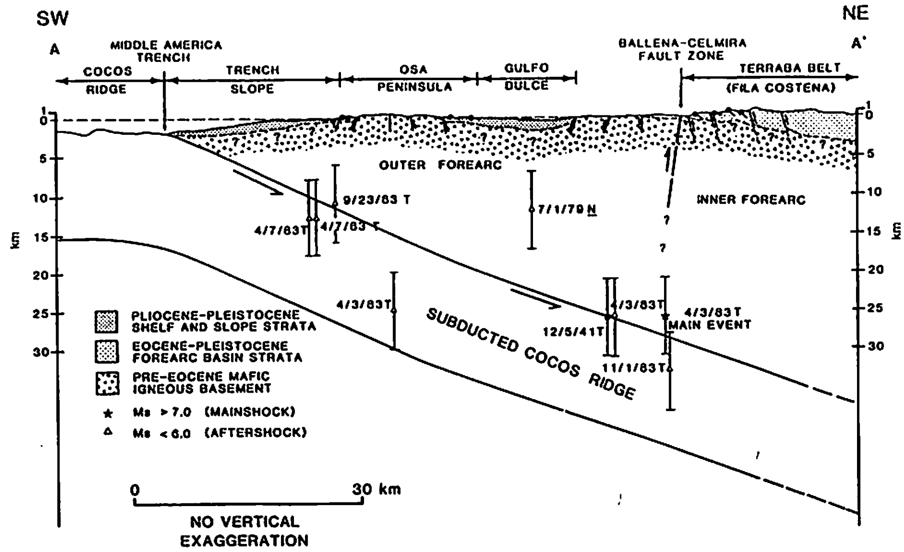


Figure 4. Cross section of the forearc in the Osa Peninsula area of southern Costa Rica where the Cocos Ridge subducts [from Corrigan et al., 1990]. These authors interpreted the forearc as igneous basement with a sedimentary cover similar to Guatemala. Seismicity does not continue along the NE dipping trend indicated in the forearc area here but is restricted to depths of < 50 km.

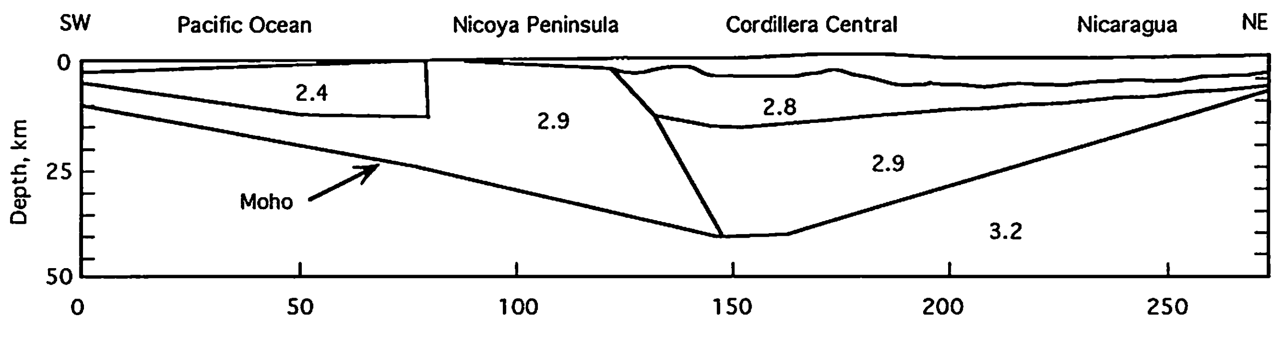
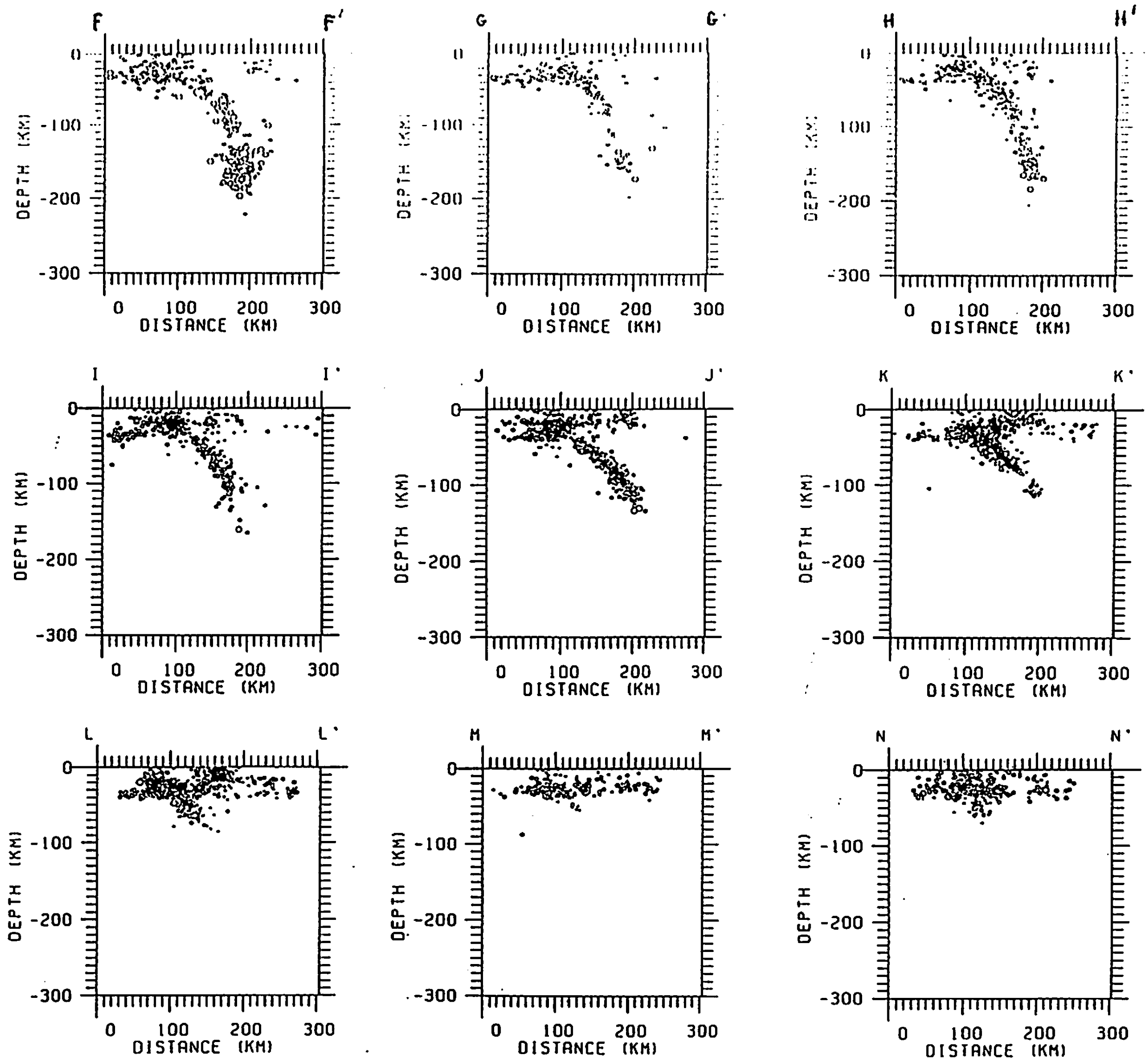


Figure 5. Crustal structure modeled from gravity data by Ponce and Case [1987]. Profile extends from the MAT, off the Nicoya Peninsula, northeast across the Central American isthmus to southern Nicaragua. The boundary between Nicoya Complex ophiolitic rock (ρ=2.9) and the accretionary complex (ρ=2.4) is modeled as a vertical interface located slightly offshore.



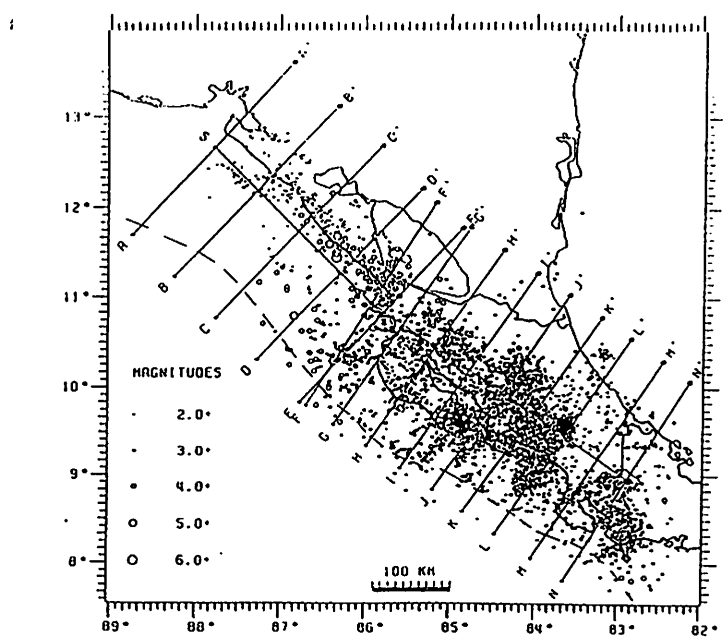


Figure 6. Seismicity cross sections F-F' to N-N' from southern Nicaragua to southern Costa Rica and location map from Protti et al. [in review]. All data are from local networks. There is no vertical exaggeration and horizontal distance is from the trench axis. The dip and depth of the seismogenic slab shallows rapidly in central Costa Rica as its length is reduced. There is also a remarkable increase in intraplate (Caribbean) seismicity from north to south. The seismic front, defined by interplate thrust earthquakes, is 30-70 km landward of the trench; deep events closer to the trench are within the subducting Cocos plate.

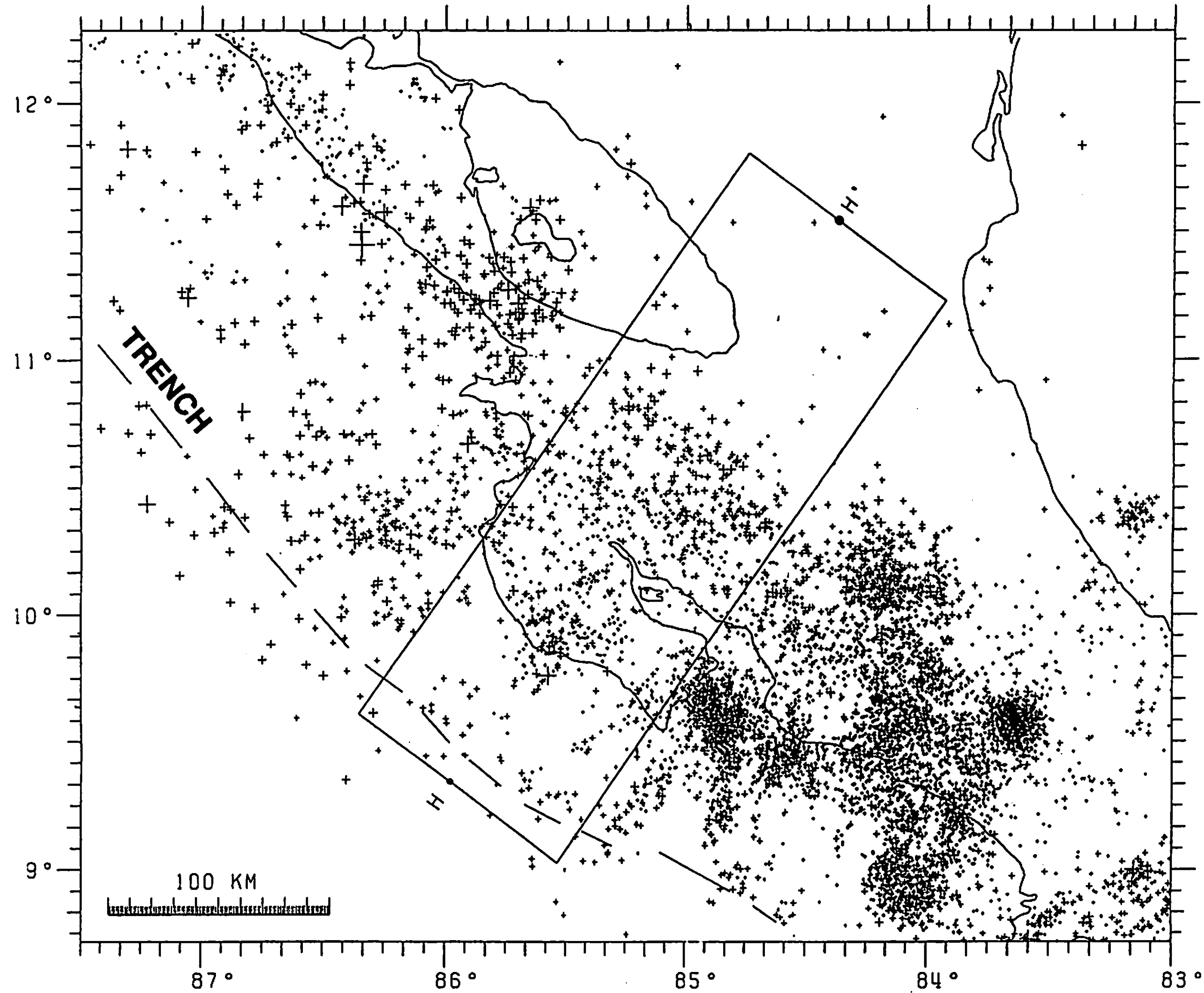


Figure 7. Earthquake epicenters recorded by local seismographic networks from 1984-1990 (plus two larger events from 1978). Note the distinct clustering of events southeast of the Nicoya Peninsula. One cluster is in the vicinity of the Cobano earthquake and two other clusters occur near our proposed Experiment 3 transect. These data are from Protti [personal communication] and include the data (the seismicity profiles) from Protti et al. [in review] shown in Figure 6 (please disregard the box H-H').

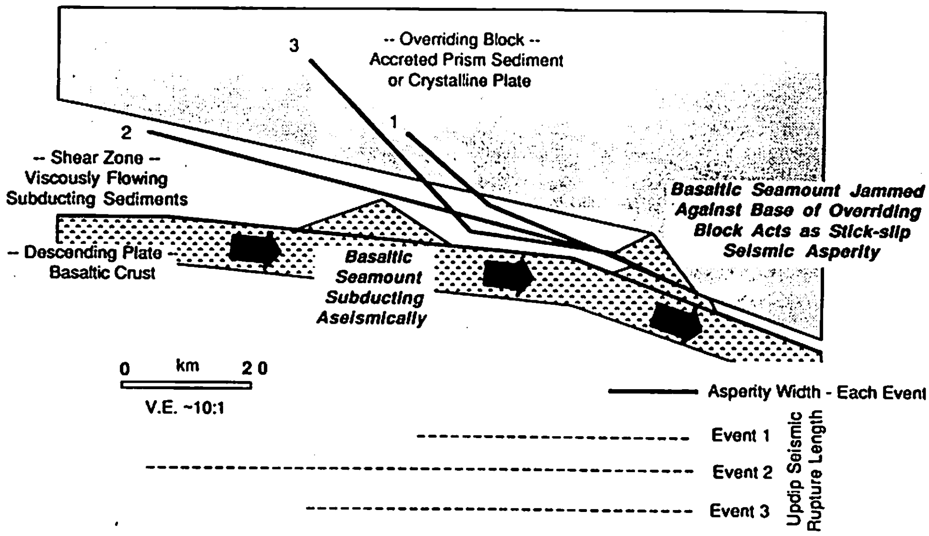


Figure 8. Schematic model for nucleation and propagation of thrust-type subduction zone earthquakes (seamount asperity model) from Cloos [1992]. Earthquakes nucleate where seamounts hit the overriding, strong backstop. The seismic front where the seamount dominated segment of the Cocos plate subducts may be determined by this type of process.

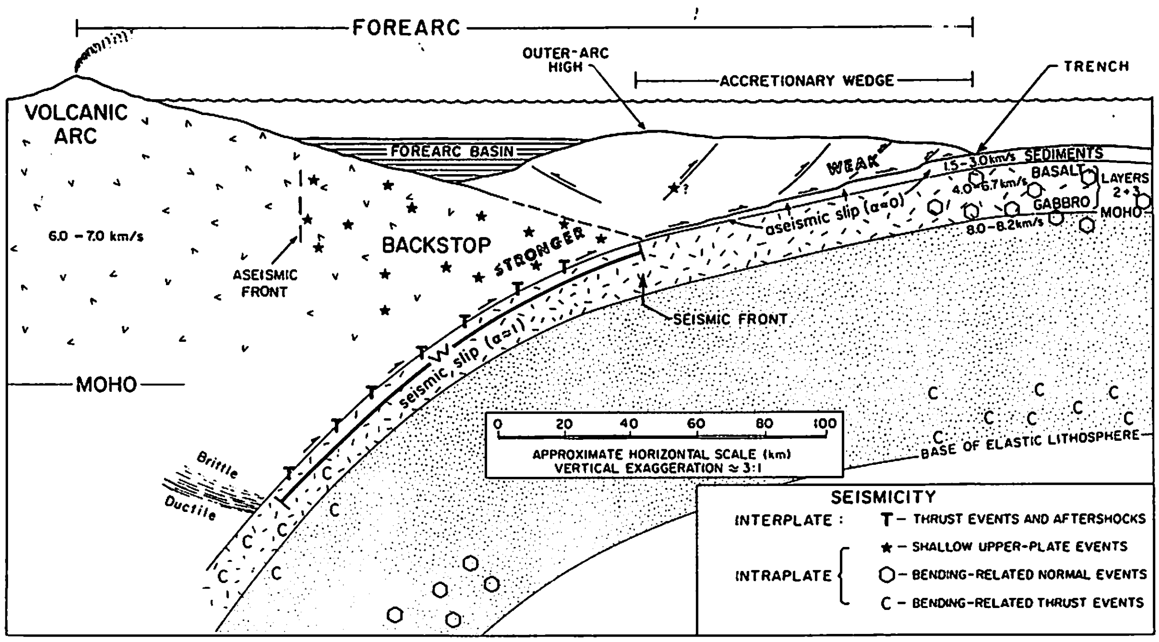


Figure 9. Schematic model of subduction zone seismicity from D. Byrne et al. [1988]. This model predicts aseismic slip beneath the relatively weak accretionary prism and a distinct seismic front marking the seaward extent of interplate thrust earthquakes. The seismic front occurs where the subducting plate is thrust beneath a stronger, arc-related backstop.

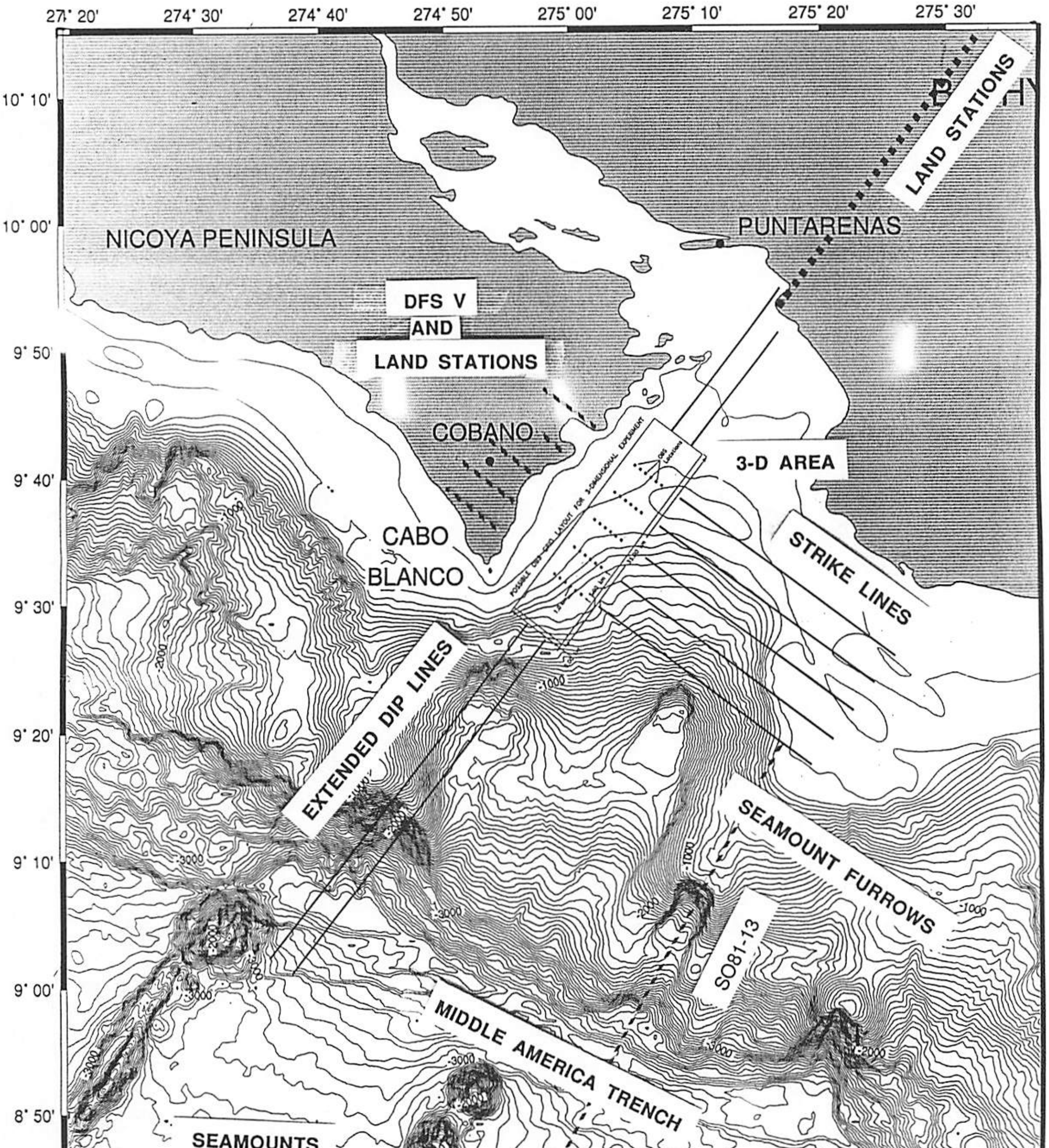


Figure 10. Map showing TICOSECT seismic experiment 2 and detailed bathymetry from von Huene et al. [in review]. The experiment includes dense shooting over a 9 X 35 km grid, two 100 km dip lines, and five 40 km strike lines. All shots will be recorded by the 30 instrument OBS and OBH array, by 30 land instruments, and a DFS V land system. Several seamounts are clearly imaged just seaward of the MAT on the Cocos plate, and three distinct furrows in the trench slope, aligned with the Cocos-Caribbean convergence vector, show paths of recently underthrust seamounts (see label). German MCS profile SO81-13 followed one of the furrows and is displayed in Figure 16. A fourth furrow is present along the trend of the Experiment 2 extended dip lines although its seaward end has been modified by another underthrust seamount located slightly landward of the -2000 contour label. This furrow may mark the path of a seamount that is now colliding with the backstop and is thus the nucleation site for earthquakes such as the 1990 Cobano event.

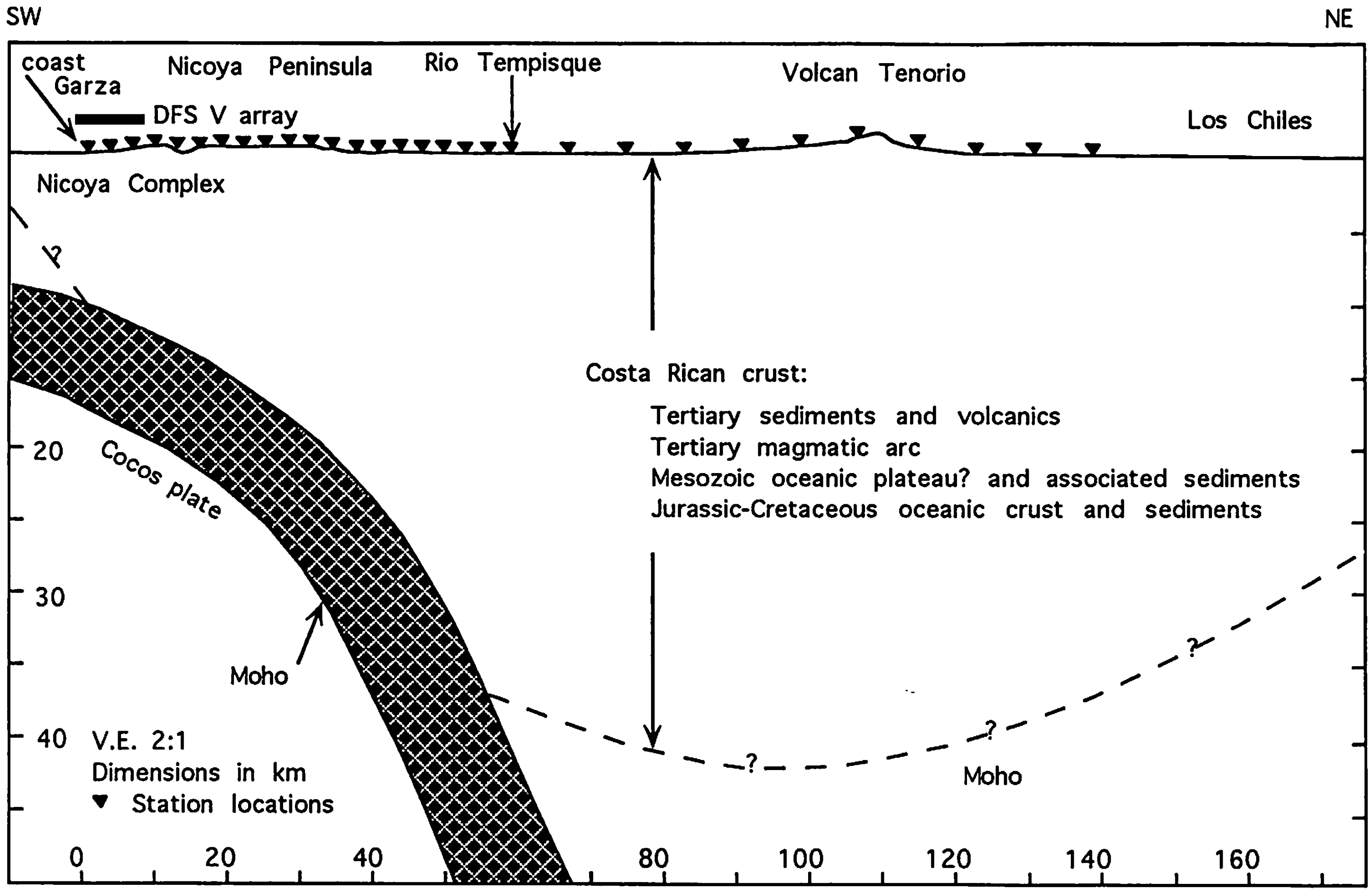


Figure 11. Schematic cross section along land portion of experiment 1. The approximate seismograph station layout is shown with 3 km spacing across the Nicoya Peninsula and 6-8 km spacing farther NE. The DFS V recording system will span 7 km near the coast. The arc crustal thickness is from Matumoto et al. [1977] and slab position approximated from Protti [1991].

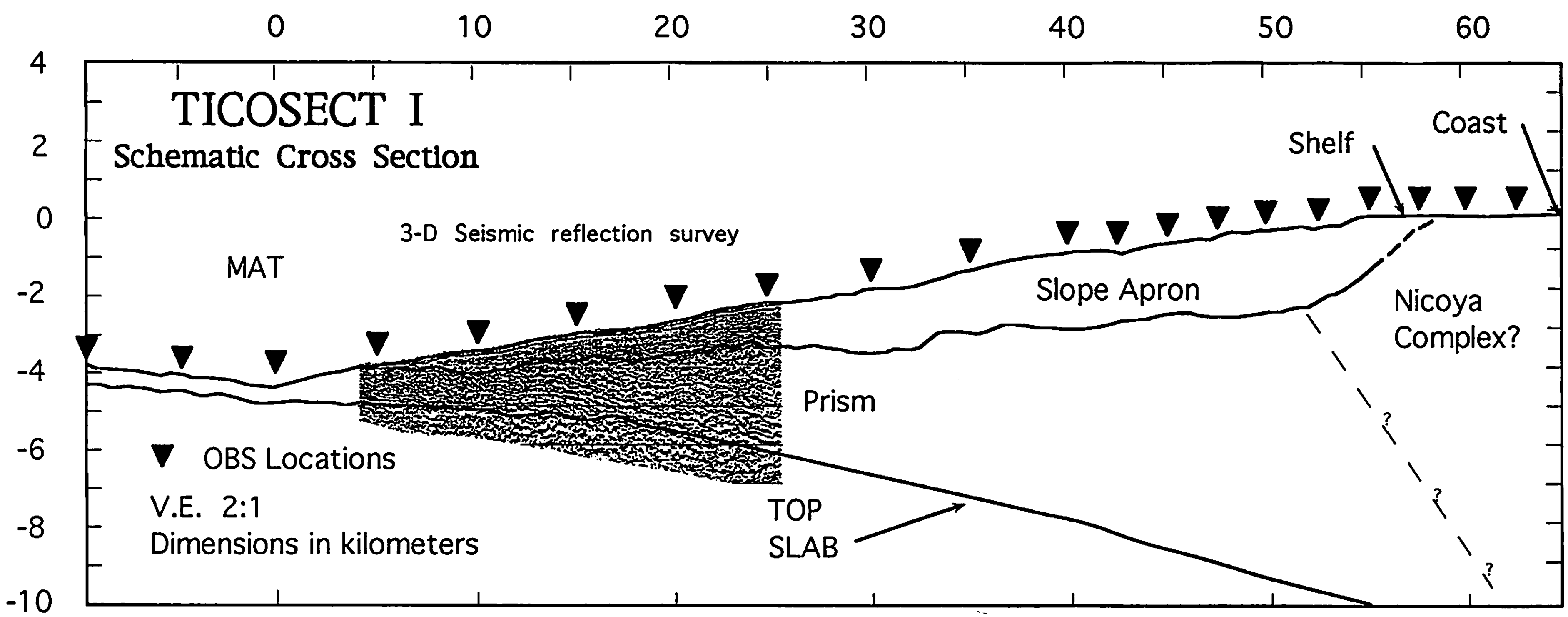


Figure 12. Schematic cross section from the Middle America Trench to the coast off the central Nicoya Peninsula. The OBS spacing will be 5 km from the trench to the middle slope and 2.5 km across the upper slope and shelf. Results of this transect will benefit imaging and depth conversion of the existing 3-D seismic survey and regional 2-D data, delineate the plate boundary beneath the Nicoya Peninsula, and indicate the seaward extent of the ophiolitic Nicoya Complex. The dense upper slope OBS coverage, 3 km land station spacing, and DFS V array at the coast will provide a good reflection image of the slab in the seismogenic zone.

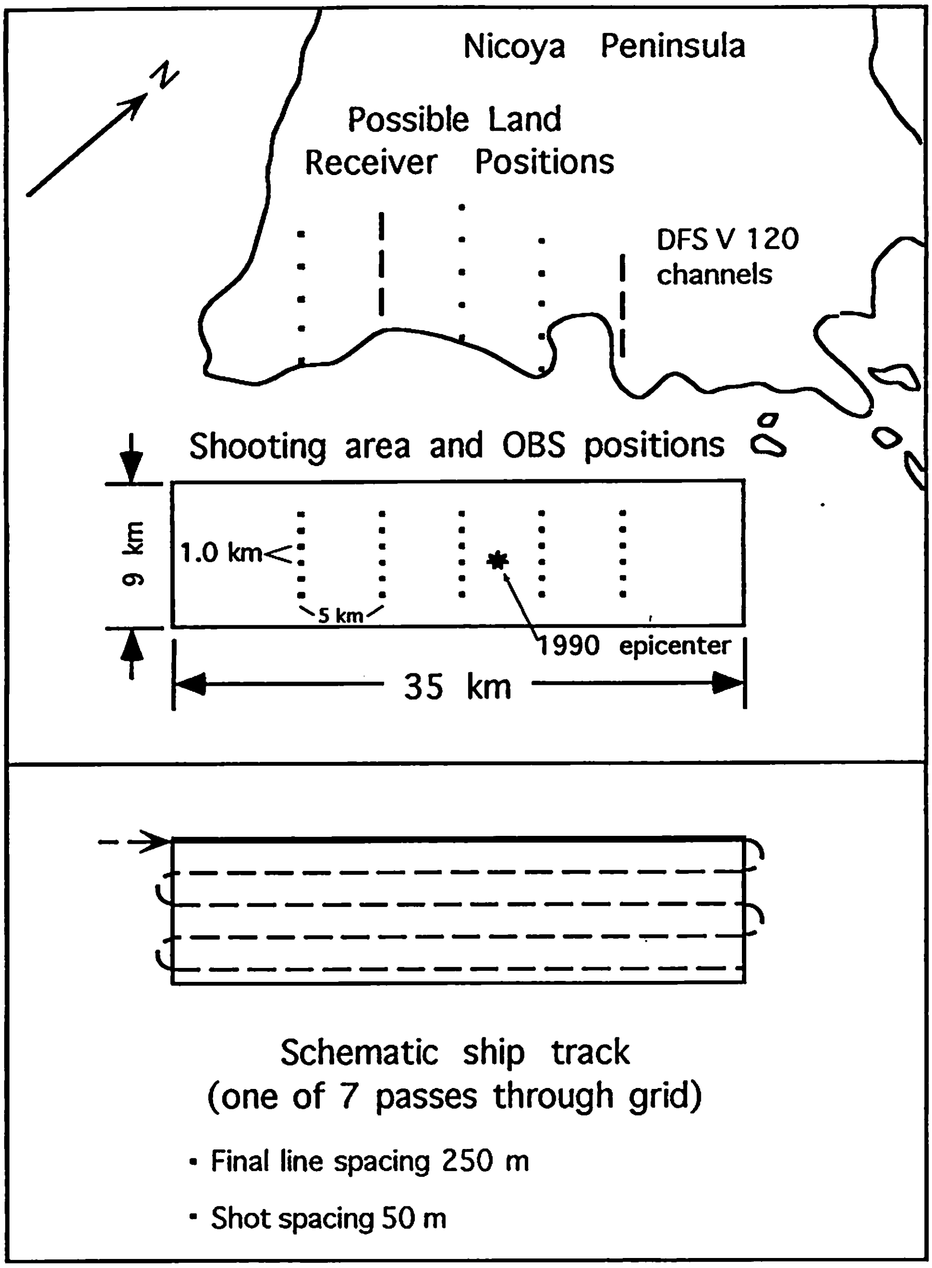


Figure 13. Detailed view showing possible shot and receiver configurations for 3-D experiment. This experiment is off the SE coast of the Nicoya Peninsula above the 1990 Cobano epicenter and above the seamount dominated segment of the Cocos plate.

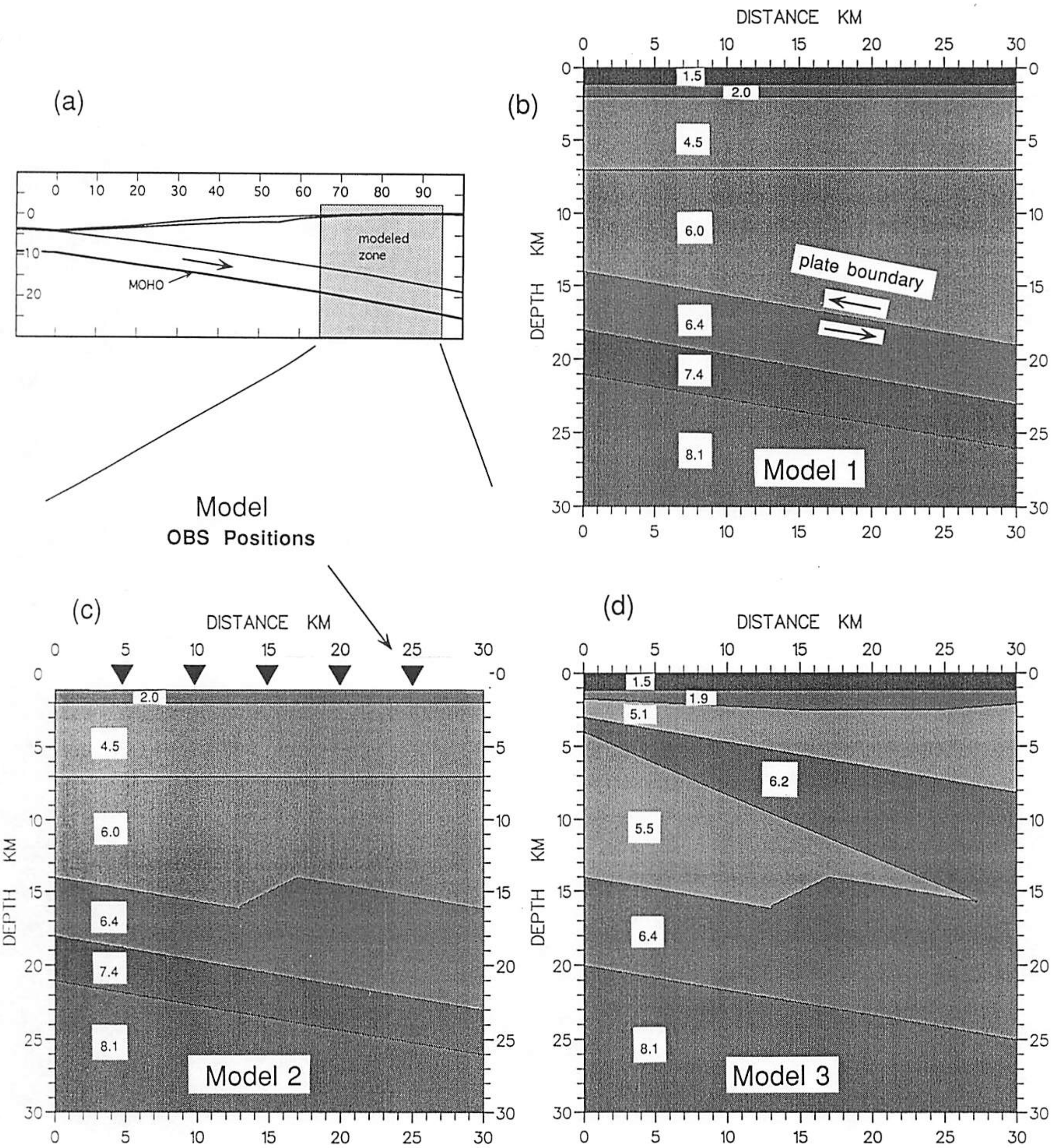


Figure 14. Structure/velocity models used for 2-D finite difference modeling to test feasibility of detecting a subducting seamount with the proposed OBS techniques. The portion of the forearc modeled is 65-95 km from the trench and 30 km thick (a). We modeled three possible cases: (b) Model 1, a slab with no seamount, (c) Model 2, with the trailing portion of a 2.5 km high flat-topped seamount, and (d) Model 3, the same seamount subducting beneath a relatively high velocity landward-dipping backstop. The unperturbed velocity structure is based on preliminary interpretation of recently acquired German refraction data off the Nicoya Peninsula [von Huene, personal communication].

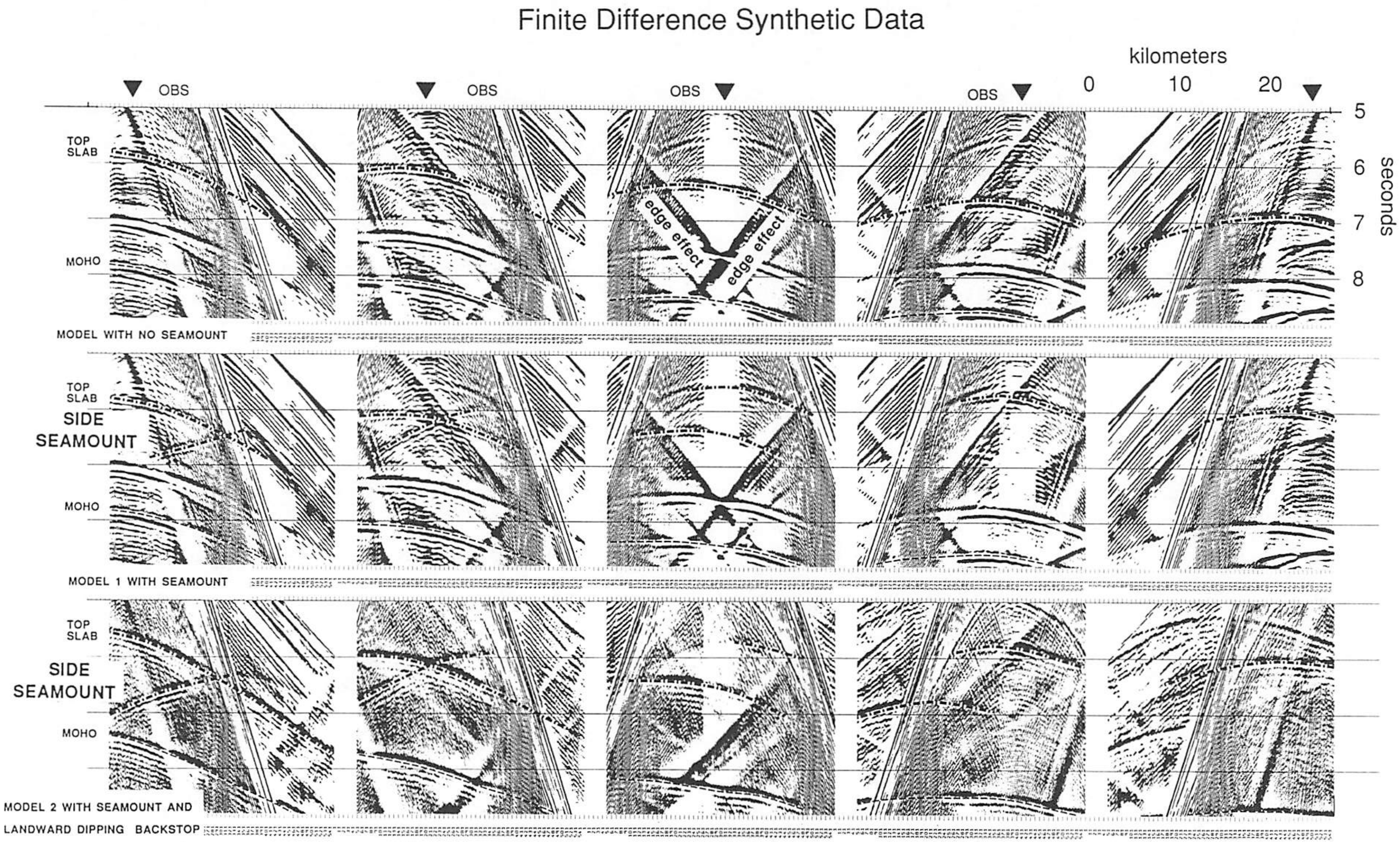


Figure 15. Finite difference synthetic OBS data. The three rows of records correspond to the three velocity models in Figure 14. Each column of records corresponds to a different OBS position, which is marked above the first row. The time window is from 5-9 s to display reflections of interest from the top of the slab and Moho (labeled on left of figure and marked with patterned tape throughout). Reflections from the side and top of the subducting seamount indicate that it is feasible to image a seamount at seismogenic depths. Further description in text.

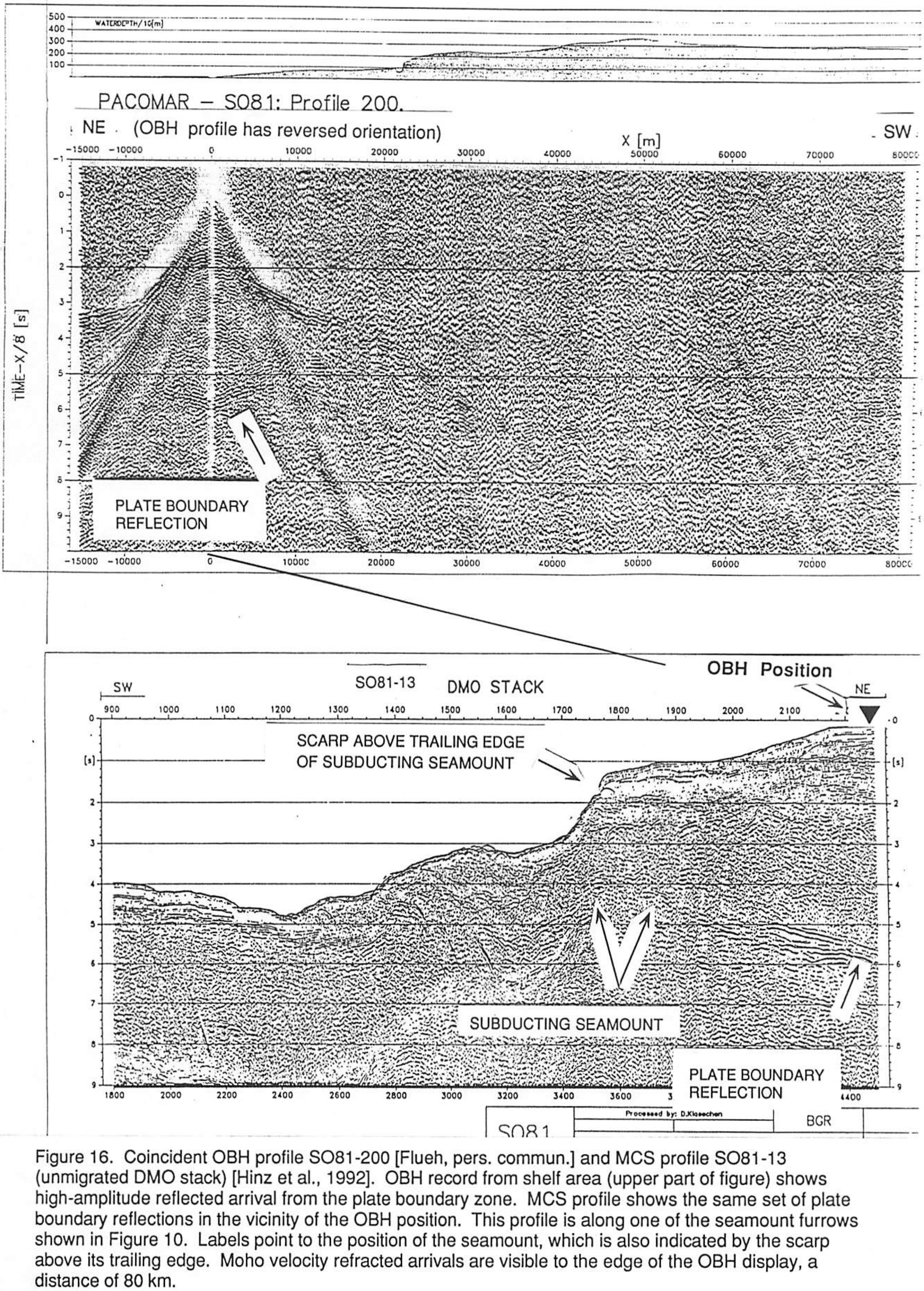


Figure 16. Coincident OBH profile SO81-200 [Flueh, pers. commun.] and MCS profile SO81-13 (unmigrated DMO stack) [Hinz et al., 1992]. OBH record from shelf area (upper part of figure) shows high-amplitude reflected arrival from the plate boundary zone. MCS profile shows the same set of plate boundary reflections in the vicinity of the OBH position. This profile is along one of the seamount furrows shown in Figure 10. Labels point to the position of the seamount, which is also indicated by the scarp above its trailing edge. Moho velocity refracted arrivals are visible to the edge of the OBH display, a distance of 80 km.

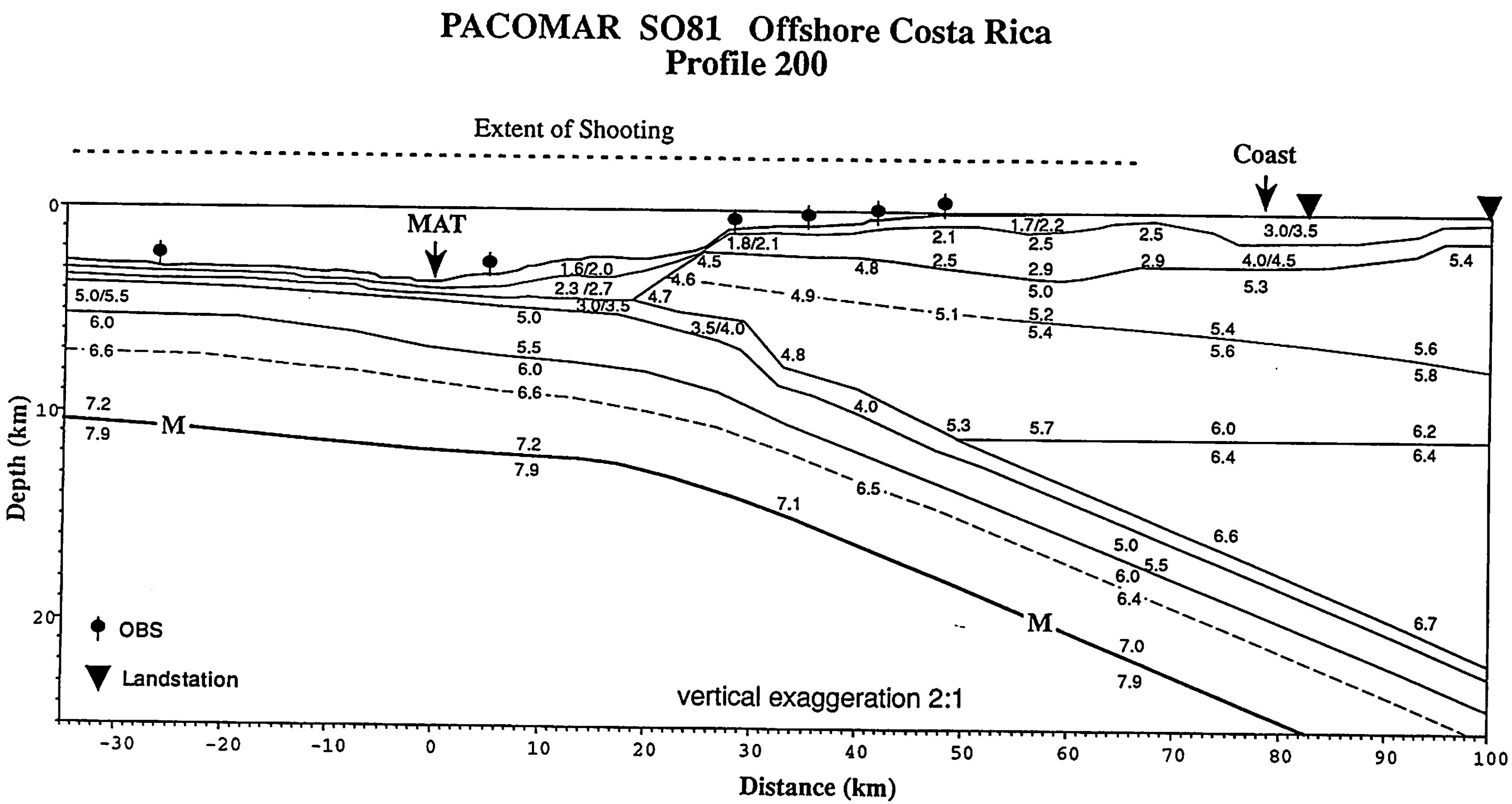


Figure 17. Interpretation of German refraction profile SO81-200 recorded with 6 OBH instruments and 2 land stations (locations shown at top of figure). The coast is at approximately 78 km and the profile location is shown in Figure 2.

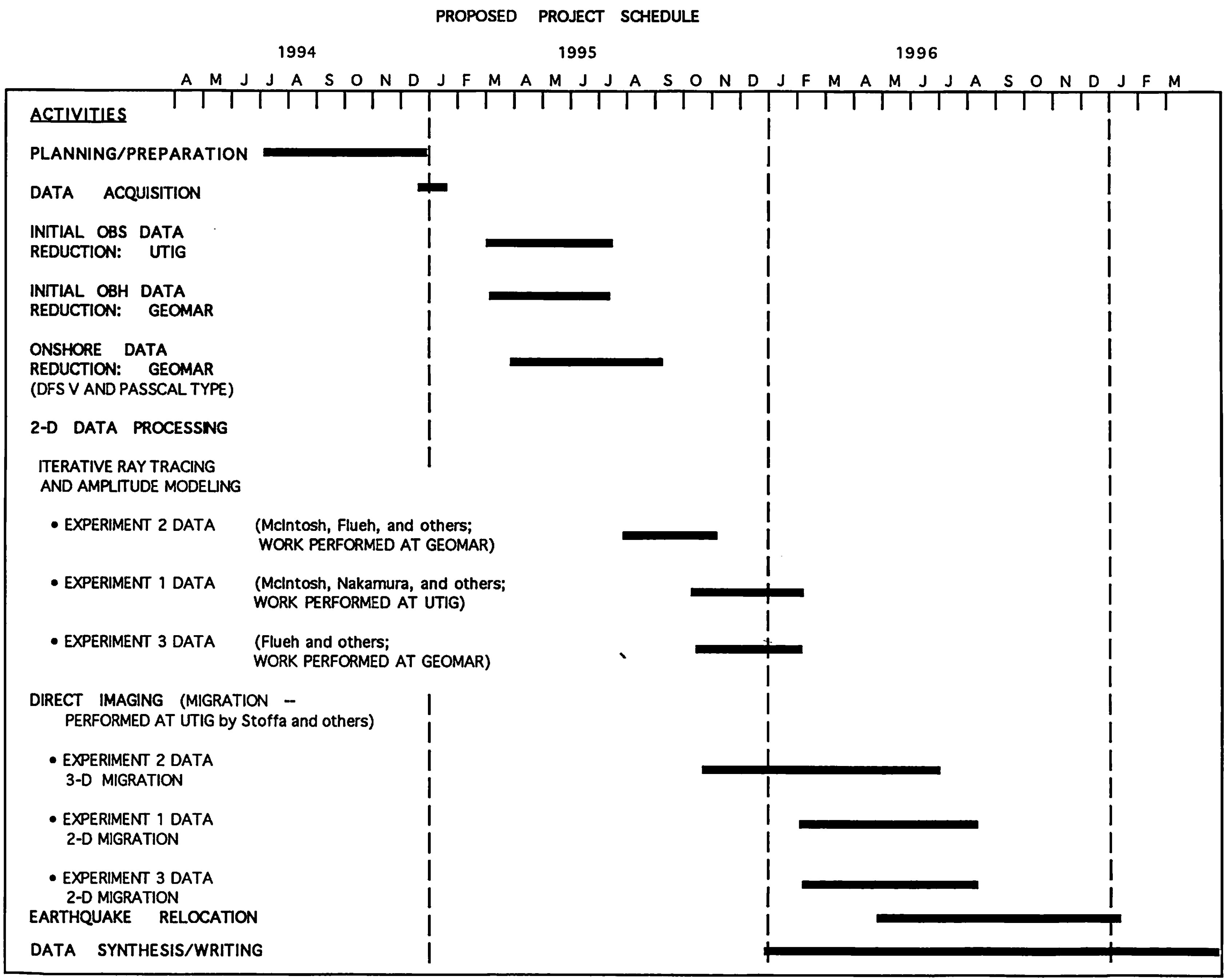


Figure 18. Proposed project schedule showing approximate timing of the activities and some of the personnel responsible.

Table I. Characteristics of UTIG Ocean Bottom Seismograph

Sensors:	3-component gimbaled geophones plus optional hydrophone
Pass band:	4.5 - 100 Hz
Alias filters:	selectable with plug-in resistor blocks
Filter roll-off:	-24 dB/oct
Sensitivity:	1.2 nm/s with Mark Products L-15B geophones
Dynamic range:	126 dB theoretical, 112 dB re rms electronic noise
A/D:	14 bits plus dynamic gain ranging
Sample interval:	1 to 255 ms at 1 ms steps, 200-999 μs optional
Number of channels:	1, 2, 3 or 4
Timing accuracy:	10 ms absolute, with pre- and post-deployment clock calibrations against standard signal and water-wave arrivals
Instrument location accuracy:	10 m or better, from post-cruise analysis of water-wave arrival data
Instrument orientation accuracy:	1°, from post-cruise analysis of water-wave arrival data.
CPU:	80C88
Temporary data memory	512 Kbytes standard, 4 Mbytes optional
Recording capacity:	depends on recording device; e.g., 450 Mbytes on Tandberg 3820 tape drive
Battery life:	6 months dormant; up to 8 weeks acquiring data on disk
Power source:	24-37 size-D lithium cells or equivalent
Pressure case:	43 cm (17") diameter glass sphere
Weight at deployment:	85 kg (190 lbs)
Weight at recovery:	35 kg (75 lbs)
Overall dimension at deployment:	128 × 128 × 145 cm (50" × 50" × 57")
Maximum depth of deployment:	7 km
Method of instrument recovery:	Timed release from anchor controlled by two independent clocks

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Request for Subcontract from the

Institute for Geophysics
University of Texas at Austin
Att: Eleanor Picard
8701 MoPac Expressway
Austin, Texas 78759-8397

by

The Trustees of Columbia University in the City of New York

DATA ACQUISITION/REDUCTION, R/V MAURICE EWING

"Investigation of Upper Plate Response to Subducting Plate Morphology and Seamounts as Subduction Zone Asperities"

Proposed Starting Date:	January 1, 1994
Proposed Duration:	24 Months
Amount Requested:	$135,781
Principal Investigators:	Dr. Kirk McIntosh

Michael Rawson
Marine Science Coordinator
Lamont-Doherty Earth Obs.
(914) 365-8367

Dennis E. Hayes
Associate Director
Lamont-Doherty Earth Obs.

Approved by:

John C. Mutter
Associate Director, L-DEO
Tel. 914-365-8525

Vivian Eng 10/18/93
Vivian S.F. Eng
Sr. Project Officer, Office of Projects and Grants
Columbia University
Tel. 212-854-6851

L-DEO Proposal No. 7184

OBS/SCS BUDGET 95 (v.9/14/93)
ESTIMATED DATA ACQUISITION AND DATA REDUCTION BUDGET - 1995
R/V MAURICE EWING EQUIPMENT SUPPORT
P.I.: McIntosh, K. (UTIG) 12 days 20 AG shooting OBS/SCS; 32 days Total: NSF
AREA: Costa Rica Margin (San Diego/Panama)

DIRECT COSTS I. DATA ACQUISITION	Rate	Days	On Campus	Off Campus	Total
BASE DIRECT COSTS (And ICR Rates)	$		$	$	$
A. Base Costs (100% Off-Campus)	1,712	0		0	0
B. MCS Base (33% on & 67% off)	Table II		5,940	12,060	18,000
C. Project Specific Equipment Use					
- MCS Ops Costs (15% On 85% Off)	Table III		1,272	7,208	8,480
- MCS Salary/OT (33% On & 67% Off)	Table IV		12,556	25,493	38,049
- PDR 12 & 3.5 kHz (33% On & 67% Off)	129	22	937	1,901	2,838
- Magnetics (33% on & 67% off)	102	0	0	0	0
- Gravity (33% on & 67% off)	103	22	748	1,518	2,266
- Ship & Comm. (all on campus)	153	32	4,896		4,896
- Base OT/SeaPay (Incl. FICA)	286	32	9,152		9,152
- Recording Media Costs (Includes Tape Shipping)					
Magnetic Tape (20 per day)	140	12	554	1,126	1,680
TOTAL ACQUISITION DIRECT COSTS			36,055	49,306	85,361
II. DATA REDUCTION					
TOTAL REDUCTION DIRECT COSTS	Table I		11,763		11,763
TOTAL ACQUISITION AND REDUCTION DIRECT COSTS			47,818	49,306	97,124
INDIRECT COSTS					
On Campus Rate	53.00%		25,344		
Off Campus Rate	27.00%			13,313	
TOTAL INDIRECT COSTS					38,657
TOTAL DATA ACQUISITION AND REDUCTION COSTS					135,781
		DAYS	COST/DAY		
III. SHIPTIME COSTS					0
TOTAL DATA ACQUISITION, REDUCTION AND SHIPTIME COSTS:					135,781

NOTE: THESE COSTS ARE ESTIMATES, FINAL COSTS WILL BE DETERMINED BY REVIEW OF 1993 OPERATIONAL YEAR COSTS.

NSF-UNOLS Ship Time Request Form

Include in all NSF proposals and send copies to UNOLS office and ship operator(s)

P.I. Name: Kirk D. McIntosh
Institution Address: Institute for Geopysics
8701 N. MoPac Expressway
Austin, Texas 78759-8397
Phone Number: (512) 471-0480
Fax Number: 512- 471-8844 E-mail: kirk@utig.ig.utexas.edu

Name of Person Requesting Ship Time (Multi-P.I. Proposals):
Institution: University of Texas, Institute for Geophysics
Phone Number: (512) 471-0480
Fax Number: (512) 471-8844 E-mail: kirk@utig.ig.utexas.edu

Will this project require use of a research vessel or special platform?
☐ No (Go to Signature)
☒ Yes
☐ Ancillary Only
☒ Principal Use of Ship
Large Program? (Ex. WOCE)

Proposal Title:
Investigation of upper plate response to subducting plate morphology and seamounts as subduction zone asperities: Cooperative German, Costa Rican, and United States project

Purpose of Ship Time: Seismic refraction/reflection survey using marine energy source, ocean bottom instruments, and land instruments.

Other Scientists Involved in Multi-P.I. Program:

Name	Institution
Thomas H. Shipley	Institute for Geophysics
Paul L. Stoffa	Institute for Geophysics
Yosio Nakamura	Institute for Geophysics
Roland von Huene	GEOMAR, Kiel, Germany
Ernst Flueh	GEOMAR, Kiel, Germany

☒ New Proposal?
Inst. Proposal # ____
NSF Proposal # ____
☐ Renewal Proposal
Grant # ____

Submitted to:
Agency NSF
Division MG&G
Program OCE

Amount Requested: $969,524
Start Date: 01 March 1994 End Date: 28 February 1997

Year	Ship(s) Requested Name or size (Ex. Large, Medium)	# of Science Days Required	Optimum Dates Month/Day/Year	Alternate Dates Month/Day/Year
1994	R/V *Maurice Ewing*	22	December 1994	Jan-April 1995
Estimated Ship Days Needed: 32		Transit: 10	Science: 22	Port:
Proposed Ports:		Start Port: San Diego, CA	Intermediate: Puntarenas, Costa Rica	End Port: Puntarenas, C. R.

Area of Operations (Use codes from standard Naval Chart [on back] and brief description) Codes: NP9, NP13
Transit: offshore California, Mexico, Central America
Science: offshore Costa Rica (Pacific)

Number in Scientific Party: 12?

Geographic Description (Latitude and Longitude):
Beginning: 33° N 117.5° W (San Diego)
Ending: 10° N 85° W (Costa Rica)

Technician Required: (CTD, SCS, MCS, SeaBeam, etc)
SCS (MCS source array)

Special Equipment Required:
Differential GPS navigation ("Wieder Watch")

Is any part of project within 200 miles of a Foreign Coast?
☐ No ☒ Yes (List countries' clearance required)
Costa Rica

Special Requirements:
(List type, quantity, and disposal plans)
Radioactive? No
Explosives? No
Other? Space for OBS Lab Container Unit

Diving? ☒ No ☐ Yes
Number of Individual Dives: ____
Number Participating Divers: ____

Signature of P.I. or Chief Scientist: Kirk D. McIntosh Date: 10-20-93

Send a copy of this form to the ship operator

Addresses of ship operators and information on available vessels may be obtained from the UNOLS office or from NSF

Ship Operations
National Science Foundation
1800 G. St. NW
Washington, DC 20550
Tel: (202)357-7837
FAX: (202)357-7621

UNOLS Office
University of Rhode Island
P. O. Box 392
Saunderstown, RI 02874
Tel: (401)792-6825
FAX: (401)792-6486

Sent to:
☐ NSF
☐ UNOLS Office
☒ Ship Operator

Special Instructions

Year:
Proposals requiring ship time must be received by the May 1 Target Date to be considered for scheduling in the following calendar year. Ship

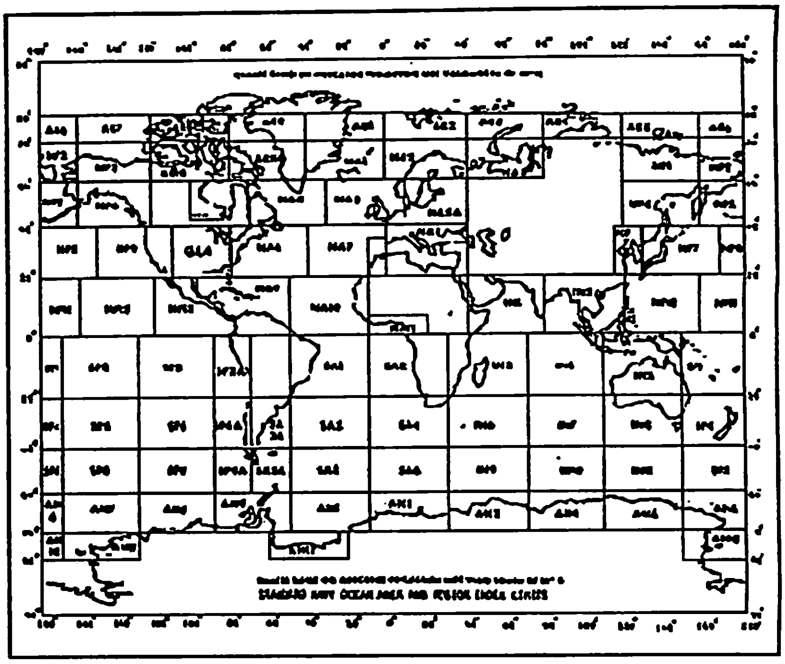
schedules for the calendar year are finalized by October of the *previous* year.

Clearances:
Clearances are required for ALL scientific work within any foreign nation's 200 mile Exclusive Economic Zone. Foreign clearance is often difficult to obtain, and in most cases, **requests should be submitted to the Department of State at least seven months prior to expected cruise date.** Requests for clearance may be submitted prior to final fundingdecisions. Contact ship operator or:

Research Vessel Clearance Officer
U.S. Department of State
OES/OA, Room 5801
Washington, DC 20520
Tel: (202)647-0240

Track:
Attach cruise track.

Standard Navy Ocean Area and Region Index Limits



INFORMATION FOR OPERATORS

Installed Equipment to be used:

Winches:
Dredge/Trawl ___
Hydro ___
CTD ___
Capstans ___

Computer/peripherals _X_
PC computers ___
SAIL System ___
Digital XBT ___
ADCP ___
Gravimeter _X_

Wire:
Mechanical
9/16" ___ 1/2" ___ 1/4
Conductor
0.680" ___0.322" ___.225"___
Single ___ Multi ___
12kHz echosounder ___
3.5 kHz echosounder _X_
Magnetometer ___
Multibeam sounder ___
Air compressor(s) _X_
Uncontaminated seawater intake ___

Navigation:
GPS _X_
Transit satellite ___
Loran ___
Other ___

Immarsat _X_
ATS ___
FAX ___
Cellular _X_

Available equipment to be used:

Pingers ___
Gravity Corers ___
Piston Corers ___
Box Corers ___
Rock Dredges ___

Chest Freezers ___
Refrigerators ___

CTD ___
Rosette Sys. ___

Vans:
Refrigerated ___
Magazine ___
Isotope Isolation ___
Lab ___
Storage ___
Berthing ___

Nets:
Dip net ___
Plankton ___
Neuston ___
Bongo ___
Mid-Water trawl ___
MOCNESS ___ (Size) ___

Airgun/watergun system: _X_
Explosive Handling Gear ___

Work Boats _?_

Auto Analyzer ___
Salinometer ___
Nutrients ___
Oxygen titration ___
Niskin bottles ___
Thermometers ___

Other Special Equipment; Comments: