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# 4. CONICAL SEAMOUNT: SeaMARC II, *ALVIN* SUBMERSIBLE, AND SEISMIC-REFLECTION STUDIES[1]

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## ABSTRACT

Conical Seamount, the edifice drilled at Ocean Drilling Program (ODP) Sites 778 through 780, is a large seamount on the outer half of the 200-km-wide Mariana forearc in the western Pacific. It is forming by the protrusion of cold, unconsolidated serpentine mudflows and debris flows and by vertical tectonic activity. Dredging on the flanks of this seamount recovered rocks and serpentine muds that are similar to sedimentary serpentinite deposits found in subaerially exposed convergent margin terranes worldwide. The dredged samples were formed by different mechanisms from those previously proposed for sedimentary serpentinite deposits. The dredged samples from Conical Seamount are primarily serpentinized harzburgite. However, serpentinized dunite, metamorphosed gabbro, and basalts have been retrieved from similar seamounts on the Mariana forearc. SeaMARC II imagery and bathymetry of Conical Seamount revealed sinuous flow forms on the flanks of the seamount. Conical Seamount also has both concentric ridges and radial fractures indicative of tumescence. *Alvin* submersible studies showed these flows to be composed of unconsolidated serpentine muds, containing clasts of serpentinized ultramafic and metamorphosed mafic rocks and authigenic carbonate and silicate minerals. Near the summit of one of the seamounts, chimney structures less than 150 yr old and composed of carbonate and silicate were sampled using *Alvin*. During sampling of a silicate chimney, cold fluids seeped from numerous orifices in the chimney. The fluids associated with the chimney are unique in composition among fluids collected in the oceans and point to a deep source, probably the subducted Pacific lithospheric slab. Small limpets and gastropods and bacterial mats were collected from the chimneys.

Faulting of the forearc region partially controls the distribution of the Mariana forearc serpentinite seamounts. Seismic-reflection profiles show that Conical Seamount is located at the intersection of at least two fault zones. The extent of the exposure of serpentinized ultramafic rocks on the Mariana forearc and the pervasive normal faulting of the region argue for considerable extension. Dredged samples from the 2-km-high wall of a deep graben adjacent to Conical Seamount include a variety of mafic rock types of arc tholeiite, boninite, alkalic basalts, and basalts of mid-ocean ridge (MORB) composition. The presence of MORBs in this part of the forearc suggests either exposure of a fragment of entrapped or accreted oceanic plate or a period of rifting with associated magma generation in the forearc.

The serpentine mud volcanoes and associated egress of fluids generated at great depth in the forearc provide a mechanism for the flux of fluids from the subducted oceanic lithosphere through the outer forearc region. The escape of circulating fluids would alleviate problems of mass balance of constituents derived from subduction in the convergent margin environment. In particular, the disparity between the observed volatile effluent from arc volcanoes and the postulated amount of dehydration of the downgoing slab could be explained by accommodation of large volumes of fluids through metamorphism of the outer forearc region.


## INTRODUCTION

Active convergence in the western Pacific over the past 43 m.y. has produced a series of backarc basins and intervening remnant arcs that form the eastern edge of the Philippine Sea Plate (Fig. 1). The Mariana arc-trench system, the easternmost of these western Pacific arcs, is well known as a classic example of an intraoceanic convergence zone. Its evolution has been studied by numerous investigators over nearly two decades (e.g., Karig, 1971; Uyeda and Kanamori, 1979; LaTraille and Hussong, 1980; Fryer and Hussong, 1982; Mrosowski et al., 1982; Hussong and Uyeda, 1982; Bloomer and Hawkins, 1983; Karig and Ranken, 1983; McCabe and Uyeda, 1983; Hsui and Youngquist, 1985; Fryer and Fryer, 1987; Johnson and Fryer, 1988). During the past 5 yr, surveying and sampling of this area resulted in the refinement of models for convergent margin evolution.

Some of the most significant changes in models of arc evolution have been with respect to aspects of the development of the Mariana forearc region. The Mariana forearc comprises a region between the trench axis and the active volcanic arc, approximately 200 km wide and 1500 km long. The eastern half of the region is unusual among western Pacific forearc terranes in that it contains more than 50 large seamounts scattered along its length within 100 km of the trench axis (Fryer et al., 1985; Fryer and Fryer, 1987). The seamounts vary in size from 10 km in diameter and 0.5 km high to 30 km in diameter and 2 km high.

The central forearc (Fig. 2) had been studied previously using several techniques, including U.S. Navy SASS bathymetry surveys (Fryer and Smoot, 1985) and SeaMARC II side-scanning sonar and bathymetry surveys (Hussong and Fryer, 1985; Fryer et al., 1987; Fryer and Fryer, 1987) between 19° to 20°N. The latter survey has facilitated detailed morphologic and structural studies of this part of the Mariana forearc. Following these studies, a series of *Alvin* dives were conducted during 1987 on two serpentinite seamounts near

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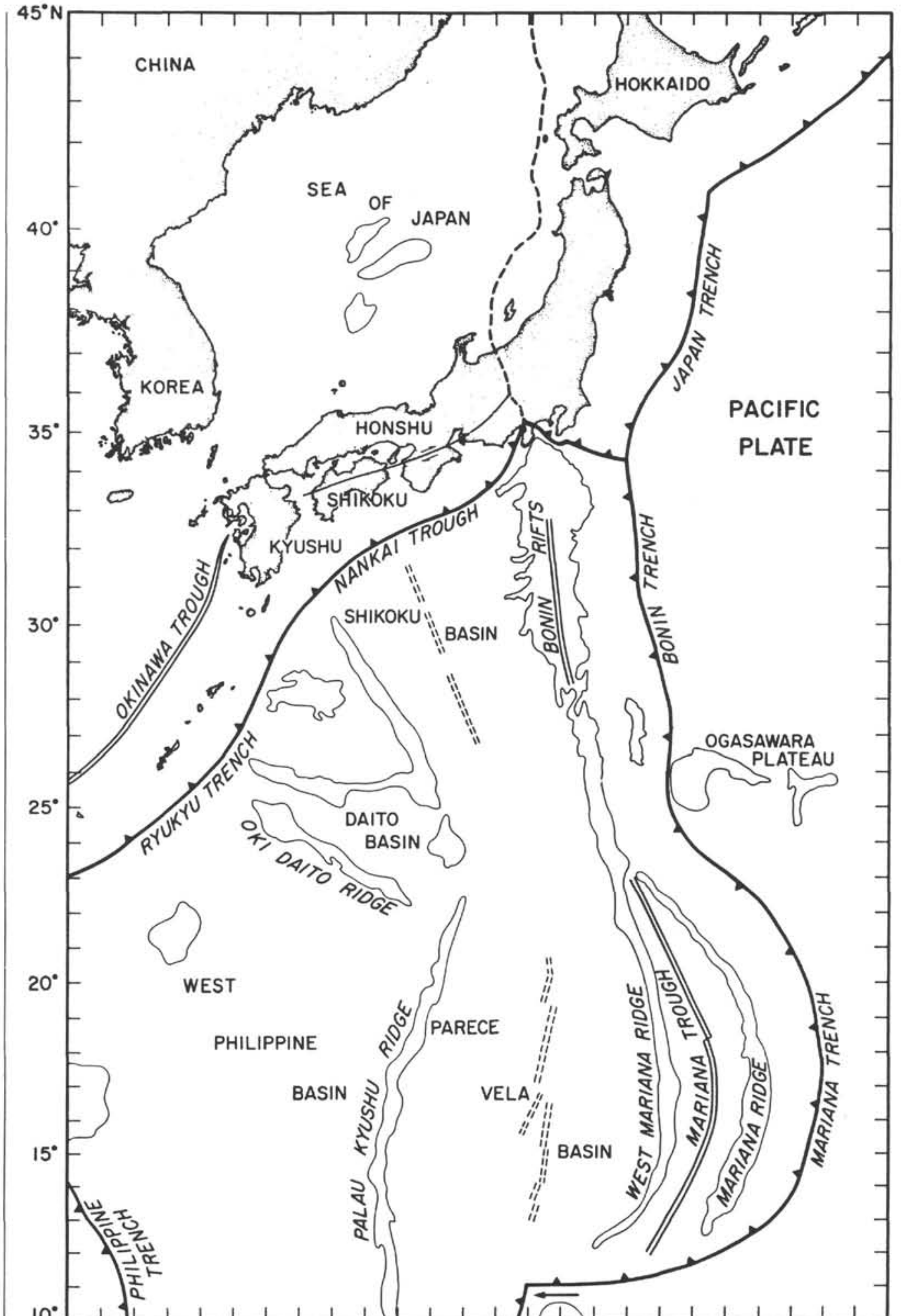


Figure 1. Bathymetry and geologic features in the Philippine Sea region. Basins and ridges are outlined by the 4-km bathymetric contour, except for the Izu-Bonin arc, West Mariana Ridge, and Mariana arc, which are outlined by the 3-km contour. Barbed lines locate subduction zones; medium double lines locate active spreading centers; dashed double lines locat relict spreading centers.

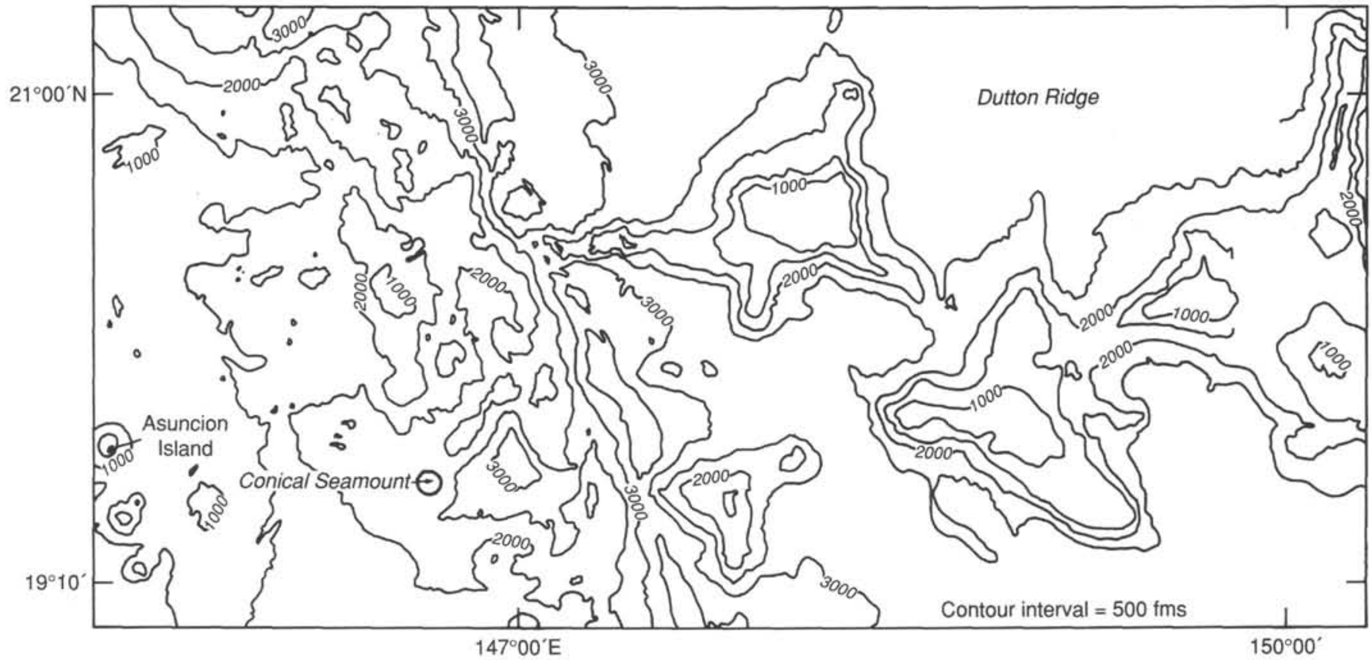


Figure 2. Bathymetry of the central Mariana arc from U.S. Navy SASS data (Fryer and Smoot, 1985).

19°30′N (Fryer et al., 1987). During Leg 125, to prepare for drilling one of these two seamounts (Conical Seamount), a digital single-channel seismic survey of the seamount was conducted using the *Fred H. Moore* in 1987. Subsequently, Conical Seamount was surveyed using a SeaBeam bathymetry system aboard the *Sonne*. These more detailed investigations provided an opportunity for scientists to focus on a number of aspects of the tectonic evolution of the forearc and of Conical Seamount that could not be examined using conventional geophysical survey techniques.

This chapter provides a summary of the regional geology of the outer Mariana forearc and the tectonic evolution of Conical Seamount. In it we present a summary of the principal results of the *Alvin* dive studies, the seismic-reflection studies, and the petrologic and geochemical studies of dredged and *Alvin*-collected samples of that seamount. These data were used in the site selections for drilling at Conical Seamount during Leg 125.

## PREVIOUS WORK

Studies of the origin of serpentinite seamounts in the Mariana forearc region have direct application to interpretation of subaerial exposures of serpentinite in former convergent margin terranes. Deposits of "sedimentary" serpentinite similar to the deposits formed on the flanks of the Mariana serpentinite seamounts have been described from numerous locations on land in former convergent margin settings (e.g., Lockwood, 1971; Phipps, 1984; Lagabrielle et al., 1986). The mechanism of emplacement of some of these subaerially exposed deposits has been compared to that of the Mariana seamounts (Carlson, 1984). Seven of the seamounts on the outer half of the Mariana forearc have been sampled and shown to consist in part of serpentinized ultramafic rocks. Many also yielded metagabbros, metabasalts, and metasediments. These results suggested that the seamounts were formed by diapiric intrusion of serpentinized ultramafic rocks into crustal levels within the eastern half of the forearc (Bloomer, 1982; Bloomer and Hawkins, 1983). A diapiric model for the origin of these seamounts implies that the rocks represent materials entrained within the rising serpentinite and thus give us an indication of the nature of the mantle and crust through which they rise and of the metamorphic processes occurring both at depth and within the individual edifices.

From a seamount at about 14°N, we dredged (KK810626-03) a small amount of an aragonite-rich carbonate having a vuggy texture (Haggerty, 1987b). Radiating needles of aragonite around minute tubes in the carbonate and the unusual composition of the carbonate were interpreted initially as evidence of venting fluids that were forming chimneys on the summit of this seamount (Haggerty, 1987a, 1987b).

The best studied of the Mariana seamounts are those near 19°30′N (Fig. 3). Dredging at the summit of these seamounts yielded serpentinized ultramafic materials, metamorphosed mafic rocks, manganese crusts with adhering pelagic sediment, serpentine muds, and some semilithified, vitric siltstones. SeaMARC II side-scanning sonar images and bathymetry of the two seamounts in this region (Fig. 4A) showed flow features of various types on their flanks (Hussong and Fryer, 1985; Fryer et al., 1985; Fryer and Fryer, 1987). The base of Conical Seamount is readily distinguishable from the surrounding seafloor. The lower flanks show concentric, long-wavelength ridges, especially on the southeast side. All flanks of the seamount are mantled with long sinuous flows. The flows extend for a maximum distance of up to 18 km from the summit, and their sinuous morphology indicates that they are composed of nonviscous material. The total area covered by the sinuous flows is approximately 550 km$^2$. The edifice covers an area of approximately 700 km$^2$. The flows on Conical Seamount were initially interpreted to be composed of normal forearc sediments mobilized into debris flows by gravitational instability and by infusion of the sediments with fluids venting from a near-surface serpentinite diapir; this implied that Conical Seamount is a large mud volcano (Fryer et al., 1987; Fryer and Fryer, 1987).

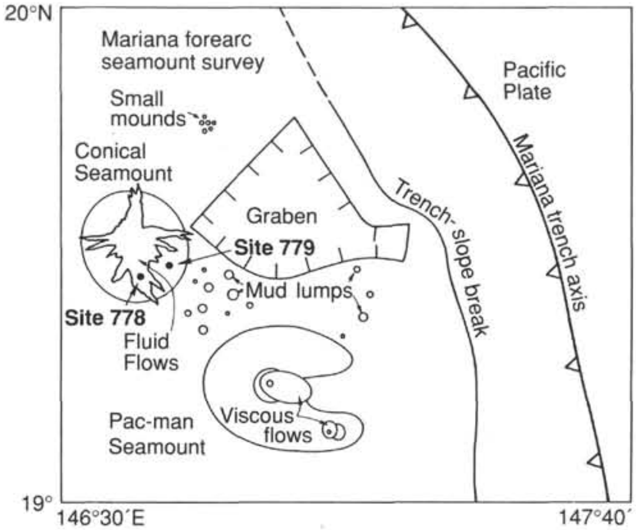


Figure 3. Geologic sketch showing the disposition of seamounts and a large graben in the vicinity of 19°N on the outer Mariana forearc.

## *ALVIN* DIVE STUDIES

The dives at Conical Seamount were designed to characterize and sample the flow features on the flanks of the edifice, to investigate the faults and deformation of the flanks of the seamount, and to study the summit region of the seamount (Fryer et al., 1987). Five dives (1851–1855; Fig. 4B) on the flanks studied the flow composition and morphology, and four dives (1859–1862; Fig. 4B) on the summit area investigated chimney structures and vent morphology.

The results of the dives at Conical Seamount provided us with the first look at an active serpentine mud volcano. The first five dives (1851–1855) were made on the flanks of the seamount to characterize the flows. The flows on Conical Seamount have a variety of surface textures and structures. A relative age discrimination, based on the degree of sediment cover on the flows, on the amount of manganese encrustation of the surface of the flows, and the degree of contortion of the surface of the flows, was applied in an attempt to map regions of recent flow activity.

The presumably youngest flows are light green, have contorted surfaces, and lack a sediment cover. These flows have numerous cobbles and boulders consisting primarily of serpentinized peridotites and dunites, with small amounts of metabasalts and metagabbros scattered over their surfaces (Fig. 5). The older flows have a smoother surface, are covered with sediment and, in places, have ferromanganese and/or carbonate encrustations (Fig. 6). Most of the young flow features are concentrated near the summit area and were best observed in dives 1859 through 1862. The flows apparently originate from near the western side of the two summit knolls, in the vent region of the seamount. Flows also are related to faulting on the flanks of the seamount and may contain remobilized older flow materials.

Normal faults occur on the summit regions and upper flanks of Conical Seamount and expose the interiors of flows. Many of the flow interiors are mottled by patches or streaks of carbonate. The interior of one such flow is shown in Figure 7 (note the lack of rock clasts in the exposure). The paucity of clasts within the fault exposures suggests that some flows consist primarily of serpentine mud. Numerous rock clasts are exposed only on the surface of the younger flow areas, and their absence from the older flow areas suggests that the clasts may sink into the serpentine muds after the flow settles. Too little of the serpentine mud was collected on the *Alvin* dives to permit detailed rheological studies. However, from the push cores we collected we surmise that the rheological properties of the serpentine muds vary considerably over small distances depending on the degree of carbonate precipitation within the muds and on the amount of entrained pore water. The percentage of carbonate in the muds is greatest in the summit areas, near the proposed vents. The distribution of carbonate is probably the result of escape of entrained fluids from the flows as they advance. With removal of the fluids, the degree of precipitation of carbonates decreases.

During dives 1854, 1855, and 1859 through 1862, at depths less than 3200 m, we observed columnar to irregularly shaped, vertical projections of serpentine mud. These structures are veined with and partially cemented by carbonate (Fig. 8), and some are topped with cobbles. The structures vary from a few centimeters to about 1.5 m high. In several cases, the structures provide a pedestal for the growth of chimneys. Escaping fluids probably precipitated carbonate, not only forming chimneys, but also cementing the matrix of the flow below the surface. We suggest that fluids rise from within the serpentinite flow and may be concentrated in one locality or disseminated throughout the flow. Where concentrated, or where impeded from escaping locally by rising beneath cobbles, the precipitating carbonates might form a fortified column. The chimney pedestals probably were exposed as the surrounding serpentinite flow receded, by current erosion, by deflation of the flow as fluid escaped, or by slumping and sliding downslope of uncemented serpentine mud.

Most of the carbonate chimneys, 0.5 to 1.5 m high (Fig. 9), were found in a small field (about 100 m diameter) at a depth of about 3150 m, west of the southern summit knoll, at the end of dive 1854 and near dives 1859 through 1862. The carbonate chimneys are composed of varying proportions of aragonite and calcite. A minor amount of a gel-like substance composed of a previously unknown magnesium silicate was discovered in vugs in the chimneys (Haggerty and Cloutier, 1988). A thin, black ferromanganese encrustation coats parts of the lower part of the chimneys. Many of the chimneys are rough and embayed and thus appear to be corroded. The depth at which these chimneys can be observed is below the local aragonite compensation depth (Li et al., 1969) and thus, the chimneys should undergo rapid dissolution after formation. A sample taken from one of the corroded chimneys contained excess $^{210}Pb$, indicating that it is less than 150 yr old (G. McMurtry, pers. comm., 1989). None of these chimneys exhibited signs of active venting.

A second type of chimney, composed of silicate, was also discovered near the summit of Conical Seamount in the same region as the carbonate chimneys (Fig. 10). This type contained only trace amounts of carbonate and did not appear corroded. Most of these chimneys are taller, ranging from 2 to 3.5 m high, and thicker, up to 2 m at the base, than the carbonate chimneys and are uniformly coated with a thin black layer of ferromanganese oxide. The top of one of the larger chimneys has a smooth, white to pale golden-brown surface. The material forming this type of chimney has the same composition as that of the silicate found in vugs within the carbonate chimneys (Haggerty, 1987b).

Scraping the top of the silicate chimney exposed a bright white interior and prompted a diffuse seeping of fluid from several locations on the scraped surface. Scattered small jets of this fluid (less than 10 cm high) escaped from pores in the chimney. Temperatures measured with the *Alvin* low-temperature probe from the interior of the chimney were slightly lower (up to $0.03° \pm 0.005°C$) than ambient seawater. Samples

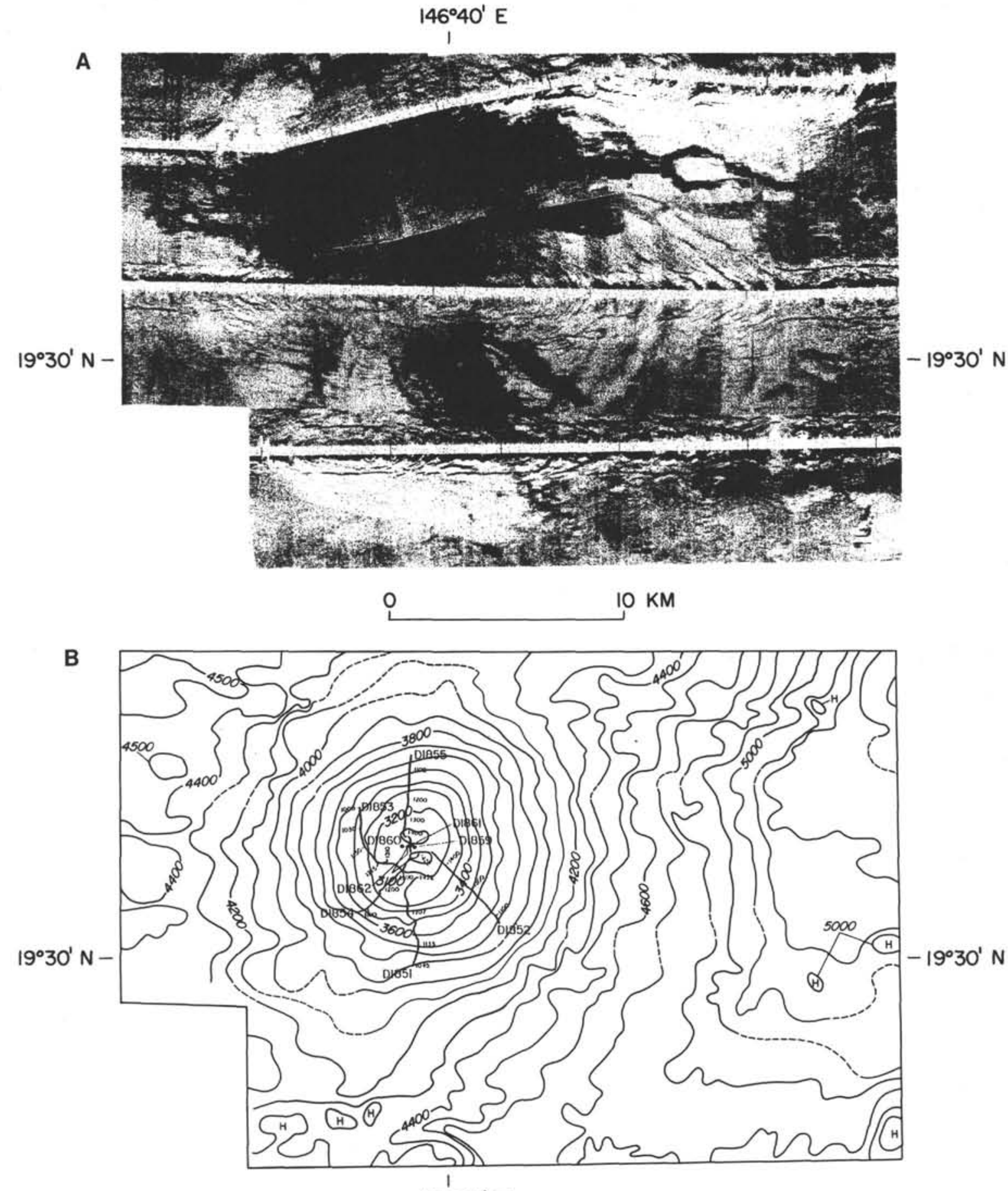


Figure 4. **A.** SeaMARC II side-scanning sonar image and bathymetry of Conical Seamount. The dark regions are areas of high backscatter. **B.** SeaMARC II bathymetry of Conical Seamount showing *Alvin* dive tracks.

of the chimney fluid and of ambient seawater were collected during dives 1860 through 1862. The pH of the vent waters is high (9.28 vs. 7.72 for ambient seawater). Alkalinity is also high (5.53 vs. 2.41 meq/L), and the vent waters are enriched in $CH_4$ (1000 vs. 2.1 nM), $SiO_2$ (0.75 vs. 0.12 mM), $SO_4^{-2}$ (30.4 vs. 28.6 mM), and $H_2S$ (2.1 mM vs. not detected in the ambient seawater). Because seawater probably mixed with the fluids during sampling, these enrichments must be considered minima. Detailed results of the chemical analyses of these fluids are reported elsewhere (Fryer et al., 1987). The primary results of the studies of the fluids imply that deep-seated serpentinization processes, interaction of seawater with crustal rocks, and interactions of seawater with the surficial serpentinite may all contribute to the composition of the fluids.

We consider the biogenic sources in the Mariana forearc crust as unlikely for generating the $CH_4$ and $H_2S$ measured in the chimney vent fluids. The forearc is not accretionary at these latitudes and does not contain a large volume of sedimentary substrate (Hussong and Uyeda, 1982). In addition,

Figure 5. Bottom photograph of an area of unsedimented (presumably recent) serpentine flow showing numerous clasts of metamorphosed rocks presumably entrained in the flow.

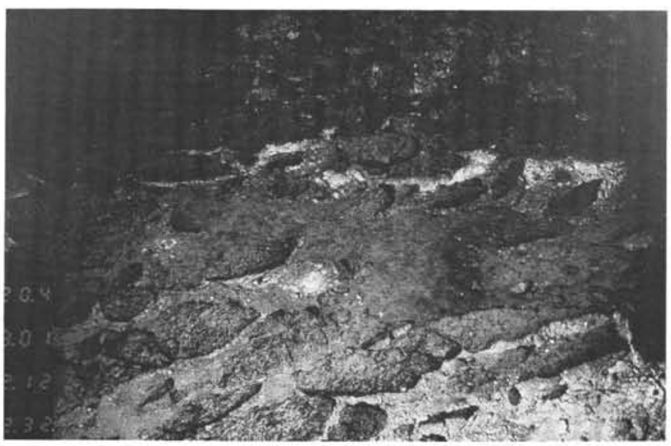

Figure 6. *Alvin* external camera photograph of ferromanganese crust on top of serpentine flow material. Fracturing of the crust is apparent in the photograph.

Figure 7. *Alvin* external camera photograph of the interior of a serpentine flow showing a paucity of clasts and apparent carbonate streaking.

Figure 8. *Alvin* external camera photograph of a pedestal of serpentine cemented by carbonate.

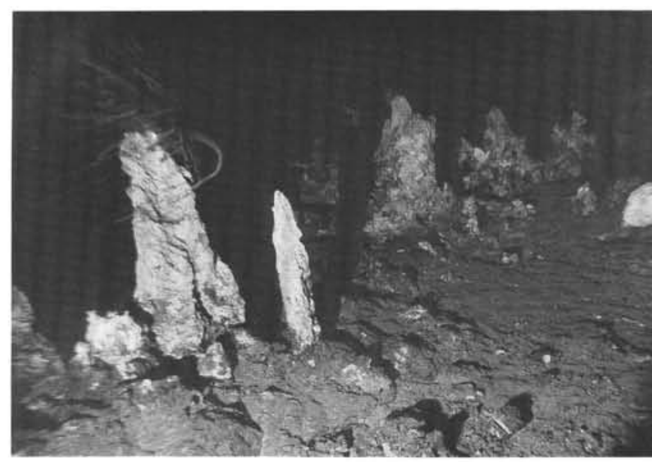

Figure 9. *Alvin* external camera photograph of a carbonate chimney near the summit of Conical Seamount. Note the corroded-appearing surface of the structure.

Figure 10. *Alvin* external camera photograph of a silicate chimney near the summit of Conical Seamount.

the small sedimentary substrate present has a low total organic carbon content, 0.06 wt.% (Schorno, 1982). Thus, the organic component in the sediments surrounding these forearc seamounts is insufficient to generate the quantity of methane noted in the vent waters. We suggest that the methane observed in the chimney samples was generated at depth beneath the forearc wedge, possibly derived from sediment on the Pacific Plate.

The carbon and oxygen isotopic compositions of the carbonate chimney precipitates are compatible with a deep source either in the forearc mantle wedge or from the subducted slab or both (Haggerty, 1987b). Mariana aragonite has a significantly lighter carbon isotopic signature, compared with aragonite found in fracture-zone serpentinite (1.2‰ to 21.2‰ for the Mariana samples vs. +0.03‰ to +1.12‰ for fracture-zone aragonite) and a heavier oxygen isotopic signature (Mariana = +5.1‰ to +7.6‰; fracture-zone = +3.16‰ to +4.87‰) (Haggerty, 1987b). Fracture-zone aragonite is precipitated at ocean-floor temperatures from seawater as a consequence of circulation of the seawater through fissures and fractures in the host rock, where the water reacts with ultramafic rocks during serpentinization (Bonatti et al., 1980). In contrast, the composition of the Mariana aragonite precludes a source involving only seawater that has reacted with ultramafic rocks. The fluids forming the Mariana aragonite originate in part by dewatering of the downgoing plate, from juvenile mantle fluids, from deep-seated serpentinization reactions, and from reactions accompanying the emplacement of the serpentinite.

Clasts of metamorphosed ultramafic rocks were recovered from the dives and in dredges from Conical Seamount (Fryer and Fryer, 1987). Preliminary analyses indicate that the clasts are primarily serpentinized harzburgite (Saboda et al., 1987). The harzburgites are 24% to 90% serpentinized and contain 1% to 8% clays, up to 7% carbonate, up to 4% iron oxide, up to 3% chlorite, and up to 1% brucite as secondary phases. Although much of the original mineralogy has been obscured, the modal percentages of the original minerals may be estimated by examination of the serpentine textures, the interrelationships between the various serpentine phases, and the relationships between the serpentine phases and the extant mafic minerals in the rocks. The harzburgite samples are estimated to have contained originally from 62% to 84% olivine, 15% to 35% orthopyroxene, 1% to 2% spinel, and up to 2% clinopyroxene. Metamorphism of the samples indicates low to moderate temperatures and pressures. Although tectonized ultramafic rocks were dredged elsewhere on other serpentinite seamounts of the Mariana forearc (Bloomer and Hawkins, 1983), none of the preliminary studies of the samples from the *Alvin* dives shows tectonized fabrics. We suggest that the harzburgites sampled from the surface of Conical Seamount are primarily upper mantle rocks that were metamorphosed in the forearc as a consequence of the flux of fluids derived from dehydration reactions within the downgoing Pacific Plate. We further suggest that these rocks were plucked from the walls of a deep-seated conduit and entrained within rising pulses of fluid-charged serpentine muds that erupted slowly from the summit of the seamount.

Igneous rocks, collected in dredge hauls on the eastern wall of the graben that lies adjacent to the seamounts, include boninites (high-magnesian andesites) and basalts similar in composition to island-arc tholeiite (IAT), mid-ocean ridge basalt (MORB), ocean island basalt (OIB), and a group of basalts transitional between the alkalic OIB and the tholeiitic IATs and MORBs (Johnson and Fryer, 1988). The samples have been altered, but their provenance can be determined using ratios of trace elements, particularly titanium, zirconium, and vanadium. The petrogenesis of the samples and interpretations of their emplacement in the forearc are presented in Johnson and Fryer (1988). The discovery of MORB in the forearc, particularly at a distance of more than 50 km from the trench axis, requires a modification of the models of forearc evolution. Rocks previously dredged from the inner walls of the Mariana Trench and along scarps in the outer forearc high are of arc composition with the exception of small amounts of OIB found in a few dredges on the inner wall of the trench. The composition of forearc crust thus was suggested to have formed by arc volcanism. The discovery of MORB lavas in the dredges from the graben adjacent to the serpentinite seamounts studied with *Alvin* is the first evidence of such rocks in the forearc of any active interoceanic arc. These lavas support the concept that either exotic fragments of old oceanic plate have been incorporated into the forearc terrane or lavas generated by suprasubduction-zone magmatism make up part of the forearc crustal sequences.

## SEISMIC-REFLECTION STUDIES OF CONICAL SEAMOUNT

A site-survey cruise was conducted in 1987 to acquire detailed seismic-reflection data over the prospective drill sites on Conical Seamount (*Fred H. Moore* Cruise 35-11). The navigation for the cruise was restricted to satellite navigation because the Yap station for Loran C had been shut down and the new station in Guam was not yet operating. The signal-to-noise ratio on one of the two Loran C stations for which we could pick up delays was too low to make reasonable calculations of the ship's position. The Global Positioning System was only functional for a few hours each day. The track plot of the survey is shown on the SeaBeam bathymetry (Fig. 11). The sound source was a tuned array of six air guns that totaled 1064 in.$^2$, with a shot interval of approximately 40 m. Reflection returns were received with an analog hydrophone streamer configured with six channels at 16.66-m group intervals and recorded digitally in demultiplexed (SEG D) format on magnetic tape. Field data were sorted into 16.66-m bins, corrected for normal moveout, and stacked (nominal twofold). The stacked traces were mixed (three traces having 1-3-1 weight), deconvolved, filtered (15– to 45-Hz bandpass to 1 s below water bottom; 9– to 35-Hz bandpass to the end of record), and migrated (finite difference) prior to final display. Migration velocities were estimated from previous refraction profiles in the Mariana forearc (LaTraille and Hussong, 1980).

The first seismic-reflection line (Fig. 12) was run east to west across the summit region of Conical Seamount. The reflectors from the sediment in the basin to the east of the seamount extend for several kilometers under the edifice and persist to a sub-bottom depth of about 0.5 s. The lower eastern slopes of the seamount show deformation indicative of folding and/or slumping of the sedimentary layers draping the seamount. Numerous weak reflectors dip inward toward the center of the edifice. These reflectors show the steepest dip on the lower flanks and flatten to become parallel to the seafloor on approach to the summit. The inward-dipping reflectors may indicate subsidence of the edifice as a consequence of loading by subsequent flows or by collapse of the edifice as flows dehydrate after emplacement. At depths shallower than the midflanks of the seamount a semicontinuous reflector can be traced at a subsurface depth that varies from about 0.18 s at the summit to about 0.15 s on the midflank. Because the sub-bottom depth of this reflector varies, we do not believe that it is a processing artifact. This reflector is particularly well-defined on the west flank and on the summit region. On the east flank several reflectors crosscut this reflector. The

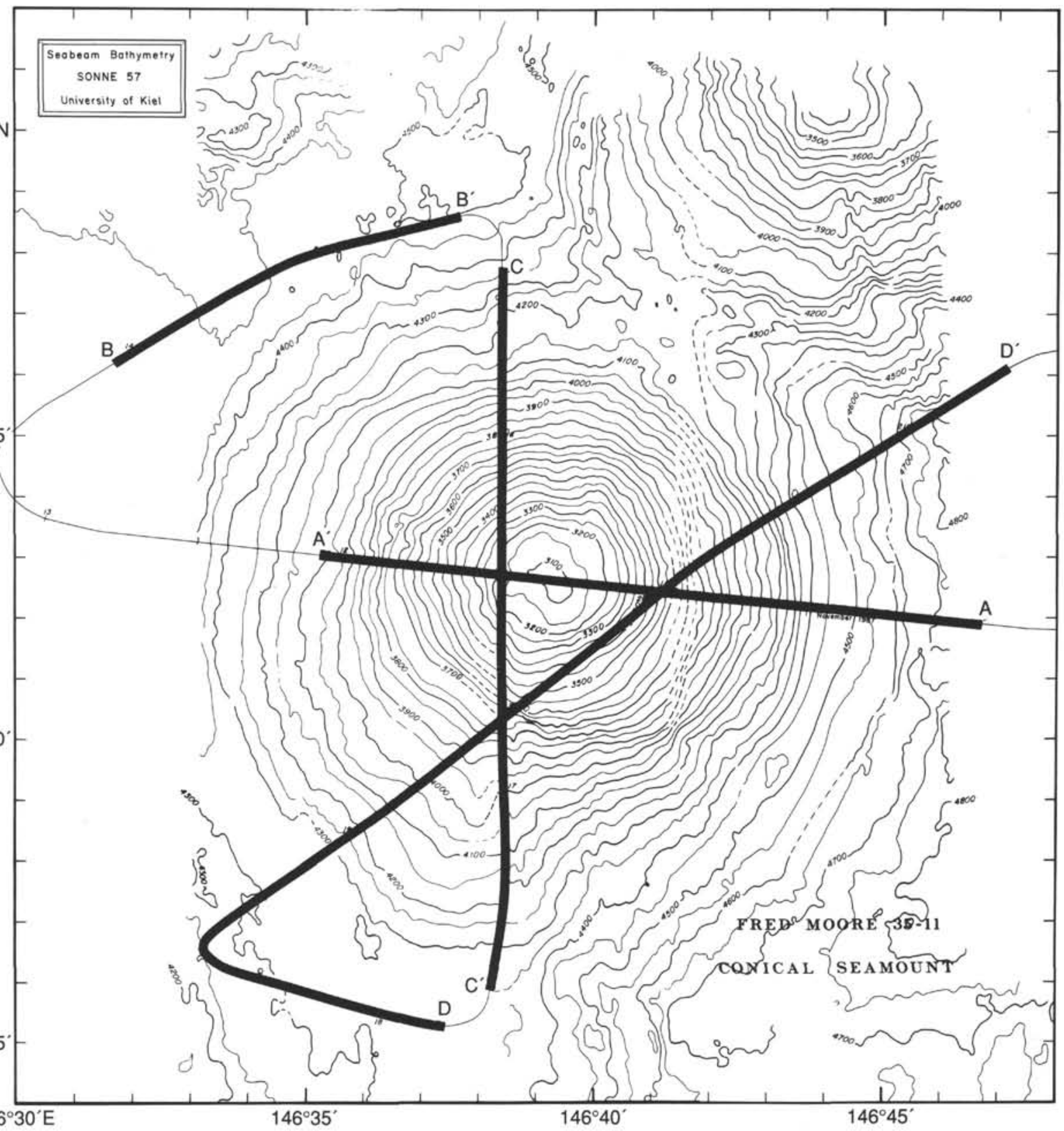


Figure 11. Track plot of the *Fred H. Moore* (FM) Cruise 35-11 seismic-reflection survey of Conical Seamount, superimposed on SeaBeam data from sonne 57. The heavy tracklines show locations of reflection profiles given in Figures 12 through 15.

nature of the reflector remains an enigma that may be resolved by drilling. The central core of the seamount lacks reflectors and is interpreted to be composed of highly unstable, fluid-charged serpentine mud rising through the seamount core. The west side of the seamount shows much better defined reflectors dipping toward the center of the seamount. The sedimentary layers on the west side of the seamount are better defined than those on the east side. Subhorizontal reflectors at a depth of about 6.5 s are apparent beneath the lower west flank. These are interpreted to represent old sedimentary sequences onlapped by serpentine flows.

Seismic-reflection line 2 (Fig. 13) was run from the western to the northern base of the seamount. This line traversed a relatively flat part of the seafloor on the northwest side of the seamount (western end of line 2 in Fig. 13). The region is dominated by thick (1.0 s), flat-lying, sedimentary sequences. At about 1415UTC the profile crosses the southwestern side of a small horst block and graben separated by a throw of about 50 m. A well-defined shallow (100 m below seafloor) reflector occurring near the top of the horst block is interpreted as a sill or buried lava flow. At about 1445UTC on the northeastern side of the horst block an apparent normal fault, down-dropped to the northeast, offsets the reflector. The reflector is deformed (downwarped) beyond 1500Z and terminates at about 1510UTC.

Seismic-reflection line 3 (Fig. 14) was run from north to south across the summit of the seamount. The sedimentary layers on the base of the north flank are severely disturbed, folded, and/or slumped. The midflank portion of the seamount shows a smooth, fairly undisturbed thin drape of sediment. The midflank reflectors are interpreted as relatively recent serpentinite flows seen on the north flank of the seamount on

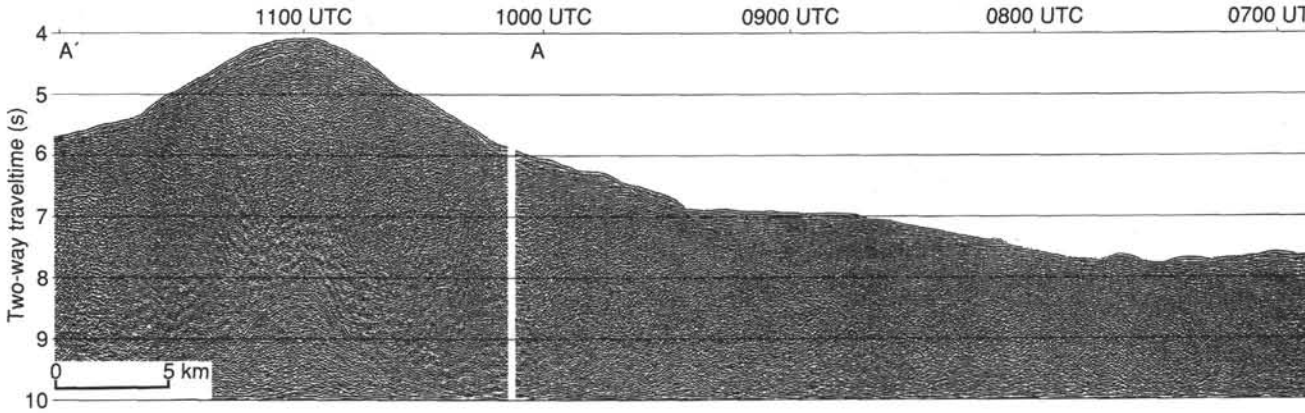


Figure 12. Seismic-reflection line 1, FM35-11.

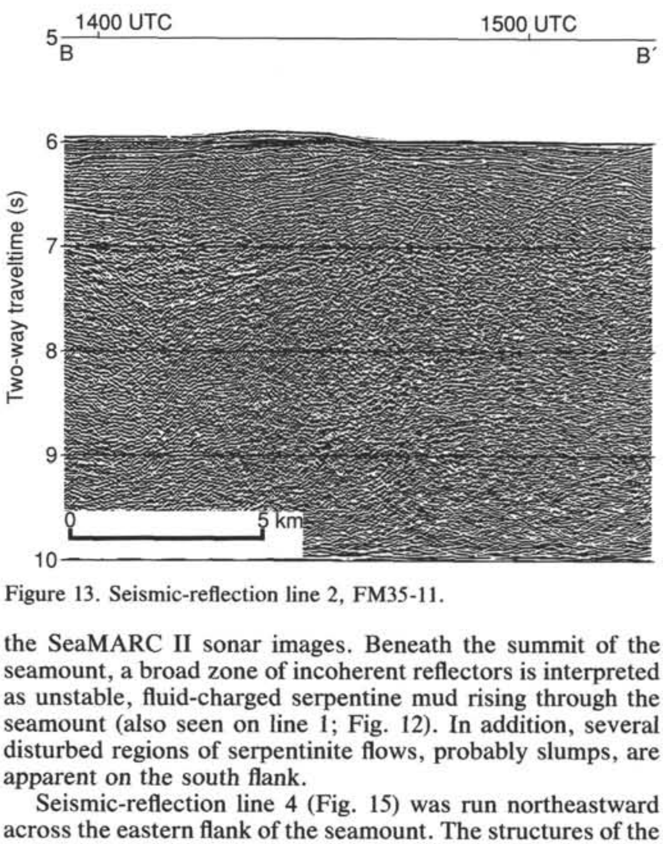


Figure 13. Seismic-reflection line 2, FM35-11.

the SeaMARC II sonar images. Beneath the summit of the seamount, a broad zone of incoherent reflectors is interpreted as unstable, fluid-charged serpentine mud rising through the seamount (also seen on line 1; Fig. 12). In addition, several disturbed regions of serpentinite flows, probably slumps, are apparent on the south flank.

Seismic-reflection line 4 (Fig. 15) was run northeastward across the eastern flank of the seamount. The structures of the seamount are less obvious here than on line 3, which was run across the summit of the seamount. A thin sedimentary reflector can be traced across the entire northeast flank of the seamount. This profile shows numerous down-bowed reflectors, which may be from surfaces of inward dipping horizons that were cut by the oblique profile. Some disturbance of the serpentinite flows is apparent on the southeast face of the seamount, which may result from slumping as seen on *Alvin* dives on that flank.

## SUMMARY AND CONCLUSIONS

Several important observations that resulted from the *Alvin* dives and the recent geophysical surveys around Conical Seamount have modified our concepts of convergent margins:

1. Metamorphism (particularly serpentinization) is pervasive in the forearc, and hydration of forearc materials acts as sink for fluids driven off the subducting slab (Fryer and ryer, 1987; Saboda et al., 1987). The extent of metamorhism in the dredge and dive samples is variable, but all of the ltramafic samples recovered are serpentinized to some deree. Prior to these investigations researchers studying the hemical balance of the convergent margins were unable to xplain the apparent inconsistencies between the amount of olatiles released in arc and backarc volcanism and the resumably much greater amount of volatiles driven off the escending slab by dehydration reactions. Fryer and Fryer 987) showed that the fields of stability of metamorphic facies ithin the Mariana forearc are more than adequate to accomodate the fluids driven off the slab.

2. The fluid flux in the convergent margin environment is ontrolled primarily by forearc processes. Fluids, derived at ast in part from the descending slab, are actively venting at vo of the serpentinite seamounts (Fryer et al., 1987; aggerty, 1987b) and in some highly faulted regions near ese seamounts. The seamount vents are capped by chimey structures composed of carbonate (calcite and aragoite) and silicate (a new mineral, a Mg-silicate analogous to lophane) (Haggerty, 1987a; Haggerty and Cloutier, 1988). The geochemical and isotopic compositions of the carbonate chimneys differ from normal marine carbonate and distinguish them from carbonates formed in association with serpentinite at fracture zones (Haggerty, 1987b). Recent fluid-inclusion work on the aragonite needles of the *Alvin* chimney samples shows them to contain methane and several varieties of the higher hydrocarbons (Haggerty, 1989). Analyses of the pore waters from push cores and particularly the vent waters collected with *Alvin* also show a high methane content. The source of these fluids and their associated hydrocarbons is interpreted to be the subducted Pacific oceanic plate sediments or sediment underplating the outer forearc.

Active convergent margins can accommodate large quantities of fluids from the subducting slab and thus develop broad regions of lawsonite-albite-chlorite/greenschist/blueschist facies stability fields beneath the entire forearc region (Fryer and Fryer, 1987). Thus, under appropriate tectonic conditions, serpentinite seamounts can be emplaced almost anywhere in a forearc, yet none show development of serpentinite seamounts on the scale of that in the Mariana system. One reason for the paucity of serpentinite seamounts in other forearcs may be that, in contrast with most others, the Mariana forearc shows extensive recent vertical tectonic deformation (Fryer and Fryer, 1987). Numerous sedimentary serpentinite deposits have been described from the Pacific margins and in the Mediterranean and Caribbean

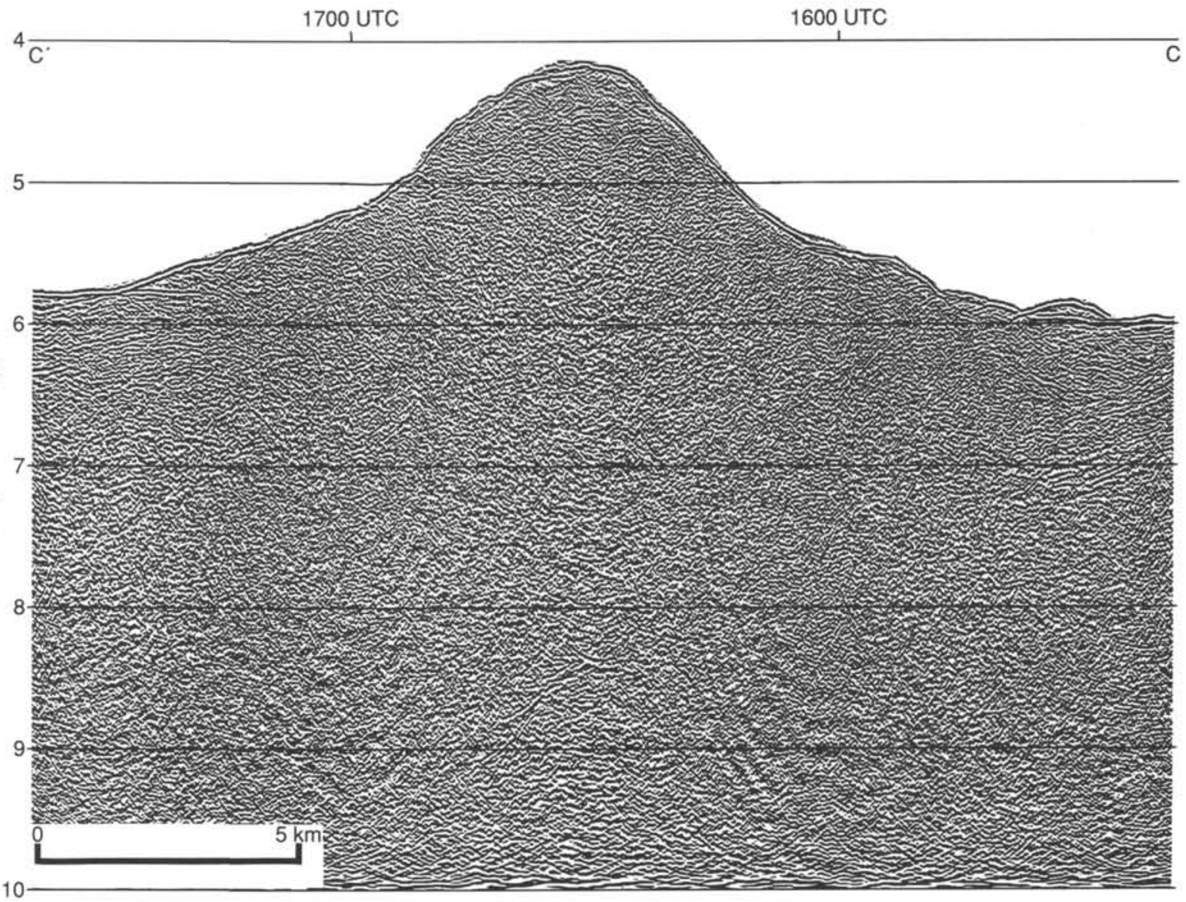


Figure 14. Seismic-reflection line 3, FM35-11.

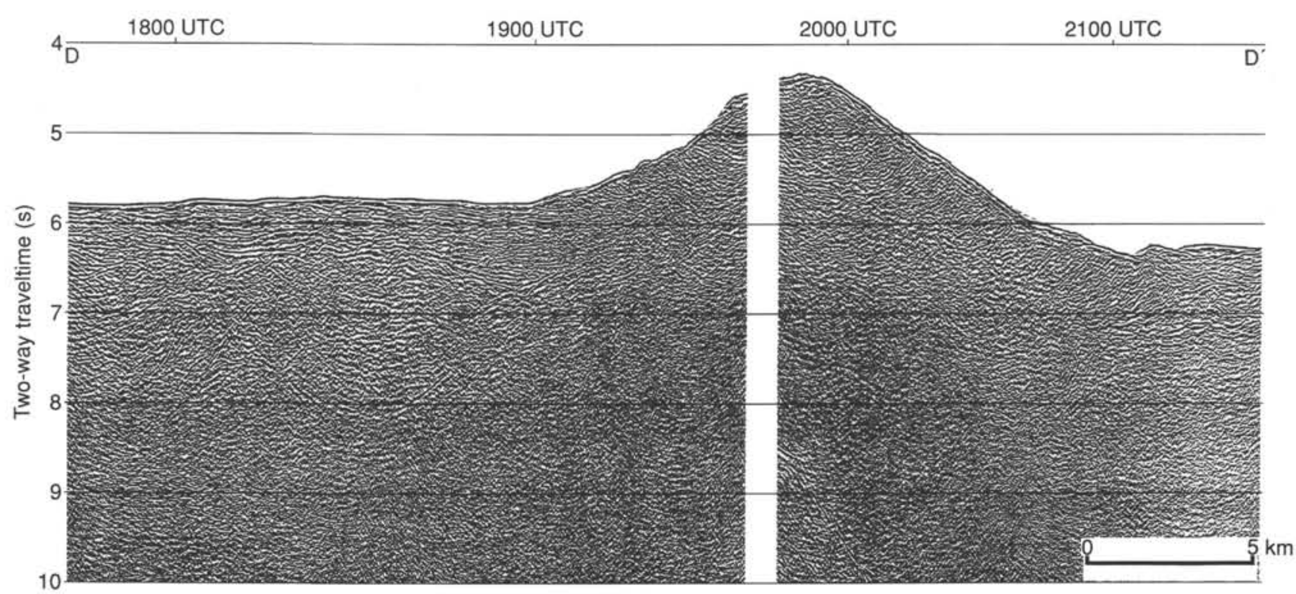


Figure 15. Seismic-reflection line 4, FM35-11.

areas (Lockwood, 1971). Several of these exposures are similar to the deposits forming on Conical and Pacman seamounts. Therefore, we suggest that Conical and Pacman seamounts may represent type localities for the study of *in-situ* formation of many of these sedimentary serpentinite bodies.

The fluid flux through the Mariana forearc must play a critical role in the evolution of the thermal structure of the forearc. The degree of flux channeled by fractures within the outer forearc may be great enough to create major local perturbations of the thermal structure. A better understanding of the distribution of active venting sites will make it possible to develop more accurate models of the thermal structure of the forearc.

3. Several different types of seamounts are present on the Mariana forearc (Fryer et al., 1987). The actively "erupting" serpentinite seamounts, such as Conical Seamount, are one end-member. The uplifted horsts of forearc crust are the other end-member, and between these types are seamounts that exhibit elements of each.

The *Alvin* observations on Conical Seamount imply that nonviscous flow morphologies correlate with active venting and with young, unsedimented serpentinite flows. Conical Seamount is considered to be an active mud volcano and a site at which forearc fluids are escaping. Clasts of serpentinized ultramafic rocks, serpentine muds, and chimney material similar to that obtained from the carbonate chimneys on Conical Seamount were dredged from an unnamed seamount at about 14°N. The chimney materials analyzed by Haggerty (1987a) are in equilibrium with fluids of the same composition as those analyzed from Conical Seamount. The metamorphic grade and composition of the ultramafic clasts and serpentine muds in the dredge hauls from this seamount are similar to those of the clasts and mud from Conical Seamount. Thus, we suggest that the southern seamount may also be an "active" serpentinite seamount. Although similarly metamorphosed ultramafic clasts and serpentine muds have been collected in dredge hauls from several other seamounts (Bloomer and Hawkins, 1983; Saboda et al., 1987), chimney materials have not been retrieved. How many of these or of the other Mariana forearc seamounts might also be "active" is unknown. Desprairies (1982) reported significant amounts of serpentine in the middle Miocene and middle Eocene sedimentary units in Hole 459B, located about 50 km south of Pacman Seamount. If these results indicate formation of serpentinite seamounts nearby, then serpentinite seamounts may have been active for at least the last 40 m.y. in the Mariana system.

4. Complex local as well as regional interrelationships exist between faulting and the distribution of seamounts within the outer forearc. The local structural setting of Conical Seamount is well known (Hussong and Fryer, 1985; Fryer et al., 1987; Newsom and Fryer, 1987; Johnson et al., 1987). Recent seismic-reflection profiles and gravity data (Newsom and Fryer, 1987) show that Conical Seamount was emplaced along local faults.

5. The first documented exposure of MORB lavas in any active forearc was discovered well arcward of the trench axis in the Mariana region during dredging of the scarp of a large graben 40 km east of Conical Seamount (Johnson and Fryer, 1988).

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