"Shinkai 6500" investigations of a resurgent mud volcano on the Southeastern Mariana forearc

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A serpentine mud volcano at 13°47'N, 146°03'E on the southeastern Mariana forearc has apparently recently been reactivated. The summit region is characterized by a resurgent protrusion in the southeastern half of the summit. Blocks of unconsolidated to partially cemented fine-grained serpentine muds are protruding at the seafloor. Fluid emanations rich in carbon and sulfur support a vigorous biologic community of mussels, snails, crabs and tubeworms. Carbonate chimney structures and encrustations mark sites of fluid egress. The source of the fluids is likely the subducted slab. The nature of the rock samples recovered with the submersible and the structures exposed at the sea floor suggest two possible reactivations of this seamount in the recent past and confirm the suggested episodic nature of activity on Mariana forearc mud-volcanoes. We interpret this seamount to have been reactivated by motion along a fault beneath the seamount, and that the fluids and serpentine muds were brought up from great depth (up to 25 km) beneath the seamount. In the long term, studies of slab fluids at convergent margins will permit a better understanding of the physical properties of the deep forearc mantle and of the subducting plate, will help to constrain the controls over seismicity at the decollement and will be critical to the understanding of global geochemical mass balance related to plate tectonic activity.

Key words : Fluids, serpentine, Mud-volcano, Seamount, Mariana, forearc

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1. Introduction

One of the most critical problems involved in the study of convergent plate margins is the physical nature and compositional variability of materials in the vicinity of the decollement between the subducting and over-riding plates. The physical conditions prevalent at this boundary are critical elements in controlling seismicity along the decollement and dehydration reactions in the down-going plate. The flux of fluids at convergent margins is an important element in understanding global mass balance and chemical transport within subduction zones. Fluid production and transport affect the thermal structure of the convergent margin, metamorphism in the supra-subduction zone region, diagenesis in forearc sediments, the composition of arc and back-arc magmas, and the physical properties of the subduction zone.

Because the Mariana convergent margin is nonaccretionary, it provides an environment conducive to the study of slab-derived fluids and deep forearc materials without the complications of a thick accumulation of accreted sediment (Fryer, 1996a). There are several serpentine seamounts on the Mariana forearc (Fig. 1) that have yielded samples indicative of active fluid egress and a deep source of materials derived from a metamorphosed forearc mantle wedge and from the down-going plate (Fryer and Fryer, 1987 ; Fryer et al., 1990 ; Fryer, 1992 ; Mottl, 1992 ; Fryer et al., 1995 ; Lagabrielle et al., 1992 ; Maekawa et al., 1992 ; 1995 ; Fryer et al., submitted). The seamounts have been interpreted as mud volcanoes that remain active over millions of years, but which experience episodic protrusion events (Fryer, 1992 ; Fryer 1996a ; Fryer et al., submitted). The natural rise of deep-seated forearc mantle material and fluids from the dehydration of the down-going plate has the potential to provide a direct access to materials from depths far greater than can be reached by conventional deep sea drilling or other sampling techniques. The active mud volcanism that has produced several large (25 km diameter, 2 km high) seamounts on the Mariana forearc is apparently unique to this convergent margin, although deposits of serpentine mud flows have been described from the Izu-Bonin arc (e.g., Fryer, 1992) and numerous accreted exotic terranes (e.g., Lockwood, 1971). In this paper we summarize the results of studies of one such seamount and introduce the evidence which suggests that the seamount has recently been reactivated.

2. Field Work

A total of three "Shinkai 6500" submersible dives were conducted on S. Chamorro Seamount (Fig. 2), a serpentine seamount at 13°47′N, 146°03′E on the Mariana forearc, in September of 1995 (Dives 280 and 281) and November of 1996 (Dive 351). This seamount is the site of a dredge haul that yielded serpentinized harzburgite and several fragments of carbonate chimney material, collected in 1981 by P. Fryer. The carbonate materials are identical in structure and composition to chimney samples collected by Fryer from another serpentine mud volcano, Conical Seamount (Fryer and Fryer 1987 ; Haggerty, 1992 ; Fryer et al., 1990). Both are serpentine seamounts forming in response to the escape of slab-derived fluids above the subducting Pacific plate (Fryer 1992 ; Fryer et al., 1995 ; Fryer, 1996a). Dives 280 and 281 were conducted on the flank and summit region of the seamount (Fig. 3), whereas Dive 351 concentrated its observations and sampling on top of the knoll in the southeastern part of the summit region.

S. Chamorro Seamount is one of three serpentine seamounts located in a small cluster at the southwestern edge of a forearc graben (Fryer, 1996b) (Fig. 2). The location of the seamount, on the edge of the break of the inner trench slope and near the edge of the forearc graben, suggests that S. Chamorro Seamount and its neighbors formed in response to vertical tectonic deformation in the forearc.

Details of the 1995 dives were described by Fryer (1996b). Dive 280 (Fig. 3) revealed freshly disrupted surfaces on the flank of the seamount and debris channels indicating recent mass wasting (Photo 1). Dive 281 traversed the summit region from northwest to southeast (Fig. 3). The northwestern part of the summit is covered with a blanket of foraminiferal sands, possibly several tens of centimeters thick. These sands have developed current ripples as high as several centimeters in places (Photo 2). Where devoid of current ripples the foraminiferal sands are partially obscured by abundant small manganese nodules (Photo 3). These

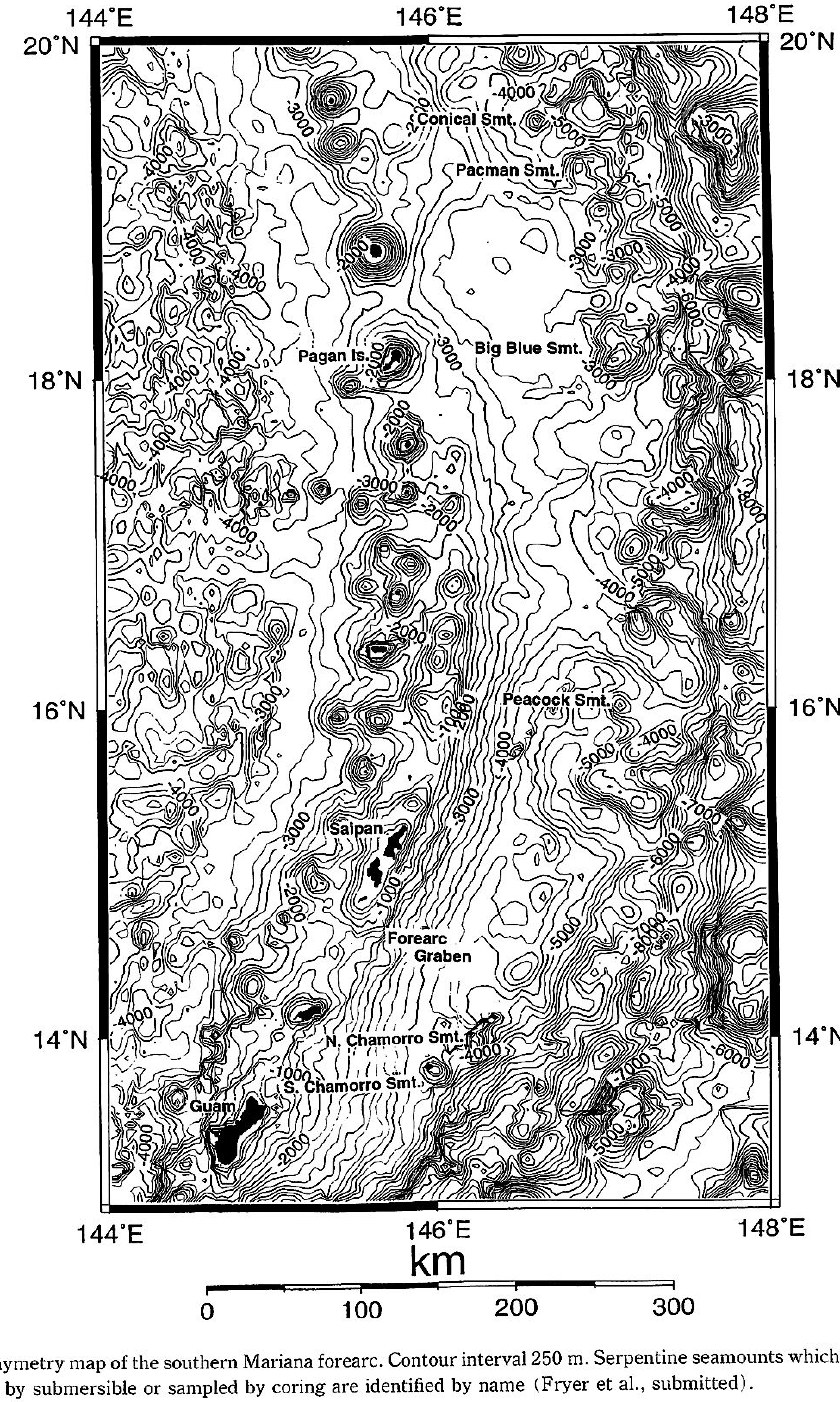

Fig. 1 Bathymetry map of the southern Mariana forearc. Contour interval 250 m. Serpentine seamounts which have been studied by submersible or sampled by coring are identified by name (Fryer et al., submitted).

foraminiferal sands are similar to those that form a blanket over one meter thick on top of serpentine muds at the summit of N. Chamorro Seamount, immediately northeast of S. Chamorro Seamount (Fryer et al., submitted).

The region of foraminiferal sands at the summit of S.

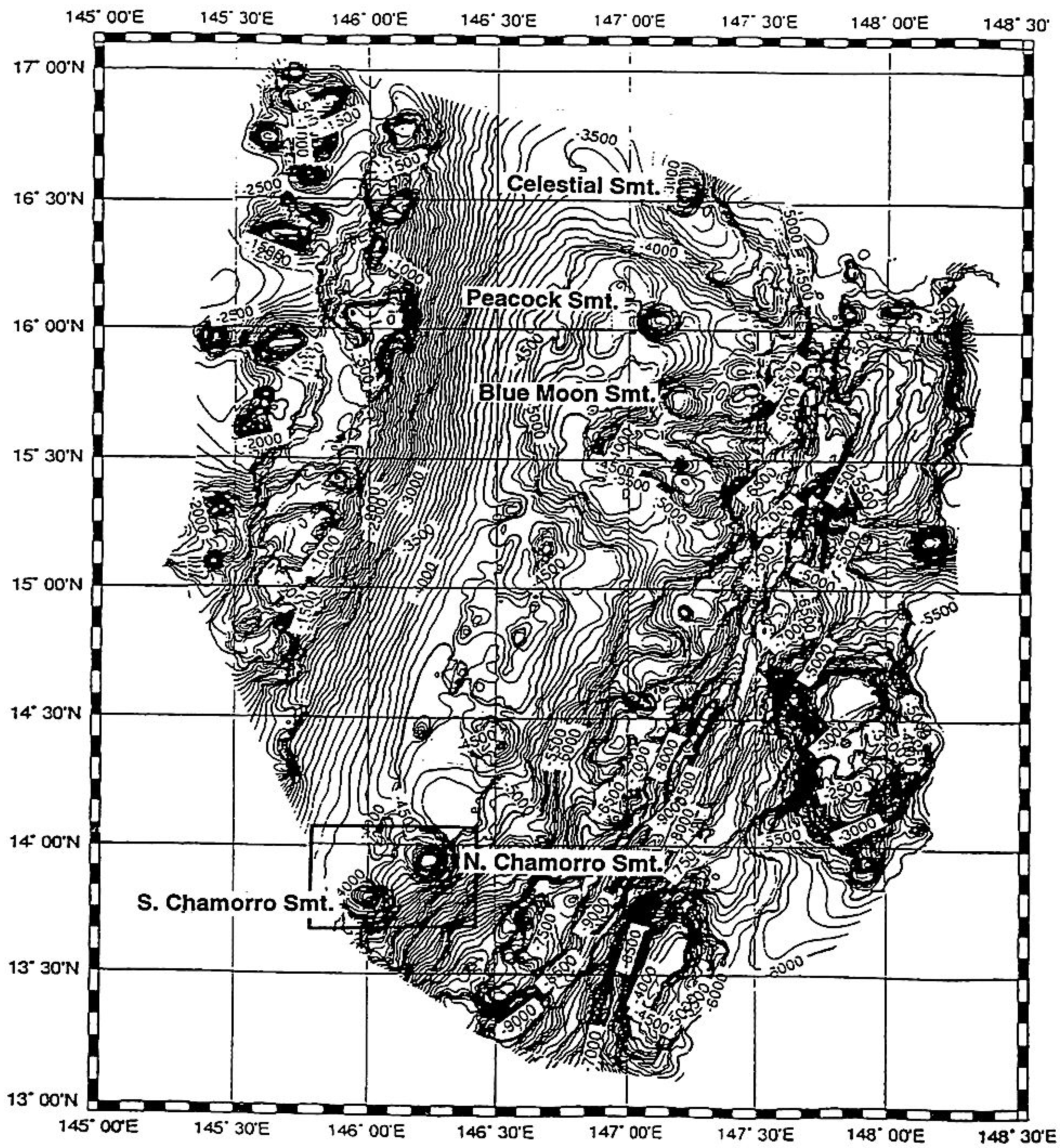

Fig. 2 Bathymetry of the southern Mariana forearc region including the S. Chamorro seamount pair. Contour interval 200 m.

Chamorro Seamount shows no deformational structures (Fryer, 1996b) ; however, there is evidence of tumescence and accompanying tensional fracturing at the top of a prominent 160-m-high knoll on the southeastern side of the summit (Fig. 4). The slopes of this knoll are steep (Photo 4) and at the top, there are randomly oriented slabs of partially cemented (by carbonate) serpentine mud that includes clasts of rock fragments of varying sizes. This material was sampled and described by Fryer (1996b). It is similar to the sort of serpentine mud flow materials recovered from the summit of Conical Seamount both in Alvin dives (Fryer et al., 1990) and in Ocean Drilling Program Leg 125 drilling (Fryer, 1992). The tensional fracturing of the surface of the knoll and the random orientation of the slabs suggests up-doming of the knoll (Fryer, 1996b). Dive 351, which explored much more of the summit region, permitted a more thorough survey of the top of the knoll. We found abundant geological evidence that the knoll was indeed formed by a resurgence of serpentine mud volcanism accompanied by fluid venting. The entire surface of the knoll is broken into slabs of the partially cemented serpentine mud (Photo 5). The deformation has produced meter-deep fissures, some oriented north-south, but many with cross-cutting orientations (Photo 6). Sediment cover is virtually absent, but many of the slabs have a partial carapace of small manganese nodules similar to those observed on the foraminiferal sands (Photo 7). In some places relatively smooth surfaces of freshly protruded serpentine muds have oozed out of the

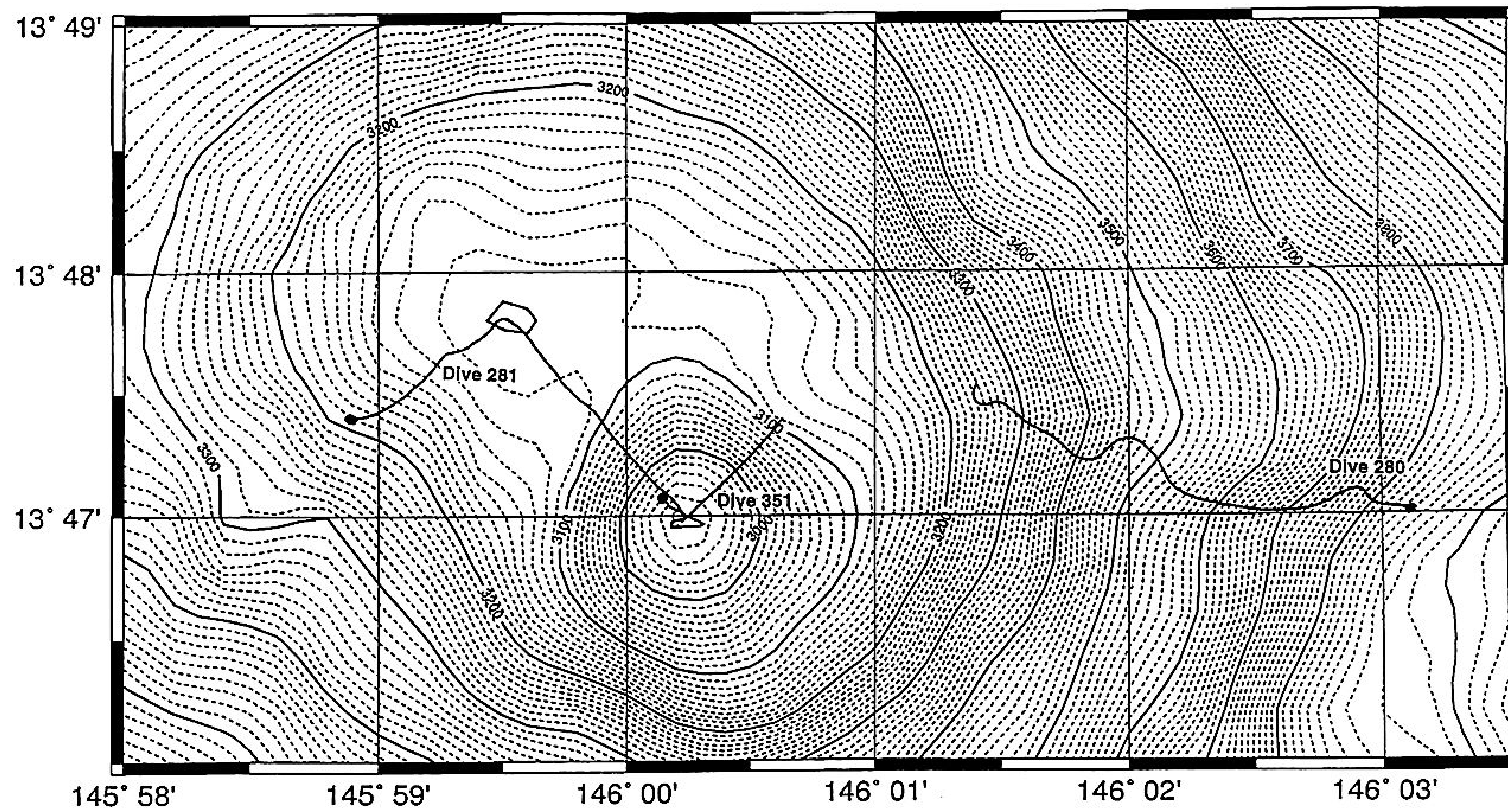

Fig. 3 Bathymetry of S. Chamorro Seamount, contour interval 10 m, showing the tracks for "Shinkai 6500" submersible Dives 280, 281, and 351. Large dots indicate start points of the dives. The flat northwestern half of S. Chamorro Seamount is blanketed with foraminiferal sands, the resurgent serpentine mud protrusion occupies the southeastern half.

fissures to partially cover edges of the blocks (Photo 8). It should be noted that in the Dive 281 samples of the serpentinite mud slabs there are pebble- to cobble-sized fragments of foraminiferal sand-stone and small manganese nodules that are surrounded by serpentine muds (Fryer, 1996b). This suggests that the serpentine mud protruded into and through a previous surface that was blanketed with foraminiferal sands and manganese nodules, engulfing those materials before being cemented by carbonate (Fryer, 1996b). It is likely the fresh serpentine flows may also have incorporated pieces of the cemented slabs at the edges of the fissure through which they protrude. In other places, rock fragments and smaller slabs are perched precariously at the edges of meter-deep fissures, attesting to the dynamic nature of deformation at the top of the knoll. The deformation is consistent with up-doming of the knoll (Fryer, 1996b). Because of the paucity of foraminiferal sands on top of the serpentine mud slabs and because there is a layer of manganese nodules blanketing portions of the upper surfaces of the slabs, we suggest that there may have been two recent episodes of tumescence. The earlier one produced the initial protrusions that engulfed the foraminiferal sands. After this event the surface was partially covered with the same manganese nodules that cover portions of the foraminiferal sands on the northwest summit region, and rising fluids associated with the protrusion event had sufficient time to cause partial cementation (with carbonate) of the muds. Subsequently, renewed up-doming fractured the partially cemented serpentine mud flows and formed the slabs and new serpentine protrusions that were observed during our "Shinkai 6500" dives.

The presence of carbonate encrustations at the periphery of the fissures (Photo 9) is evidence of fluid egress. Numerous carbonate chimney structures and encrustation features have been noted on other serpentine seamounts of the Mariana forearc (e.g., Fryer et al. 1990 ; Fryer, 1996a). Carbonate encrustations and small chimneys were observed on Dive 281 (Fryer, 1996b). Dive 351 provided stronger evidence of active fluid egress. We observed and sampled one obvious carbonate chimney that had 6–8 live mussels clinging to it prior to sampling. This 15 cm high chimney proved to be hollow, with porous walls punctured by several cm-sized holes (Photos 10 and 11). We collected one large

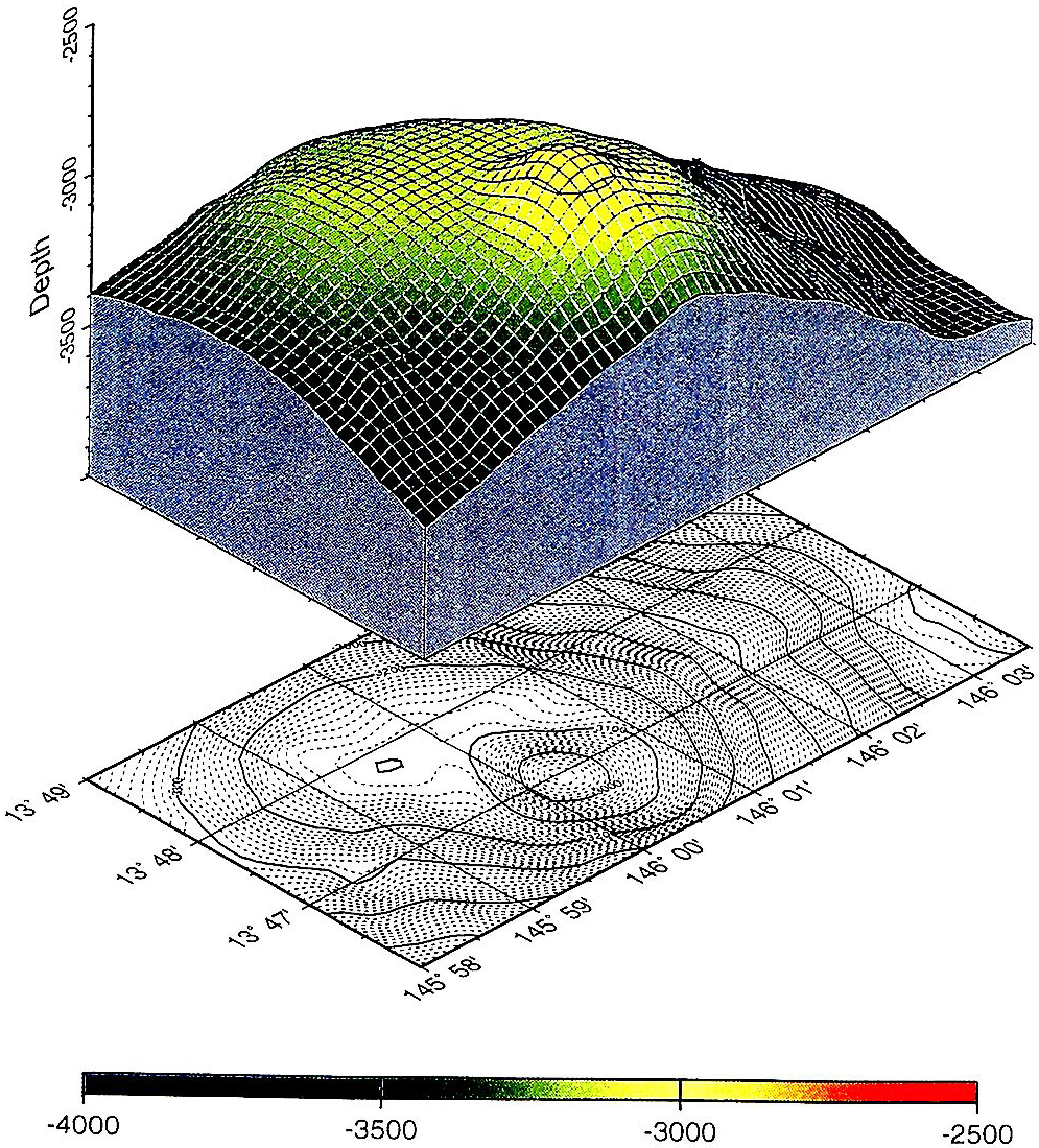

Fig. 4 Bathymetry (bottom) and a perspective rendering of S. Chamorro Seamount (top) depicting the resurgent summit knoll. Viewing azimuth is to the northeast. Image prepared by M. Sekine

carbonate crust as well. These carbonate structures are believed to precipitate at a reaction front near the sea floor, where the deep upwelling fluids, rich in dissolved carbonate ions, mix with Ca-rich seawater. Vigorous biological communities were observed at the summit in the region traversed by Dive 351. Samples recovered from the fissures in which the communities were active were enriched in dissolved sulfide, as attested to by a strong hydrogen sulfide smell.

3. Biologic communities

There are at least three regions in which communities of organisms were observed on Dive 351. Although no venting of water was observed or sampled directly, slow upward seepage of water is indicated by dense fields of mussels in areas of extensive deposition of carbonate crusts and chimneys. The mussels are concentrated along fissures up to about one meter deep (Photos 9 and 12). The mussels probably contain chemosynthetic bacteria which provide nourishment using reduced chemicals in the upwelling fluids. At least two of the fields are large (over 30 m long). The mussels are likely of the genus Bathymodiolus, a genus that contains methylotrophic symbionts in their gills (Fisher, 1990) and requires high concentrations of methane in the fluids on which they feed (K. Fujikura pers. comm., 1996). Mussels of this genus were discovered in the Mariana backarc basin at hot vents on the spreading axis (K. Fujikura, pers. comm., 1996). Individuals observed range in size from 2 to 20 cm long and were observed in feeding positions clustered within the fissure regions (Photos 9, 12, and 13). In addition to mussels, galatheid crabs (Photos 12 and 13) and gastropods (Photos 12, and 14) were also observed in the fluid egress regions. Clusters of tubeworms (2–3 mm diameter, tan-colored) are distributed randomly or in intertwining clumps over the surface (Photo 13).

We collected about a dozen mussels, one gastropod, and two clumps of small tubeworms from the three vent fields. The mussels will be analyzed for their included bacteria to verify that they are indeed living off chemosynthesis, fueled by reduced chemical species in the venting fluids.

The seamount is actively venting fluids that cause precipitation of carbonate materials similar to those of Conical Seamount. The locality, however, supports a far richer biological community than did that observed at the summit of Conical Seamount, where only limpets and high-spire gastropods were observed and sampled. Analysis of the carbonate material and detailed investigation of the biological specimens collected at S. Chamorro Seamount are underway.

4. Chimney structures

X-ray diffraction analysis (XRD) of the carbonate encrustations and chimney structures shows that they are composed of aragonite and calcite (Fig. 5). Most of the carbonates are found either mantling the surfaces of fissures or forming at the top of the fissures as masses overhanging the cracks. Small chimney structures do occur in some localities (Photo 11), but they are unlike the large well-developed structures common at the conduit region on Conical Seamount (Fryer et al., 1990) and are also different from the delicate brucite chimneys (Photo 15) that form on Pacman Seamount (Fryer, 1995). The difference in the size and distribution of the carbonate chimney structures and encrustations on S. Chamorro

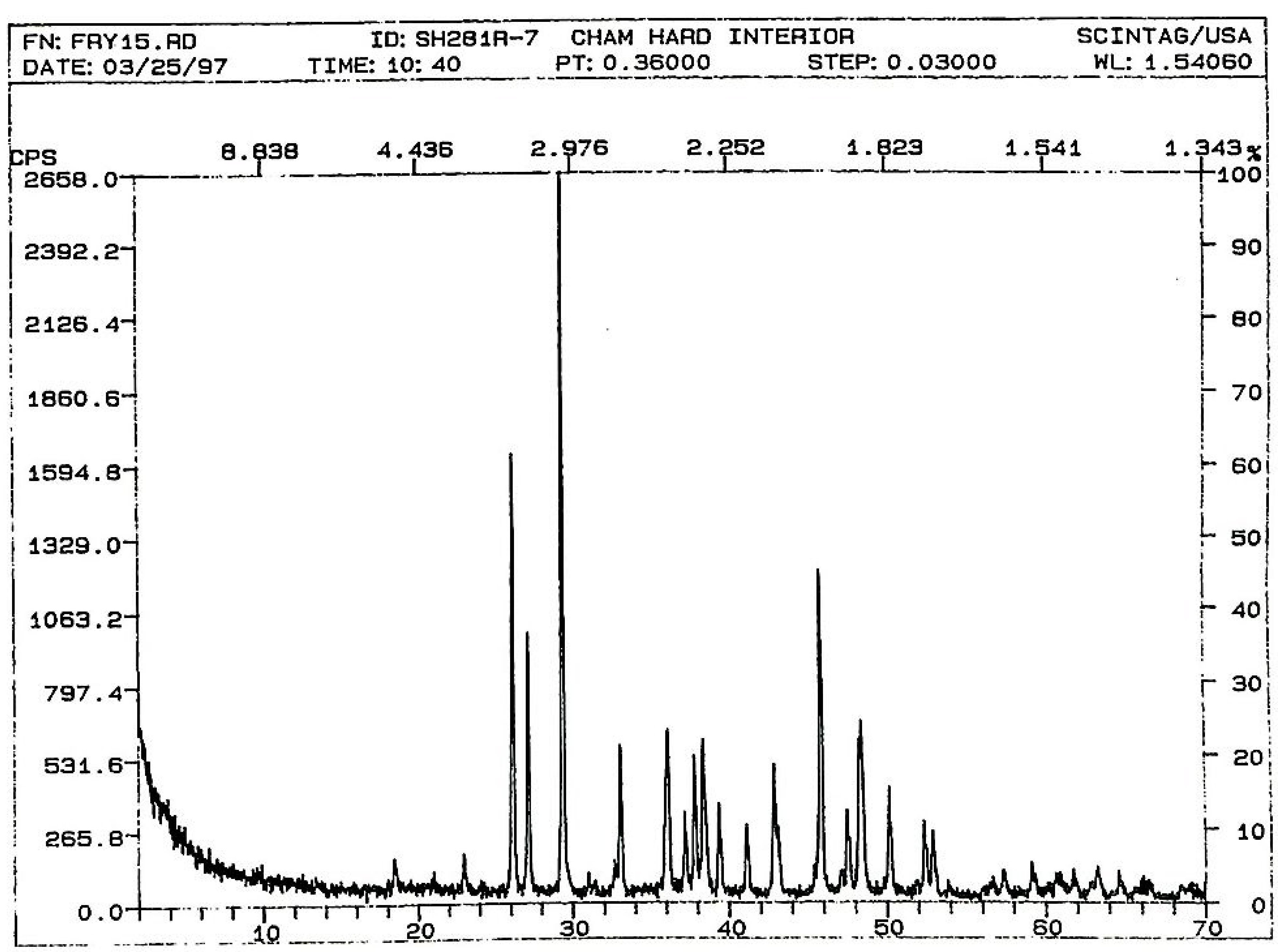

Fig. 5 XRD pattern for the hard interior of a chimney structure collected on Shinkai 6500 Dive 281. Calcite peaks are at 2-thetas of 22.9°, 29.3°, 39.3°, 43.1°, 47.4°, 48.3° and aragonite peaks are at 26.1°, 27.1°, 33°, 36°, 38.3°, 45.7°.

Seamount, with respect to these other sites, suggests that the carbonate structures are newly forming there. This interpretation is consistent with the observations of newly disrupted seafloor and the intricate engulfing textures of the serpentine/foraminiferal limestone samples recovered on the 1995 dives.

5. Discussion

The studies of drill samples from Conical Seamount (Fryer, 1992 ; Fryer and Mottl, 1992) suggest at least 6 episodes of protrusion events separated by periods of inactivity. There is meager evidence that the seamount was sedimented between major protrusion episodes. Little pelagic sediment was recovered from depth in the seamount during ODP Leg 125 drilling (Fryer and Mottl, 1992). The flanks of Conical Seamount are at depths well below the carbonate compensation depth. It is possible that no accumulation of carbonate sediments ever occurred there. The lack of carbonate sediments on the flanks of Conical Seamount makes comparison with the sediment accumulations observed on S. Chamorro seamount and N. Chamorro Seamount difficult. The fact, however, that a thick layer of foraminiferal sands has accumulated on both seamounts of the Chamorro group suggests a significant dormancy for these two seamounts. S. Chamorro Seamount may have remained active over millions of years, but probably experienced only episodic protrusion events separated by lengthy dormant intervals. We suggest that the stimulus for reactivation of the seamount may be seismicity at the source region for the serpentine muds. The suggested mechanism for generation of the muds is movement along a fault which contributes to formation of fault gouge coupled with expansion during serpentinization (Fryer, 1992). This ground up rock flour can them be mobilized by fluids rising along the fault plane. A channel to the surface may be opened along such a fault plane, permitting the fluids and muds to reach the sea floor relatively rapidly, thus preserving the most pristine possible signal from the slab-derived fluids and bringing deep-seated materials to the surface where they can be readily sampled (e.g., see Fryer, 1996a). Although this interpretation is consistent with data from other Mariana forearc serpentine seamounts, to-date there have been no detailed seismic reflection surveys of the region surrounding S. Chamorro Seamount. Thus, we have no data regarding the subsurface structure of the seamount.

6. Future work

Side-scan sonar imaging surveys and detailed sampling by coring and dredging will be conducted in August of 1997 in the central and southern Mariana forearc regions aboard the R/V Moana Wave by P. Fryer and G. Moore. Six-channel seismic reflection surveys, as well as magnetics and gravity data will also be collected along the survey tracks. These studies will further clarify the roles of both the serpentine seamounts and forearc faults as sites for the study of deep-sourced rock materials and slab-related fluid egress on the Mariana forearc.

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(Notice) Photos are given on the following pages.

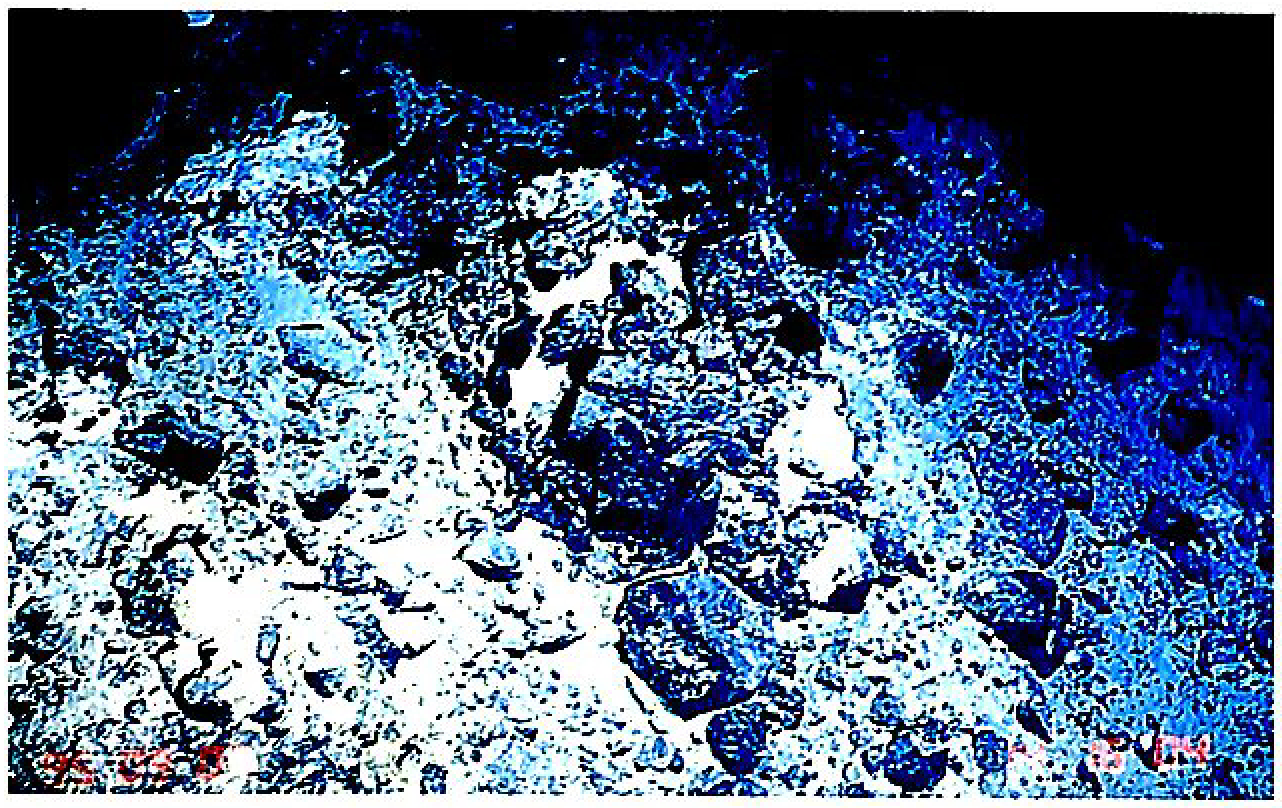

Photo 1 "Shinkai 6500" external photo of the mid-flank region of S. Chamorro Seamount on Dive 280, showing debris chutes (left and right) and a mass of fragmented serpentinized peridotites (large boulder in lower middle is about 80 cm in diameter).

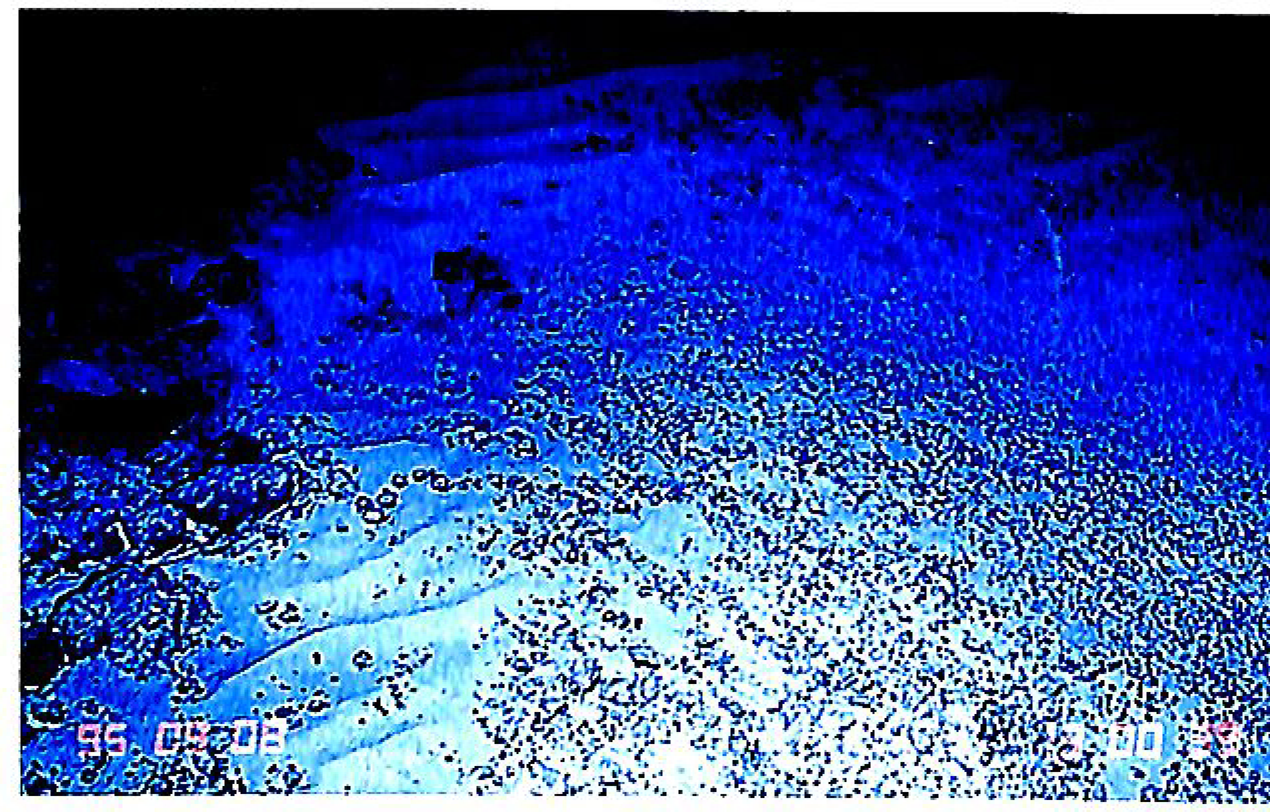

Photo 2 "Shinkai 6500" external photo from Dive 281 showing current ripples in foraminiferal sands at the summit of S Chamorro Seamount. A patch of small manganese nodules covers part of the foraminiferal sands region in the lower right of the field of view. Outcropping boulders of serpentinized peridotite are exposed on the far left side of the photo.

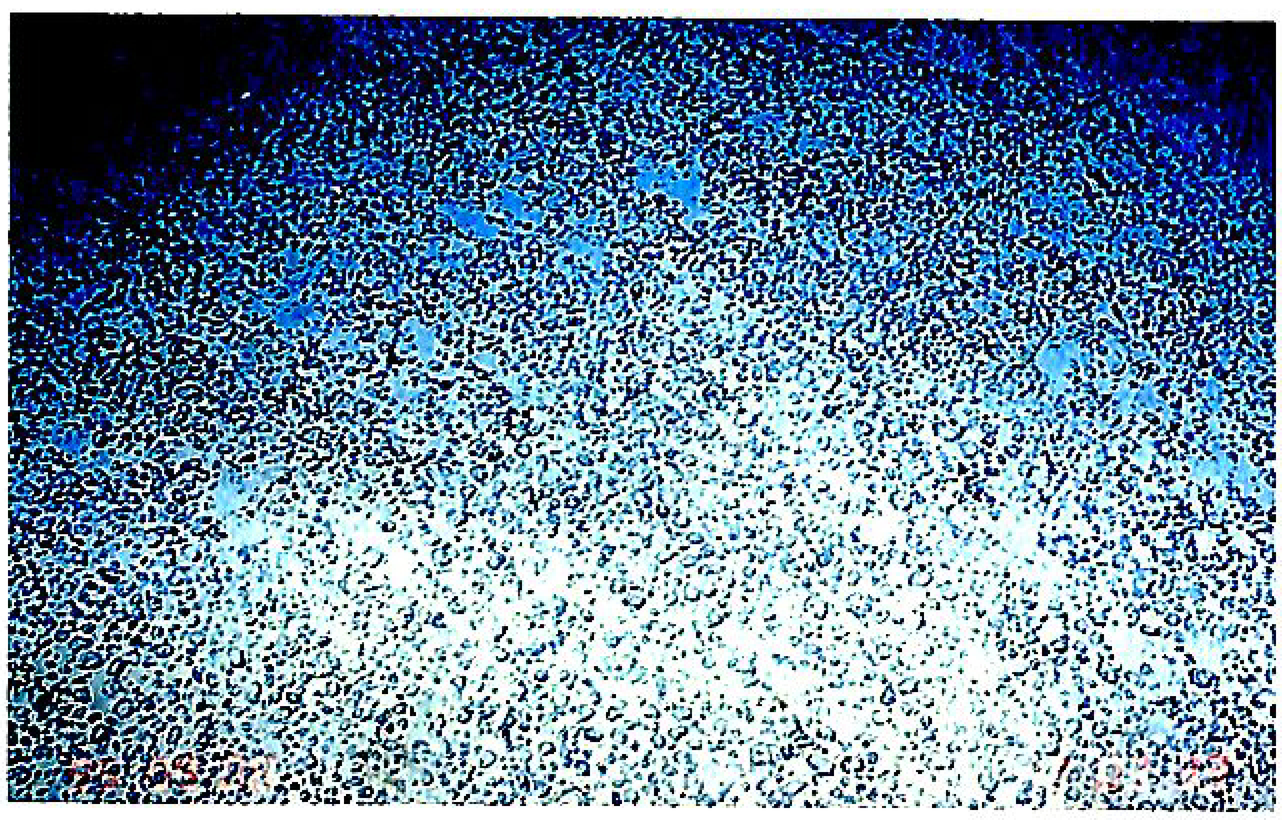

Photo 3 "Shinkai 6500" external photo from Dive 281 showing foraminiferal sands at the summit of S. Chamorro Seamount that are nearly completely covered with small pebbles of manganese.

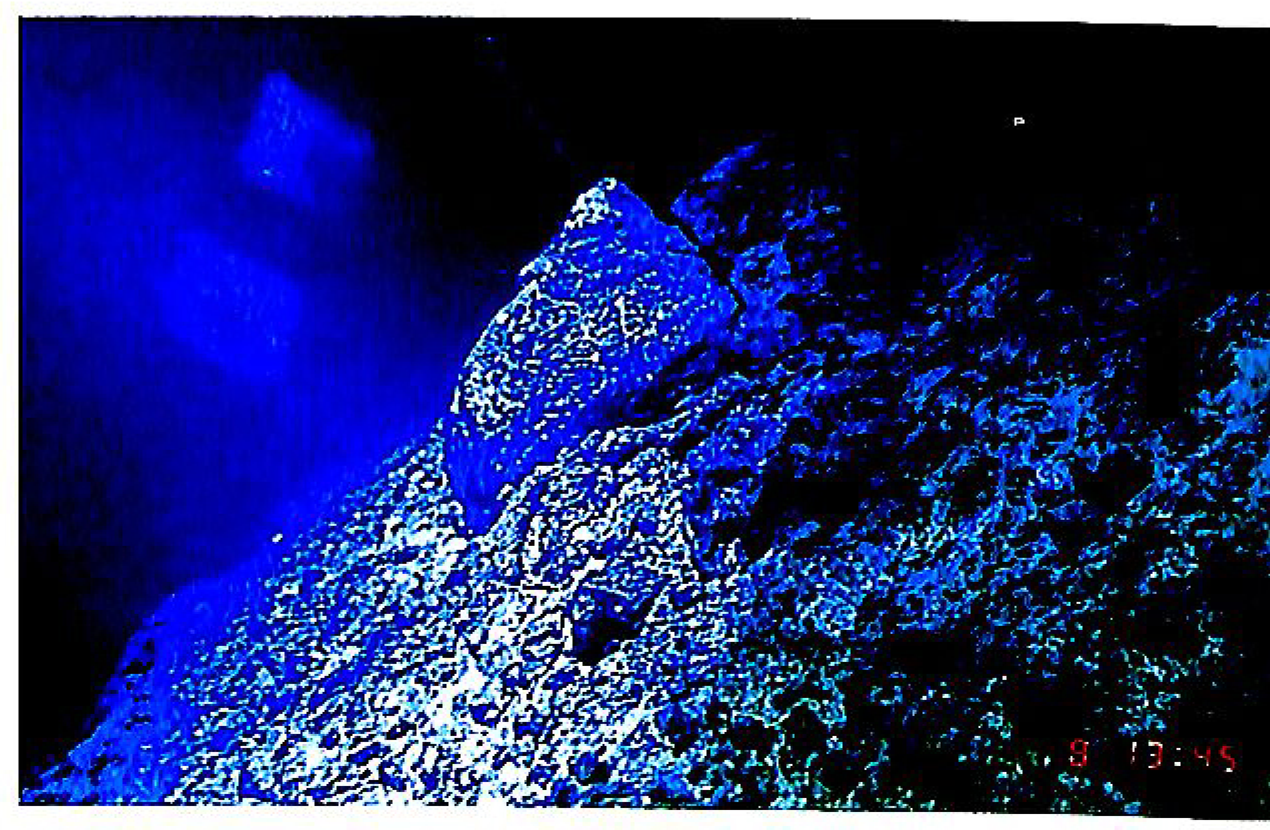

Photo 4 "Shinkai 6500" external photo from Dive 281 showing the steep slope at the base of the summit knoll on S. Chamorro Seamount (approximately 45° slope). The large boulder in the center of the field of view is about a meter in diameter.

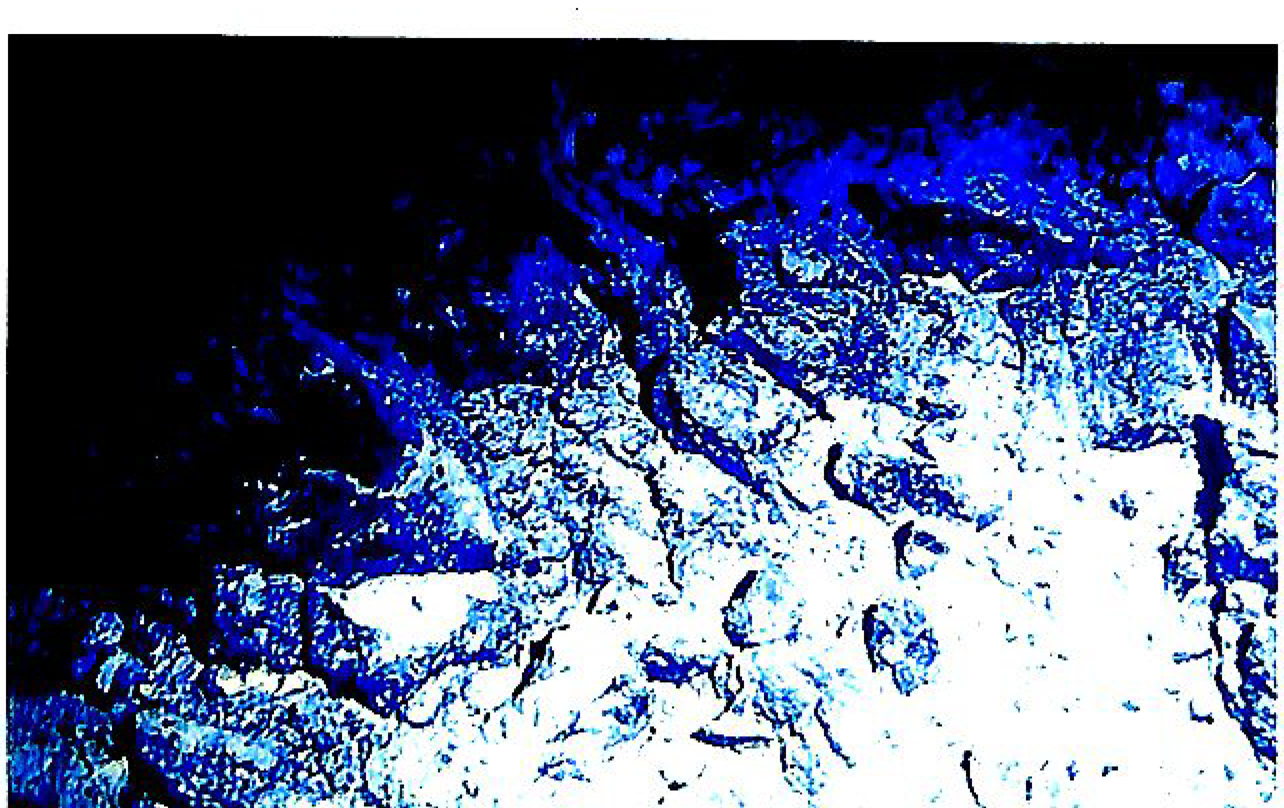

Photo 5 "Shinkai 6500" external photo from Dive 281 showing partially cemented serpentine mud that is covered with a thin, dark coating (manganese oxide?), and is fractured into a series of slabs that have partially collapsed into a fissure in the foreground. The large slab at the center of the left edge of the photo is about 1.5 m in diameter.

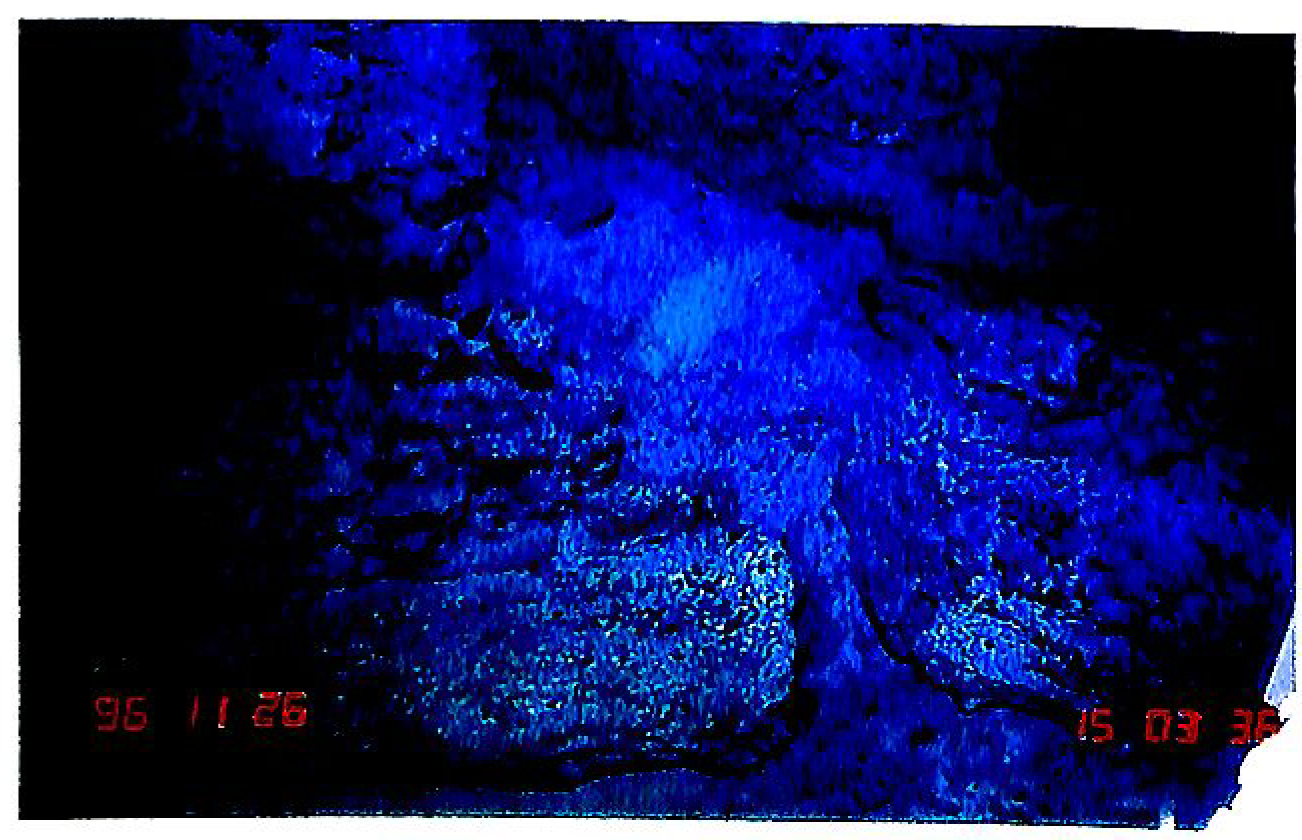

Photo 6 "Shinkai 6500" external photo from Dive 281 showing partially cemented serpentine muds with included rock clasts that have been fractured and disrupted by apparently recent tumescence of the summit knoll. The slab at the bottom left is approximately 2 m long.

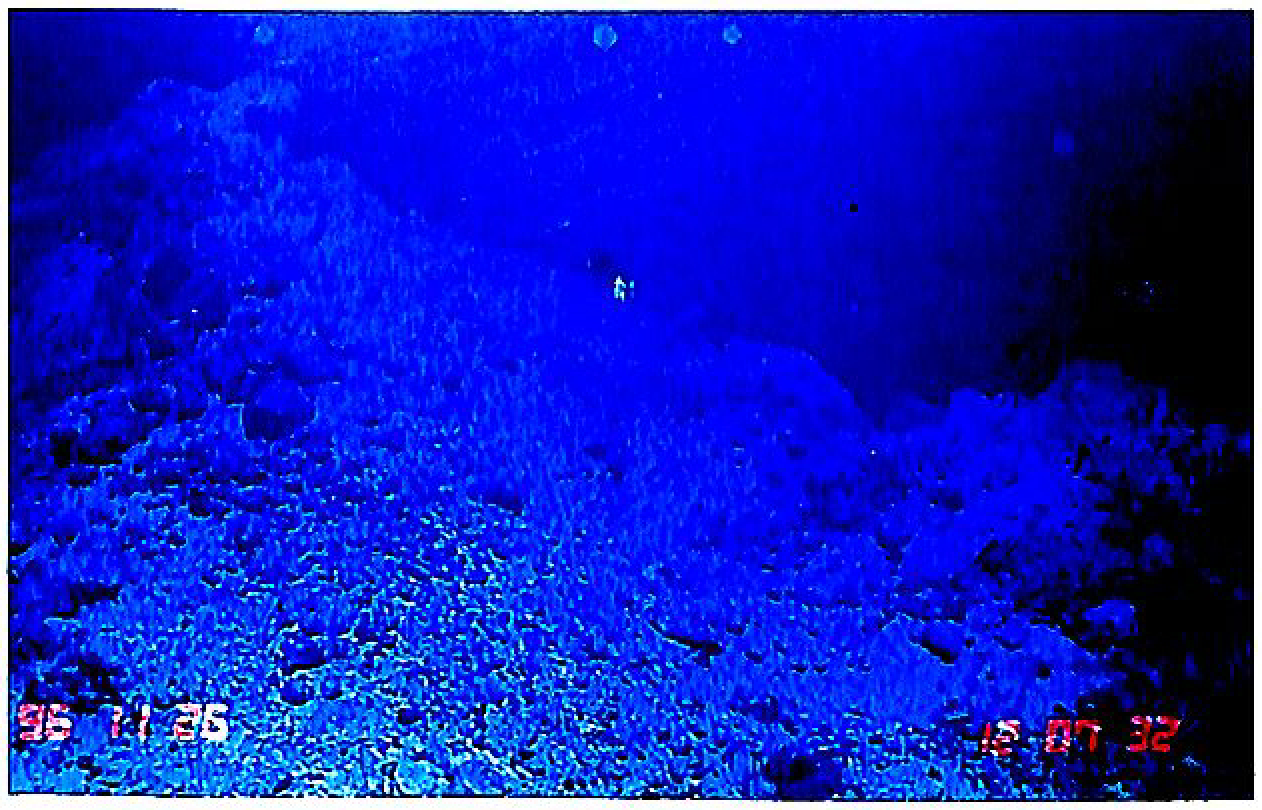

Photo 7 "Shinkai 6500" external photo from Dive 351 showing a region of the summit knoll on S Chamorro Seamount with fractured partially cemented serpentine mud covered with a partial blanket of small manganese nodules.

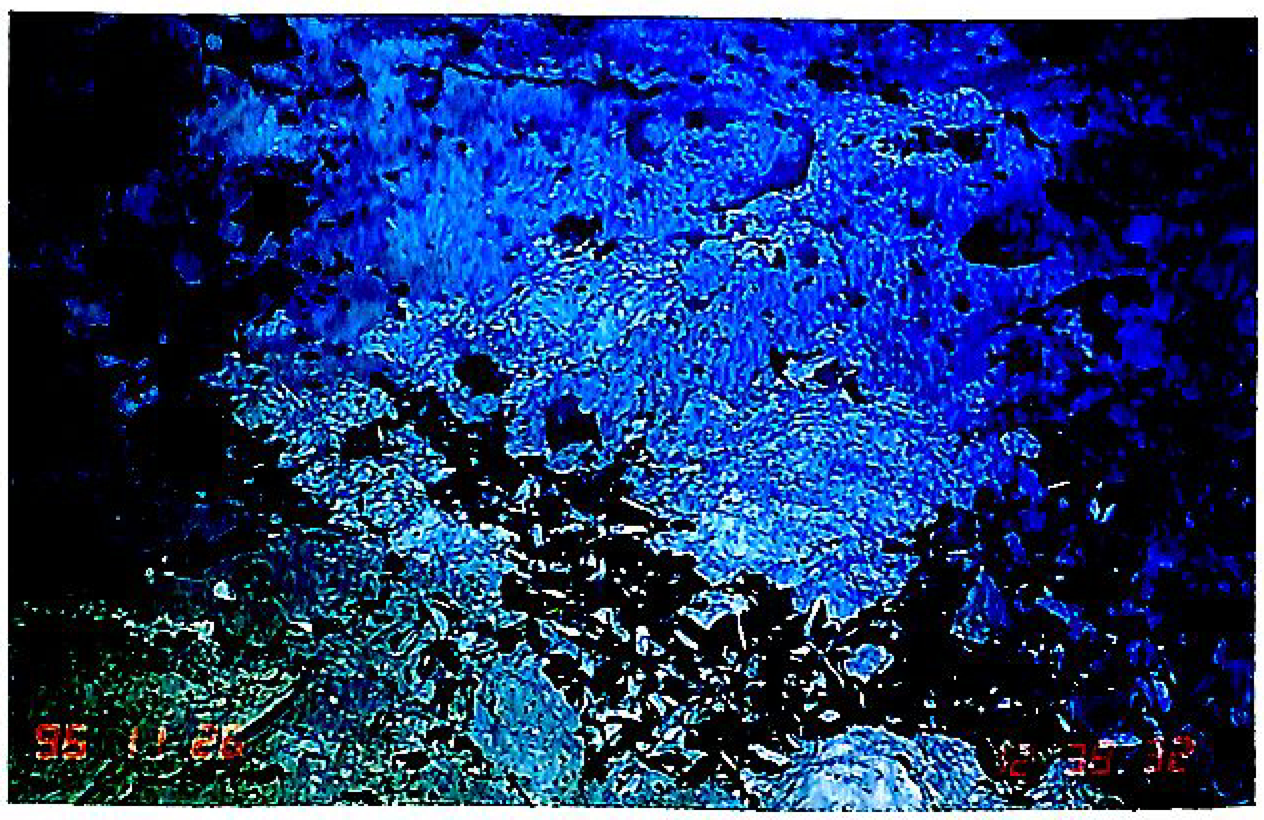

Photo 9 "Shinkai 6500" external photo from Dive 351 showing a region of disrupted slabs of partially cemented serpentine mud. The center of the photograph shows numerous mussels (2 to 20 cm long) clustered in fissures between the slabs. The whitish areas in the lower foreground are patches of carbonate encrustations that armor the edges of the fissures.

Photo 11 "Shinkai 6500" external photo from Dive 351 showing the manipulator of the submersible sampling the chimney structure shown in Figure 11. Note the tubeworms on the chimney and the indentation in the base (lower right portion) of the chimney. The chimney is partially hollow and very porous.

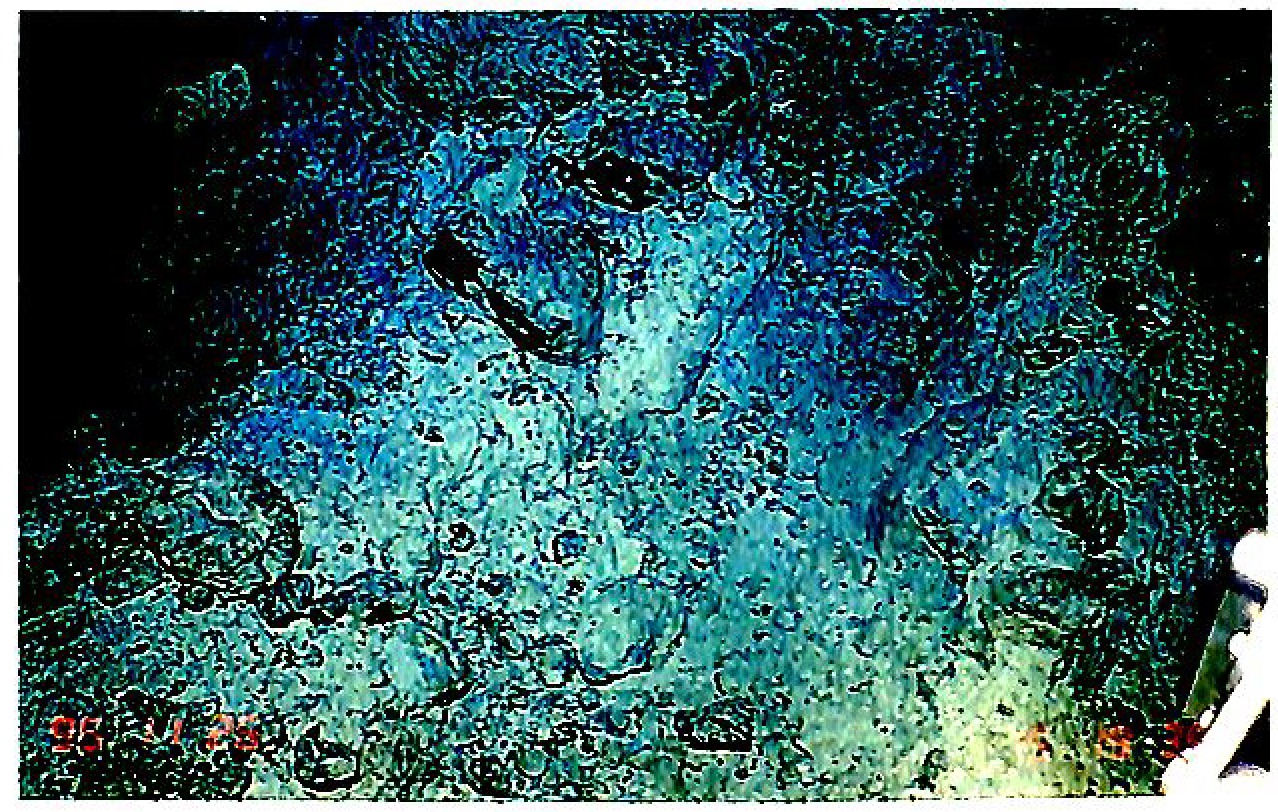

Photo 8 "Shinkai 6500" external photo from Dive 351 showing a region of newly protruded serpentine mud (lower half of photo) including clasts of rocks. Slabs of the previously partially cemented serpentine muds are in the upper right corner of the photo.

Photo 10 "Shinkai 6500" external photo from Dive 351 showing the manipulator of the submersible approaching a small (15 cm high) chimney structure (immediately below and slightly to the left of the claw) of carbonate that has several mussels clinging to it. In the foreground there is a slab of serpentine mud that has a slight overhang (shadowed) under which a clump of mussels of varying sizes (2 to 20 cm) is situated. A brittle star in the right center foreground is attached to a rock that is about 30 cm long.

Photo 12 Close-up of a "Shinkai 6500" external photo from Dive 351 showing the manipulator arm about to sample some of the mussels and gastropods clustered in a crack between a patch of carbonate encrustation (right) and some fractured masses of partially cemented serpentine mud (left). Note also the galatheid crab touching one of the gastropods immediately below the claw.

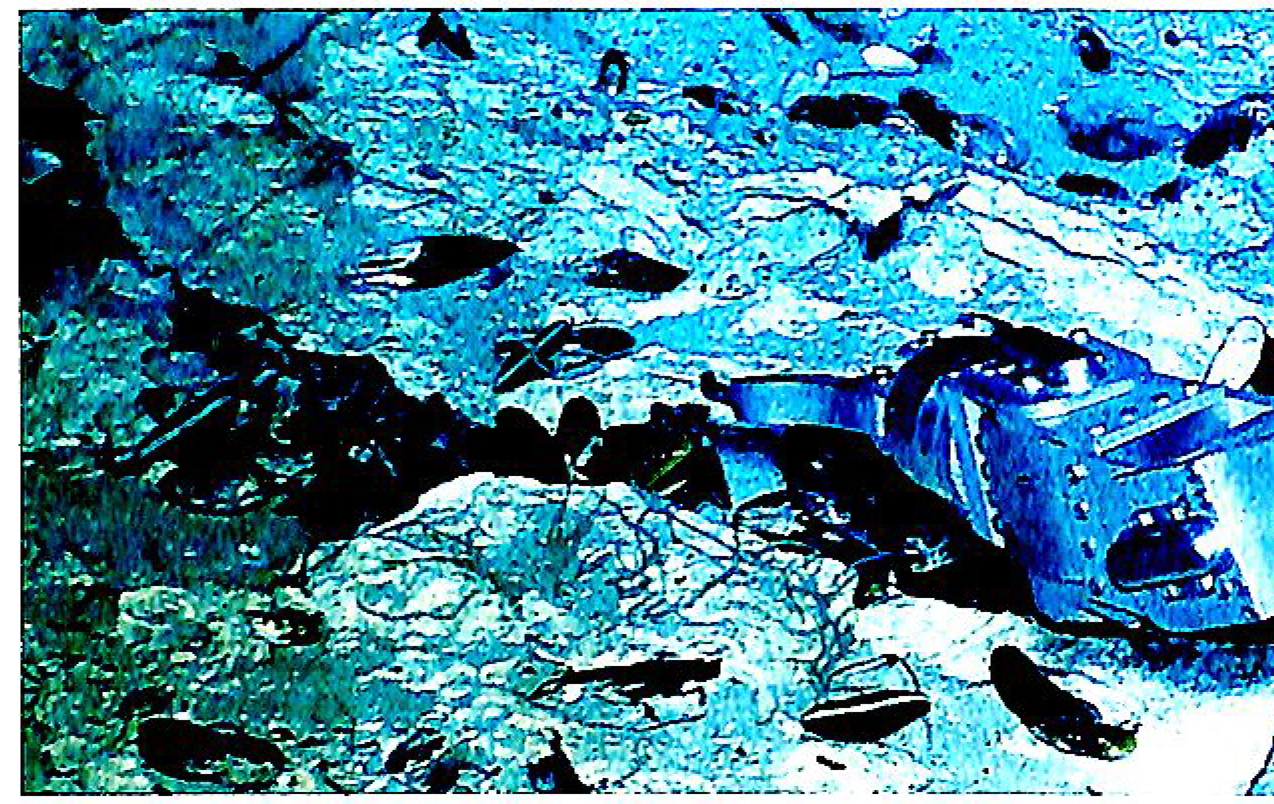

Photo 13 Close-up of a "Shinkai 6500" external photo from Dive 351 showing the manipulator about to sample some mussels clustered in a fissure between several slabs of partially cemented serpentine mud. There is a tangle of tubeworms immediately below the claw (fibrous looking). There is a galatheid crab at the bottom right of the image, among some mussels.

Photo 14 Close-up of a "Shinkai 6500" external photo from Dive 351 showing a patch of carbonate material in the left foreground, a gastropod on a dark rock in the left middle of the photo and a large fish on the right.

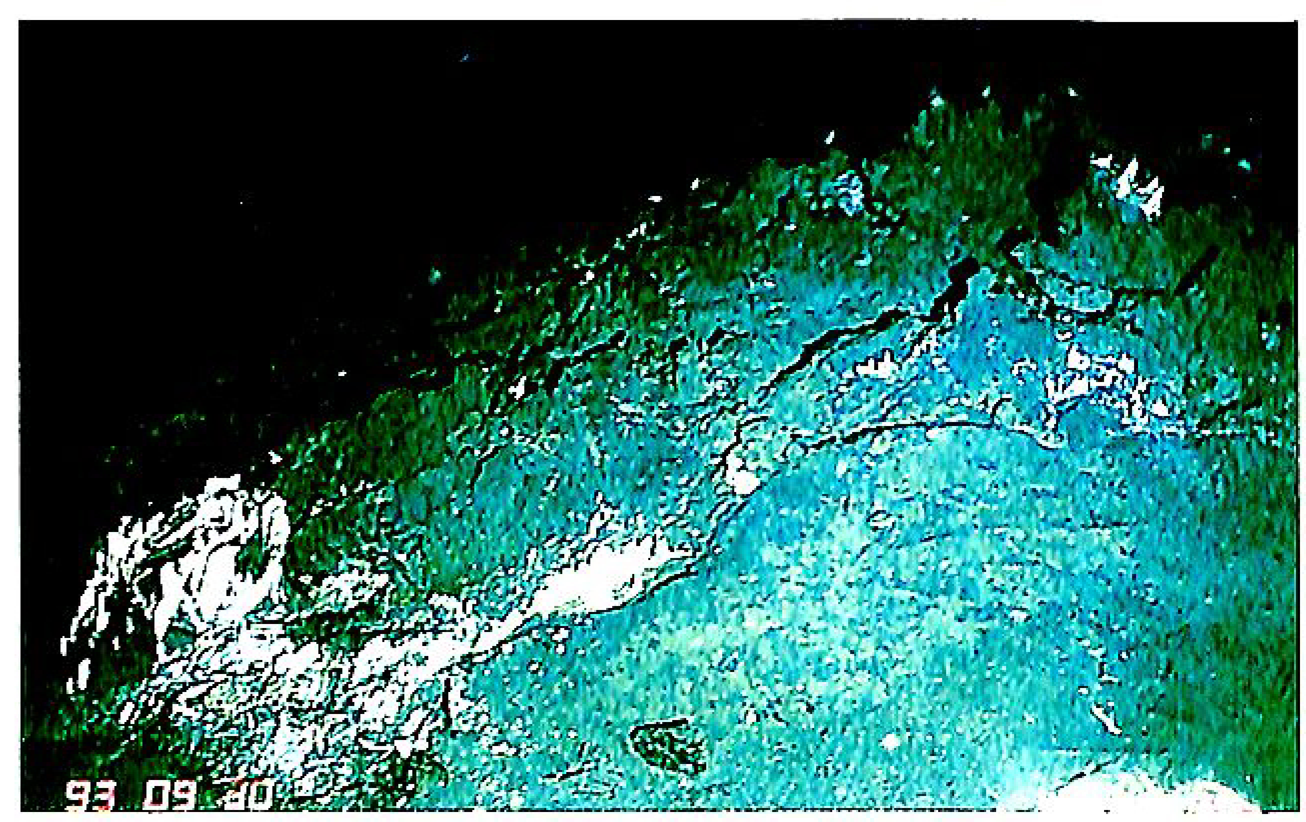

Photo 15 "Shinkai 6500" external photo from Dive 178 showing delicate brucite chimney structures growing in small fissures in a lightly sedimented region of Pacman Seamount (Fryer, 1996a) that is cut by recent tumescence associated with protrusion of serpentine muds and egress of slab-derived fluids (Fryer et al., submitted).