MBARI's 2000 Expedition to the Gorda Ridge

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Introduction

The Monterey Bay Aquarium Research Institute (MBARI) conducted a joint multidisciplinary cruise with scientists funded through the National Undersea Research Program to the Gorda Ridge in August 2000 using the *R/V Western Flyer*. Sixteen dives were completed (Figure 1) in 14 days utilizing MBARI's *ROV Tiburon* to explore and sample at a number of hydrothermal and geologic targets along and near the Gorda Ridge. Four dives were at the active *Seacliff* hydrothermal site (Rona et al., 1990) and three were at the northern Escanaba hydrothermal site (NESCA, Morton et al., 1994). The NESCA site was drilled by ODP Leg 169 in 1996 (Fouquet, Zierenberg, Miller, et al., 1998). Neither of these sites had been visited by a submersible vehicle since 1994 and we planned to document changes at these sites. Other hydrothermal objectives included locating and determining if some of the ODP sites drilled in the NESCA area had become active hydrothermal recharge or discharge sites (as observed at Middle Valley, Zierenberg et al., 1998), mapping the deposits from the southern Escanaba site (SESCA, Morton et al., 1994), exploring another sill complex south of SESCA to determine if it had an active or fossil hydrothermal system, and collection of fauna and bacterial mats from active hydrothermal sites.

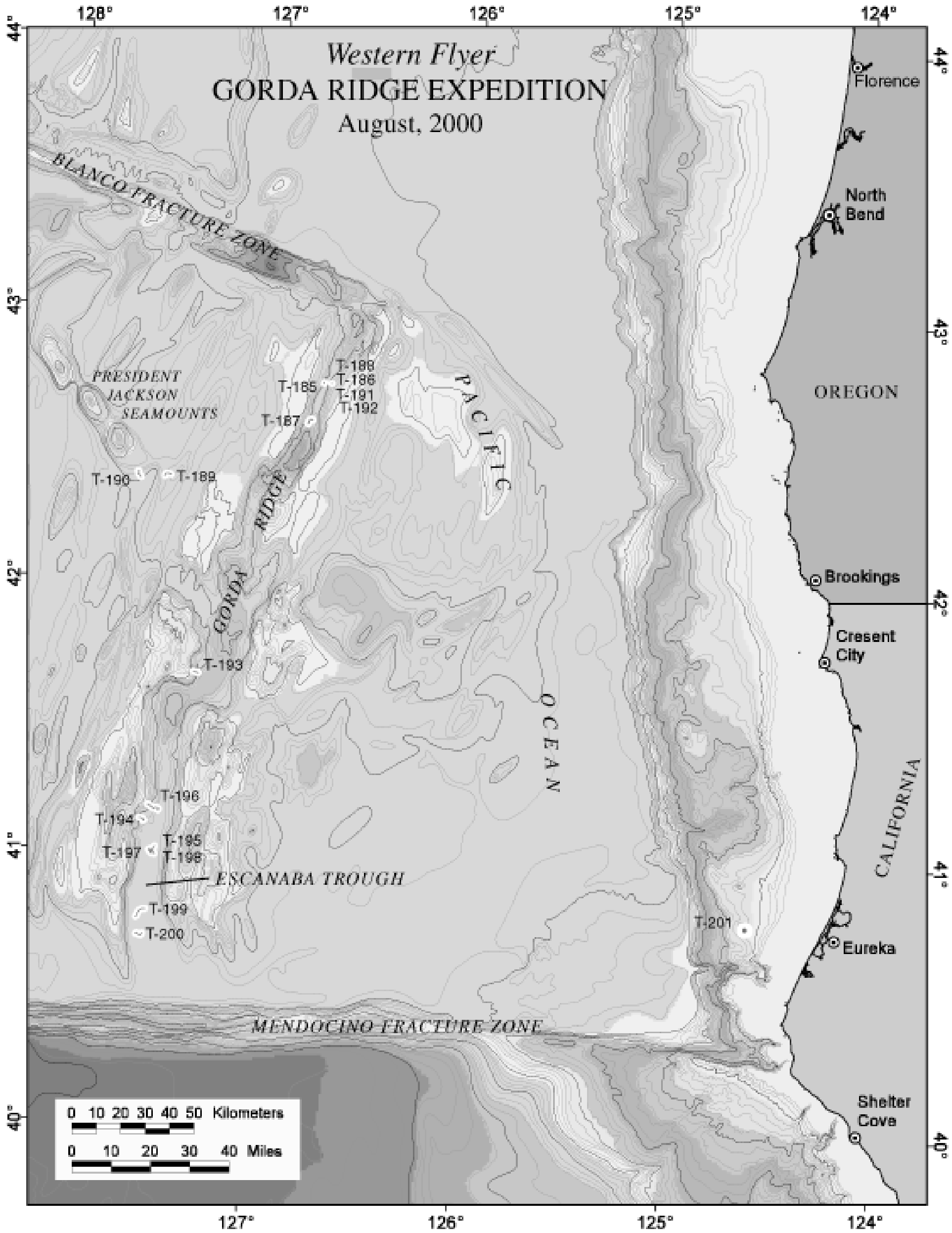

Figure 1. Sixteen dives, T185 through T200, completed by MBARI's ROV Tiburon along and near the Gorda Ridge.

Geologic and petrologic objectives included a detailed sampling of axial lavas between the shallowest part of the northern ridge axis at Narrowgate and the inferred southern end of the 1996 eruption site at 42.61°N (Chadwick et al., 1998), sampling of a scattered group of small volcanic cones southeast of the President Jackson Seamounts (Clague et al., 2000; Davis and Clague, 2000) and exposed along seafloor faults in that region, collection of samples from the large sill complexes and associated lava flows at NESCA and SESCA to further evaluate the assimilation of sediment by these lavas (Davis et al.,1994, 1998), and mapping and sample collection from a group of volcanic cones in the axis of the ridge at the northernmost end of the Escanaba Trough. Two dives were also spent exploring the western walls of the axial valley near the largest transform offset in the ridge and near the northern end of the Escanaba Trough.

During these 16 dives, the *ROV Tiburon* collected 213 samples of lava, hydrothermal deposits (some very delicate) and lithified sediments; 61 push cores of sediments, fine-grained unconsolidated hydrothermal deposits, and fine-grained volcanic debris; 5 scoops of coarser unconsolidated volcanic debris; 46 animals; and 23 water samples (11 gas-tight samplers and 12 major samplers). In addition, we measured temperatures of hydrothermal fluids at the *Seacliff* and NESCA sites and tested and collected 5 samples with a new suction sampler designed to sample volcanic glass from young flows. Observations and digital video recordings were made along slightly more than 52 km of transits during the dives. The dives all took place between 2590 m and 3375 m depth. We also collected 8 gravity cores and 30 wax-tipped rock cores during night operations on the cruise.

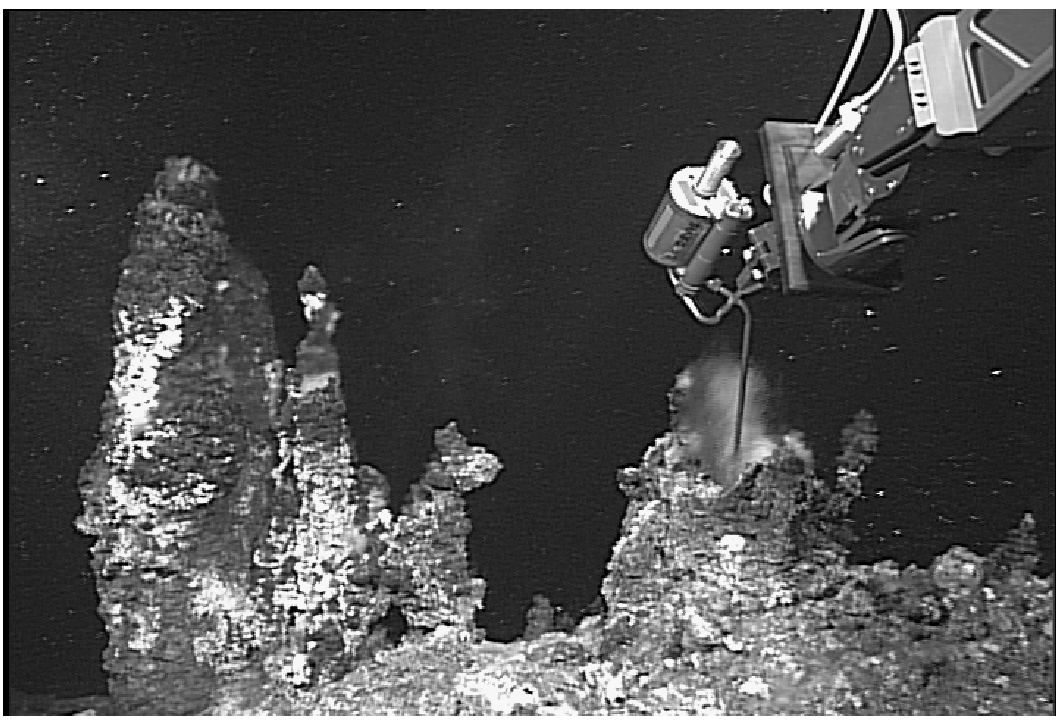

Figure 2. One of several vigorous chimneys venting clear fluids.

***Seacliff* Hydrothermal Site**

The *Seacliff* hydrothermal field was discovered during dives using the *Seacliff* submersible in 1988 (Rona et al., 1990) following detailed sampling and mapping using towed camera systems (Rona and Clague, 1989, Clague and Rona, 1990) that in turn had focussed on a region where a chronic hydrothermal plume was discovered (Baker et al., 1987). The hydrothermal vent field is located about 300 m above and 2.6 km east of the neovolcanic zone of the northern Gorda Ridge. The *Seacliff* measured the temperature of the vent fluid at 247°C, but was unable to collect water samples. A sample of the hydrothermal chimney consisted mainly of barite and amorphous silica, with minor sulfide phases with an outer zone of mainly anhydrite and stevensite (a trioctahedral smectite) and sphalerite (Zierenberg et al., 1995).

We were able to map the entire *Seacliff* hydrothermal vent field during the four dives (T186, T188, T191, and T192 on Figure 1) to the area. We observed many more active vents than were seen in 1988, perhaps because of temporal changes in the field, or because of the limited bottom time available in the original cruise. We measured temperatures at several vigorous chimneys emitting clear fluids of up to 304°C and collected vent water samples using both major an gas-tight bottles (Figure 2). The fluids have lower-than-seawater salinities and low metal and sulfide contents. We also collected lava and sediment samples, hydrothermal deposits, and vent fauna and bacterial mats. The active chimneys consist mainly of anhydrite and pale green smectite with minor sulfide phases including pyrrhotite, wurtzite and isocubanite. The chimneys are very fragile and were difficult to sample. They are surrounded by debris derived from collapse of former chimneys and dissolution of the anhydrite. These light-colored sediments appear to consist mainly of amorphous silica. Within several m of the vigorously venting chimneys are extensive zones with shimmering water leaking through barite crusts and low mounds covered by tubeworm colonies.

The biologic community includes a great variety of vent-specific and other fauna. There were no animals present in the talus as we approached the *Seacliff* site from the south. We moved from talus into debris from the hydrothermal mounds where we saw dead tubeworms clumps covered in iron oxyhydroxides. A relatively barren zone in which very few animals were found surrounds the most vigorous vents, the exception being limpets (*Lepetodrilus* sp.), palm worms (mostly *Paralvinella palmiformis*), and bright blue mat-like foliculinid ciliates, which covered much of the hydrothermal area. Temperatures within the ciliate mats measured 3-6°C and the polychaete *Amphisamytha galapagensis* that was found in close proximity to the foliculinid mats had bright purple heads, indicative of consumption of the ciliates. Approximately 10-20 m south of the central area of venting, we found large mounds of *Ridgeia piscesae* tubeworms, limpets, pycnogonids, and more blue ciliate mat, with associated nematodes. Most animals were associated with diffuse flow areas, although limpets and paralvinellids were again in direct contact with shimmering water. Large tubeworm clumps, with red-armed anemones (Acitnostolidae?), were very extensive, up to 80 m from the area of most venting. A list of species identified in our collections from the crusts and low

Table 1. Gorda / Escanaba taxa

Phylum Class	Family	Genus	Species	Site
Ciliophora				
Spirotrichea	Folliculinidae	*Folliculina*	*?*	S
Cnidaria				
Anthozoa	Actinostolidae			S, NE
Annelida				
Polychaeta	Sibloginidae??	*Ridgeia*	*piscesae*	S, NE
Polychaeta	Hesionidae	*Hesiospina**	*vestimentifera*	S
Polychaeta	Polynoidae	*Lepidonotopodium*	*piscesae*	S, NE
Polychaeta	Polynoidae	*Levensteiniella*	*kincaidi*	S, NE
Polychaeta	Polynoidae	*Opisthotrochopodus*	*tunnicliffeae*	S
Polychaeta	Alvinellidae	*Paralvinella*	*palmiformis*	S, NE
Polychaeta	Alvinellidae	*Paralvinella*	*sulfincola*	S, NE
Polychaeta	Ampharetidae	*Amphisamytha*	*galapagensis*	S, NE
Mollusca				
Solenogaster	Simrothiellidae	*Helicoradomenia**	*juani*	S
Gastropoda	Peltospiridae	*Depressigyra*	*globulus*	S
Gastropoda	Peltospiridae	*Melanodrymia*	*brightae*	SE
Gastropoda	Neolepetopsidae	*Neolepetopsis*	*gordensis*	S, NE
Gastropoda	Pseudococculinidae	*Amphiplica*	*gordensis*	S, NE
Gastropoda	Pyropeltidae	*Pyropelta**	*sp.*	NE, SE
Gastropoda	Clypeosectidae	*Clypeosectus*	*curvus*	S
Gastropoda	Lepetodrilidae	*Lepetodrilus*	*fucensis*	S, NE
Gastropoda	Provannidae	*Provanna*	*laevis*	S
Gastropoda	Provannidae	*Provanna*	*variabilis*	S, NE
Bivalvia	Solemyidae	*Solemya^*	*sp.*	NE
Bivalvia	Vesicomyidae	*Calyptogena^*	*sp.*	NE
Arthropoda				
Pycnogonida	Ammotheidae	*Ammothea*	*verenae*	S, NE
Crustacea	Philomedidae	*Euphilomedes*	*climax*	S

S=*Sea Cliff* Site (GR14), NE = NESCA, SE = SESCA * tentative identification, ^ only shells collected, observed. Additional small polychaetes and cnidarians have not been identified.

mounds around the most active vents is presented in Table 1.

Northern Gorda Ridge Axis

We conducted two dives (T185 and T187 on Figure 1) and collected 18 wax-tipped rock cores along the axis of the ridge near the Narrowgate region, just south of the region studied by Davis and Clague (1990). The first (northern most) dive was aborted after only a short time on the bottom due to technical problems with the vehicle and the second searched for the proposed southern lava flow from the 1996 eruption (Chadwick et al., 1998). This southern dive also explored and sampled one of the larger of the flat-topped volcanic cones in the axis of the Gorda Ridge. No young glassy flows or active or inactive hydrothermal fields were observed. The proposed southern lava flow for the 1996 eruption at 42.61°N does not correspond to the small depth anomalies identified by Chadwick et al. (1998) and may not exist. The samples are currently being studied as part of an MS thesis evaluating the variation in lava composition at the Narrowgate region of the North Gorda segment.

Figure 3. The planar fault surfaces of the greenstone blocks.

President Jackson Seamounts

The eight seamounts that comprise the President Jackson Seamounts form a linear chain that formed near the Jackson segment of the Gorda Ridge; they are now located on crust between 2.18 and 3.97 Ma old (Clague et al., 2000). The seamounts range in volume from 24 to 68 km^3. To the southeast of the southeastern seamount, the seafloor is dotted with small volcanic cones that may represent an incipient ninth seamount, but one that never developed into a single large edifice. We did two dives in this region (dives T189 and T190 on Figure 1) and collected lavas erupted from at least 9 of these scattered vents. All the recovered samples are N-MORB, most quite primitive (MgO>8%) like the majority of lavas from the President Jackson Seamounts (Davis and Clague, 2000). In addition, we collected a suite of samples from a 200-m tall ridge-parallel fault to sample crustal rocks erupted along the ridge axis contemporaneous with the larger seamounts. These too are all N-MORB. Samples from the small volcanic cones include hyaloclastite and a light-colored ash deposit draping the top of the fault scarp, apparently the ash is derived from one of the nearby cones or larger volcanoes since it contains small glass fragments of MORB composition.

West Wall of the Axial Valley

We also did two dives on the western scarp of the axial valley, one near the southern end of the Central segment and the other near the northern end of the Escanaba segment (dives T193 and T194 on Figure 1). The northern dive site (T193) was of interest because prior to several hundred thousand years ago, the Gorda Ridge was morphologically more like other spreading centers in the Pacific and lacked the deep axial valley. The recovered samples were selected to sample lavas that predate the formation of the present-day deep axial valley, and will be compared to those erupted during the current period of magma starvation that has formed the deep valley. The dive progressed up a stair-step slope of alternating blocks of greenstone and glassy pillow lavas. The greenstone has planar fault surfaces (Figure 3) and is mainly volcanic breccia with abundant secondary quartz, chlorite, and albite. Quartz veins up to 4 mm thick occur within the breccia samples. Sediment scoops collected volcanic glass and also recovered small fragments of vein quartz, often including small crystals. Some of the analyzed glasses have up to 0.53 wt.% K_2O and fall outside the range of previously described samples from Gorda Ridge (Davis and Clague, 1987).

The second dive on the valley walls (dive T194 on Figure 1) explored an area of bright acoustic backscatter on side scan sonar map of the valley floor in the northern Escanaba Trough that was though to represent a recent volcanic eruption. The area was entirely covered in sediment and no lava was seen, nor were any fissures. The high backscatter may be caused by a young lava flow, but it is no longer exposed on the surface and could not be sampled. The dive continued up the eastern 660-m high wall of the Escanaba Trough where we encountered thick, well-indurated sedimentary rocks. Atwater and Mudie (1968, 1973) had used geophysical data to hypothesize that the valley wall in this region consisted of faulted sedimentary rocks. The wall, as they proposed, consists of a stairstep of discrete fault blocks. The more massive of these units are sand to siltstone with vertical tabular joints. This is apparently the same sediment sequence that fills the Escanaba Trough and was emplaced during the late Pleistocene Missoula floods (Zuffa et al., 2000). The 660 m of uplift of the axial valley wall, although accomplished with movement on a series of ridge-parallel faults, has apparently mostly taken place within the past 10 ka. Lava flows crop out in the uppermost wall, indicating that the outermost and now uppermost fault block predates the sediment filling of the valley.

Volcanic Cones at north end of Escanaba Trough

One dive explored a cluster of conical volcanic vent structures near the northern end of Escanaba Trough (dive T196 on Figure 1 and the cover). These cones appear to be older to the west and each has a distinct composition. The westernmost cone has a large summit crater that is breached to the east. Lavas from all the cones are N-MORB, including a few moderately vesicular lavas (25% vesicles) from the breached cone.

NESCA

We did three dives at NESCA including two to explore the hydrothermal vents and ODP drill sites (dives T195 and T197 on Figure 1) and one to explore the extensive lava flow that covers about 12 km^2 in the region (dive T198). A few samples from this flow were recovered previously (Davis et al., 1994,1998), but no systematic collection of samples from the different parts of the flow had been attempted, nor were there but minimal visual observations of the flow. We not only mapped and collected these flows during the three dives, but also collected 9 samples of glass from the distal edges of the flow field using a wax-tipped rock corer. The compositions of all the 43 samples analyzed to date are similar despite some parts of the flow predating uplift of the sediment hills and other parts post-dating the deformation. One area that we had inferred to be the vent complex for the flows based on detailed bathymetric and sidescan coverage, turned out to be lava flows disrupted and broken during uplift above a deep sill.

The main high-temperature vent had essentially an identical 215°C temperature it had when discovered in

Figure 4. ODP hole 1038A drilled to a depth of 115 m through the sulfide structure which is host to the main high-temperature vent.

1988 (217°C, Campbell et al., 1994) despite the fact that ODP hole 1038A (Figure 4), located approximately 4 m away, was drilled to a depth of 115 m through the sulfide structure on which the venting occurs. The drill hole itself was diffusely venting hydrothermal fluid and was colonized by palm worms and other hydrothermal fauna. Although the temperature of venting at this mound had remained stable, the hydrothermal field had all but shut down, and the numerous mounds venting low temperature fluids and supporting extensive colonies of tube worms in 1988 were inactive with essentially no signs indicating the former abundance of vent fauna.

We searched for and found five other ODP drill holes, including Hole 1038I which was drilled to a depth of 404 m stopping in basaltic basement, but found no evidence for fluid flow in any of these holes. The drill string that was lost at the conclusion of Leg 169 was observed to be folded on itself once and laid out across the seafloor about 0.5 km from the location where it was lost.

Hydrothermally derived asphaltic petroleum was recovered in several of the push cores, impregnating several of the sulfide samples, and as a rounded mound of tar (Figure 5). The material in the push cores and sulfide samples, which commonly had a strong diesel smell, appears similar to materials described previously (Kvenvolden et al., 1987, 1994). The tar mound appears to be a hollow chimney structure formed when hot tar erupted onto the sea floor and is unlike any previously collected sample.

After exploring numerous massive sulfide mounds, we found one still-active site (6X), out of the many that were active in 1988 and 1994. The temperature of 6X vent was 207-212°C. There was only one moderately sized clump of *Ridgeia piscesae* present in the area and the temperature surrounding these animals was 11-45°C. Paralvinellids (*Paralvinella sulfincola*) were very abundant, as well as various bacterial mats mat types (which we collected via pushcore). Vesicomyid shells were spotted at the top of Central Hill but the encounter with the lost ODP drill string prevented further exploration of potential clam/bacterial mat areas on the east side of the Central Hill. Likewise, solemya shells were seen on sulfide mounds in the area, although we never saw any living individuals.

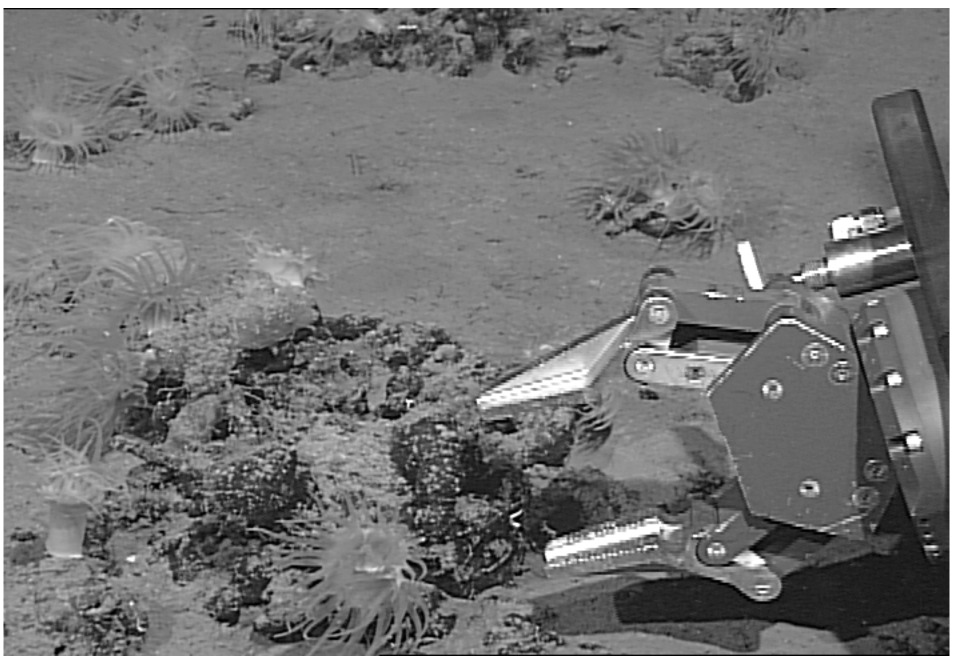

Figure 5: A mound of hydrothermally derived tar.

SESCA

A single dive at SESCA (T199 on Figure 1) discovered abundant large hydrothermal deposits, mainly on top of the large flat-lying sill complex. No active hydrothermal vents were found and all the deposits have a similar appearance in terms of alteration and degradation. Sixteen previous camera tows, 9 dredge hauls, and 5 submersible dives (Morton et al., 1994) had observed far less hydrothermal deposits and lava flows than we encountered on our one dive. Highly weathered sulfides were observed with dead *Ridgeia* tubes encrusted with iron oxides and orange-brown iron oxidizing filamentous microbial mats. Closer microscopic inspection of the mat revealed heavily encrusted interwoven twisted filaments resembling *Gallionella* spp. Filter feeding animals were very abundant on old sulfide mounds. In general the fauna on the old lava flows is typical for the deep-sea: sponges, gorgonians, sea stars, and anemones. However there were some vent associated limpets (*Pyropelta* sp.) in the area.

The margin of a shallowly emplaced sill is exposed where slumping of sediment has exposed it. Fifteen lava samples from the exposed sill and from the surficial flows are similar in composition to the 2 samples described previously (Davis et al., 1994,1998), but vary in MgO from 7.7 to 8.2%. These flows are cut by numerous fissures, some several m wide, indicating that the volcanic activity here is quite old. This observation is consistent with the apparent old age of the hydrothermal deposits and suggests that their formation was directly tied to a single period of sill emplacement and eruption. There are two types of sills in the area-large shallow sills that have the outline of lava flows, but are roughly 30 m thick, and deep sills that uplift small steep-sided hills of sediment (Denlinger and Holmes, 1994). Much of the hydrothermal activity was associated with the large shallow sills which suggests that the hydrothermal convective cells penetrated only to shallow depths (tens of meters) in the sediment above the sill.

South of SESCA

A single dive was done on another sill complex south of SESCA (dive T200 on Figure 1). Examination of side-scan data suggested that lava flows were absent from this area and our dive found no exposed lava or glass fragments in the sediment to suggest that lava erupted nearby. As at SESCA, however, hydrothermal deposits, all inactive, are abundant on the steep sides and top of the shallow sill complex. These deposits have similar degrees of alteration and degradation, consistent with the idea that the deposits form during a relatively short time interval after emplacement of the sills. The observations and samples suggest that this complex is older than that at SESCA. Both pyrrhotite-rich massive sulfide and barite-rich samples were recovered. Several samples have abundant sphalerite and galena, similar to previously described samples from Escanaba Trough (Koski et al., 1994). Many of the push cores contain asphaltic petroleum and have a strong diesel smell, as does one small sulfide chimney recovered from the sediment. A second small mound of tar, similar to that from NESCA, was recovered here.

Summary

The many observations and samples collected during the cruise are still being processed. The *R/V Western Flyer* and *ROV Tiburon* were able complete 16 dives in rather poor weather conditions on the Gorda Ridge. During the cruise we documented the conditions at two active hydrothermal vent fields on Gorda Ridge and sampled high-temperature vent fluids, vent fauna (including a colorful blue ciliate), and delicate sulfate/clay chimneys. We also sampled hydrothermal deposits at two additional regions where activity has ceased. We searched for the proposed southern lava flow for the 1996 eruption and conclude that no eruption took place at this location. We sampled the lavas, hydrothermally altered lavas, and sediments that form the steep axial valley walls on Gorda Ridge and will be able to examine any changes in lava chemistry through time. We collected comprehensive suites of lava samples from several flows to evaluate how and where sediment assimilation by these lavas occurs. Finally, we collected a suite of lavas from the Narrowgate region of the northern Gorda Ridge to evaluate the small-scale variability in magmatic processes at this moderate spreading-rate ridge.

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