

Recent eruptions on the CoAxial segment of the Juan de Fuca Ridge: Implications for mid-ocean ridge accretion processes

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Abstract. The 1993 seismic swarm and volcanic eruption on the CoAxial segment of the Juan de Fuca Ridge was the first verified mid-ocean ridge accretion event monitored by the National Oceanic and Atmospheric Administration/U.S. Navy Sound Surveillance System (SOSUS). Ambiguity in the location of the initial seismicity resulted in an uncertainty as to whether the dike intruded from the summit and north rift zone of the adjacent Axial Volcano or whether it arose locally within the CoAxial segment. However, analyses of multibeam, side-scan sonar, towed camera, submersible, and geochemical data show that the CoAxial segment is morphologically, structurally, and geochemically distinct from the north rift zone of Axial Volcano. There is no geologic or geochemical evidence that dike injections from Axial Volcano have extended north of 46°18'N in the past, whereas the 1993 eruption site is at 46°31'N. Furthermore, all seafloor manifestations of the 1993 dike injection lie along the central neovolcanic zone of the CoAxial segment. Analyses of repeat SeaBeam surveys combined with seafloor observations show that two other eruptions of approximately the same volume as the 1993 eruption occurred along the CoAxial segment in the 1981–1991 interval. These three diking events may have relieved decades of accumulated stress over ~35 km or more of this segment. The spatial pattern and hydrothermal history of the 1993 event is consistent with a dike with a significant lateral component of injection.

1. Introduction

The realization in the 1960s that the world-encircling mid-ocean ridge (MOR) generates most of the Earth's volcanic activity has led to an increasing focus on this system with progressively more powerful mapping systems [Detrick, 1986]. Although the scale of the feature (~60,000 km) and its relative remoteness have been impediments to a comprehensive study, the combination of digital swath mapping bathymetric and side-scan sonar systems, detailed MOR basalt (MORB) geochemical analyses, common depth point seismic profiling, and the use of deep-towed cameras and submersibles has re-

sulted in significant progress during the last 2 decades in defining the major volcanic and tectonic “units” of the system [Detrick *et al.*, 1987; Lonsdale, 1977; Macdonald and Fox, 1983; Sempere *et al.*, 1993] and in understanding some of the fundamental accretionary processes which occur at the ridge crest [Ballard *et al.*, 1979; Kappel and Ryan, 1986; Macdonald and Fox, 1983; Tucholke and Lin, 1994]. Although these studies have provided good definition of long-term (~10⁴–10⁶ years) patterns of crustal accretion and the tectonic framework of the oceanic crust, a detailed understanding of the temporal and spatial dynamics of MOR magmatism has been lacking. Unlike terrestrial volcanic areas, many of which are closely monitored with local seismic arrays capable of detecting and locating volcanogenic seismic events ($M < 4$), most of the MOR is monitored solely by the worldwide seismic net, which is limited to a detection threshold of $M \geq 4$ [Fox, 1993/1994].

The first significant data about processes associated with discrete accretion events along the fast and intermediate spreading rate portions of the MOR became available from studies of sites on the Juan de Fuca Ridge (JdFR) and northern East Pacific Rise through the serendipitous discovery of seafloor eruptions [Chadwick *et al.*, 1991; Embley *et al.*, 1991; Haymon *et al.*, 1993]. Detection of volcanic events on the Juan de Fuca and

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Gorda Ridges became possible in 1991 when the U.S. Navy allowed the National Oceanic and Atmospheric Administration (NOAA) access to the Sound Surveillance System (SOSUS) submarine hydrophone arrays in the northeast Pacific. The high efficiency of sound propagation in seawater in the Sound Fixing and Ranging (SOFAR) channel of the upper ocean lowers the detection threshold by about 2 orders of magnitude and increases the location precision by about 1 order of magnitude, making possible remote detection of, and subsequent response to, volcanic events in this area [Fox, 1993/1994]. As of late 1999, three eruptions on northeast Pacific spreading centers have been detected with this method and verified in the field [Dziak and Fox, 1999; Dziak et al., 1995; Fox and Dziak, 1998]. The first one was at the CoAxial segment in 1993.

In June 1993, within a week after the real-time acoustic monitoring system became operational, an unusual seismic swarm began on the northern part of JdFR just north of Axial Volcano (Figure 1) [Fox et al., 1995]. The swarm initially migrated north along the ridge axis for at least 25 km [Dziak et al., 1995] to the northern (deeper) end of the segment, where it subsequently became concentrated at approximately the center of the axial valley at 46°31'N [Embley et al., 1995] (Figure 1). The only known eruption associated with the 1993 event occurs within this cluster of seismicity [Embley et al., 1995] (Figure 1). Several rapid response cruises took place between July and October 1993 and included water-column plume surveys from the research vessels *Tully*, *Discoverer*, and *Atlantis II*, dives with the Remotely Operated Platform for Ocean Science (ROPOS) and manned submersible *Alvin*, and near-bottom surveys with the Scripps Deep-Tow and a U.S. Geological Survey (USGS) towed camera system. The details of the 1993 seismic swarm and the initial documentation of the water-column and seafloor manifestation of the diking/eruption episode have previously been described in a series of papers [e.g., Fox, 1995].

The initial data sets generated several intriguing questions that have major implications not only for this particular event but also for the nature of MOR crustal accretion. An important first-order question was: Where did the dike come from? The first tertiary water-borne seismic wave (*T* wave) epicenters were located west of CoAxial's axial valley, and the activity was originally thought to have begun on the north rift zone of Axial Volcano, which overlaps with the southern part of the CoAxial segment (Figure 1). However, the fresh lava and the active hydrothermal sites discovered during the 1993 cruises were aligned along the neovolcanic zone of CoAxial, with no indication that Axial had been involved. Water-column and bottom surveys during the 1993 cruises localized three discrete venting sites (Flow site, Floc site, Source site) which were separated by 15–20 km from one another (Figure 1). So, a second question was: What was the geologic and hydrothermal manifestation of the event along the path of dike in-

jection? Detailed seafloor mapping of the segment and time series measurements at these vent sites over several years subsequent to the diking event have helped us interpret what parts of the segment were perturbed by this event and which were unaffected. A third question was: Was the dike an isolated event or part of a longer-lasting episode of crustal accretion for this section of ridge? On the central volcanos of Iceland (our closest subaerial analogy to the MOR), stress builds up over long periods of time (hundreds of years) and is released during multiple events that occur on a decadal timescale [Björnsson, 1985], but until now, there has not been an analogous record of crustal accretion observations anywhere on the submerged portion of the MOR.

To answer these questions, the initial event response expeditions were followed by several other surface ship and submersible cruises in 1993–1996. Submersible dives in 1994–1995 continued the chemical and biological time series studies at the vent sites discovered in 1993 and conducted detailed mapping of the sites. A segment-scale mapping program in 1994–1996 used deep-towed side-scan sonar surveys, camera tows, and rock coring along the CoAxial neovolcanic zone and the north rift zone of Axial Volcano in order to place the detailed work at the active vent sites into a regional context.

This paper synthesizes the available SeaBeam, side-scan, towed camera, and submersible data to relate the 1993 CoAxial accretion event to the recent structural and magmatic history of the area and to the broader issue of MOR accretion processes. We believe our data demonstrate that (1) the 1993 dike intruded from a magma source beneath the CoAxial segment (rather than Axial Volcano) with a significant component of lateral propagation along the neovolcanic zone of the segment, and (2) the 1993 eruption was not an isolated event but was one of at least three volcanic events in the 12-year period between 1981 and 1993 which must have relieved a significant level of stress along the segment.

2. Sources of Data

2.1. Multibeam Bathymetry

The initial SeaBeam surveys of the axis of the Juan de Fuca Ridge were collected in 1981–1982 on the NOAA ship *Surveyor* and were navigated by Loran-C, which provided good relative positioning for swath matching but only approximate geodetic control. These data were subsequently shifted to geodetic “space” using Transit satellite fixes taken during the original surveys. Following the 1990 discovery of the young eruptive mounds on the southern Juan de Fuca Ridge [Chadwick et al., 1991; Fox et al., 1992] another survey of the entire neovolcanic zone of the Juan de Fuca Ridge was made from the NOAA ship *Discoverer* in 1991. A third survey with GPS navigation over the northern portion of Axial Volcano and the CoAxial segment was made immedi-

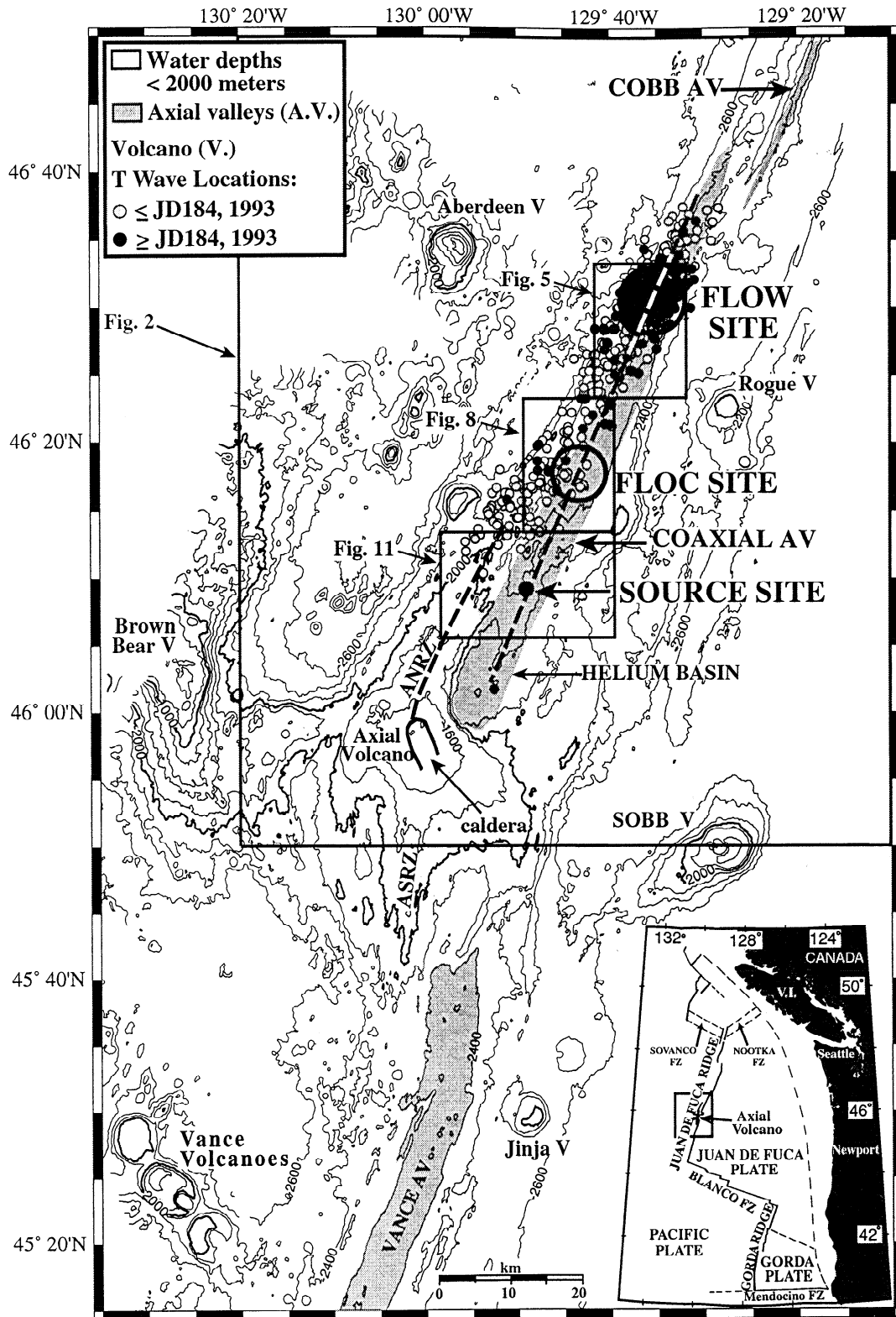


Figure 1. Location map of central Juan de Fuca Ridge with place names used in text. Inset at bottom right corner shows location of area relative to northwest United States and Canada. AV is abbreviation for axial valley, V is for volcano, and FZ is for fracture zone. Location of epicenters from June–July 1993 seismic swarms. Dashed lines show trends of Axial Volcano North Rift Zone (AVNRZ) and CoAxial neovolcanic zone. Diameters of circles are approximate length along axis of venting as observed in 1993. Contour interval is 200 m. Boxes outline areas covered by Figures 2, 5, 8, and 11.

ately after the 1993 eruption. These three surveys were the basis for the SeaBeam differencing calculations presented by *Chadwick et al.* [1995]. The database used for the SeaBeam base maps in this manuscript is a combination of the older Loran-C/Transit navigated data and the 1993 GPS survey.

2.2. Side-Scan Sonar

Data from two types of side-scan sonar systems, SeaMARC II and AMS-60, are used in this study to provide an excellent regional structural context within which to view higher-resolution data sets. The SeaMARC II system is a surface-towed side-scan sonar system operating at 12 kHz. The SeaMARC II data used in this study were collected in 1983 and 1985 by the Canadian Pacific Geoscience Center, the USGS, the University of Washington, and the University of Hawaii. These surveys were navigated by Loran-C and Transit satellite fixes. In 1996, comprehensive surveys of the neovolcanic zone of CoAxial and the north rift zone of Axial Volcano were made using an AMS-60 (60 kHz) deep-towed side-scan operated by Williamson and Co., Seattle, Washington, towed from the NOAA ship *Discoverer*. The position of the side-scan sonar was calculated using the setback of the towfish from depth, wire out, and the GPS position of the ship. The AMS-60 side-scan data were processed to a resolution of 1 m using the USGS Mini Image Processing System (MIPS) software. The AMS-60 side-scan data provides information on the morphology, structure, and texture of the seafloor and can be used to distinguish young volcanic terrain from older tectonized seafloor.

2.3. Submersible and Camera Tow Data

These data were collected using the NOAA Pacific Marine Environmental Laboratory (PMEL) and the USGS deep-towed camera systems (1993–1994), *ROPOS* (1993), and the manned submersible *Alvin* (1993–1995). The *ROPOS* and *Alvin* data used in this paper include video and still photographs and microbathymetry (derived from adding the pressure depth and altimeter output). The deep-towed camera data consist of color 35-mm film, color video, and temperature from the USGS system and monochrome video, color 35-mm film, temperature, and microbathymetry from the NOAA camera system. The seafloor images were digitized and characterized according to the scheme of *Fox et al.* [1988]. All of the *Alvin* dives and most of the deep-towed camera data were collected within long-baseline transponder nets that provide a positional accuracy of ~20 m. These near-bottom observations were used to delineate the location of the neovolcanic zone on both the CoAxial segment and the north rift zone of Axial Volcano.

3. The Structural and Volcanological Context of the Central Juan de Fuca Ridge

The Juan de Fuca Ridge extends from the Blanco Fracture Zone at 44°30'N northward to the Sovanco Fracture Zone at 48°45'N (Figure 1). General descriptions of the ridge and its various segments have been published previously [*Crane et al.*, 1985; *Delaney et al.*, 1981; *Embley and Chadwick*, 1994; *Embley et al.*, 1990; *Johnson and Holmes*, 1989; *Kappel and Normark*, 1987; *Kappel and Ryan*, 1986]. The dominant morphologic feature on the Juan de Fuca Ridge is the anomalously shallow edifice of Axial Volcano, the youngest in a series of volcanos generated by the Cobb-Eickelberg hotspot [*Desonie and Duncan*, 1990] (Figure 1). The general characteristics of the Axial Volcano segment have been described by *Delaney et al.* [1981], *Johnson and Holmes* [1989], *Johnson and Embley* [1990], *Appelgate* [1990], and *Embley et al.* [1990]. The bulk of the volcanic edifice lies between about 45°30'N and 46°20'N and consists of a summit plateau and caldera centered at 45°55'N, 130°00'W, two major rift zones around the caldera, and several other smaller plateaus and volcanic rift zones and ridges (Figures 1 and 2 and Plate 1). Axial Volcano and its major rift zones probably overlie the spreading axis between the Vance and CoAxial segments [*Delaney et al.*, 1981].

To better understand the segmentation of the ridge in this complex area, we constructed a structural map based on the SeaBeam bathymetry and SeaMARC II side-scan data (Figure 2). In older maps based on these data [*Davis and Currie*, 1993; *Johnson and Holmes*, 1989] the Axial Volcano North Rift Zone (AVNRZ) overlaps with the Cobb segment beginning at about 46°40'N and what is now known as the CoAxial segment was not recognized as an active spreading segment. However, the CoAxial segment is clearly delineated as a separate spreading segment by inward facing faults between 46°00'N and 46°40'N (Figures 2, 3a, and 3b). These faults structurally define an axial valley that is between 3 and 5 km in width with up to 150 m of relief. The southern portion of the CoAxial segment overlaps with the AVNRZ for at least 25 km (46°00'–15'N), and the northern end of CoAxial segment overlaps with the southern portion of the Cobb segment by 10 km. The southern end of the CoAxial valley was named "Helium Basin" because of the unusually high $\delta(^3\text{He})\%$ found in hydrothermal plumes from this area in the early 1980s [*Lupton*, 1990].

Most of the faults digitized from the SeaMARC II and SeaBeam data are oriented at or close to the trend of the Juan de Fuca Ridge (~N020°E), but oblique or curvilinear ridges occur at several locations. Curvilinear constructional volcanic ridges occur on the eastern side of the AVNRZ and at the southern and northern ends of the CoAxial segment where it overlaps with the AVNRZ

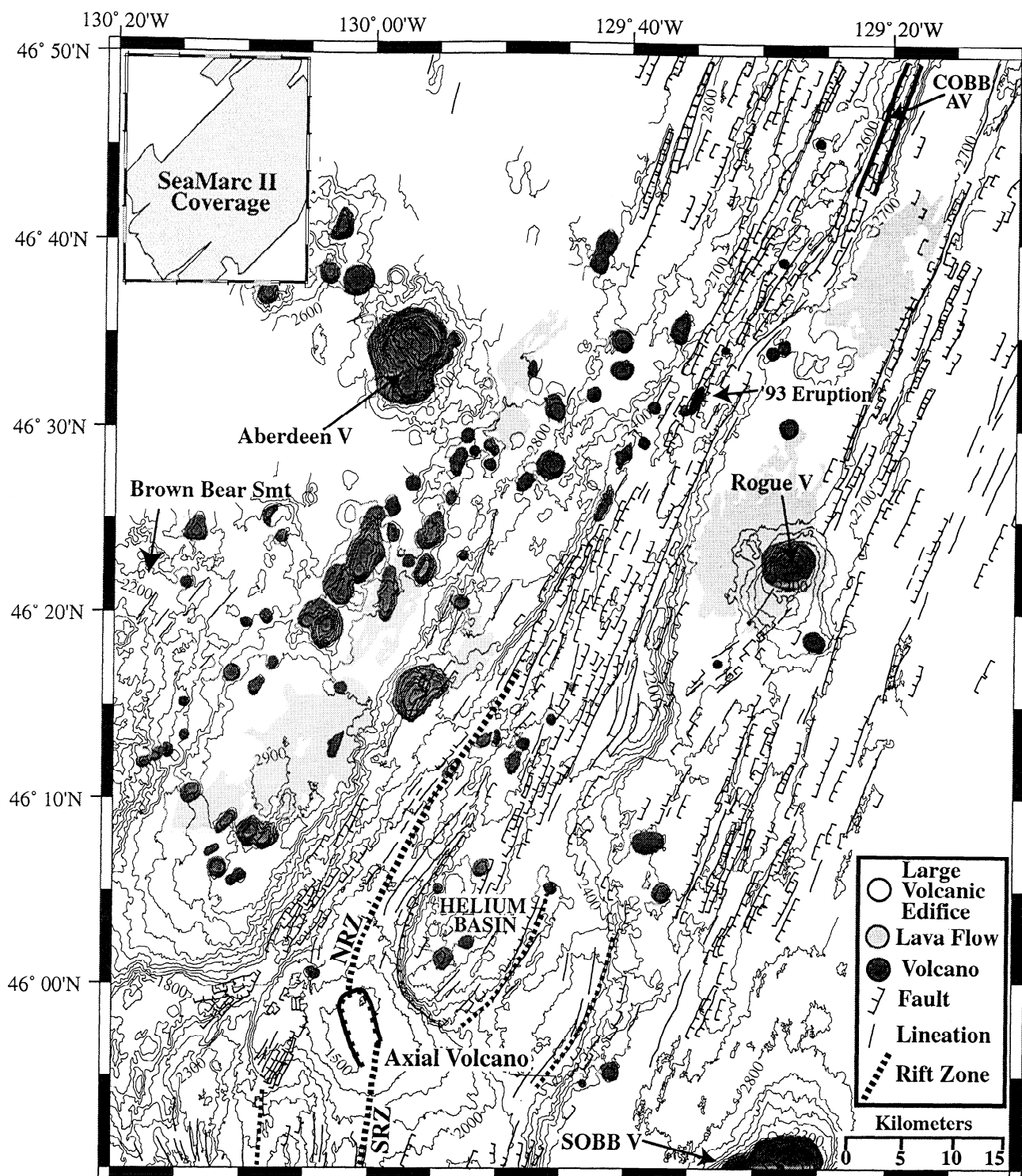


Figure 2. Interpretative map of Axial Volcano and CoAxial segment based on SeaMARC II side-scan sonar and side-lit SeaBeam bathymetry. Dark shaded areas are major off-axis volcanos, medium shaded zones are high backscatter areas marking most recent off-axis lava flows, and light shaded zone marks approximate limit of major hotspot edifices of Axial Volcano and Brown Bear Seamount to the east. Faults are hachured. SeaBeam contours are lightly shaded and their limit marks limit of SeaBeam coverage. Coverage of SeaMARC II side-scan sonar surveys in 1983 and 1984 are shown in inset. SRZ is south rift zone, NRZ is north rift zone, SOBB is Son of Brown Bear Volcano.

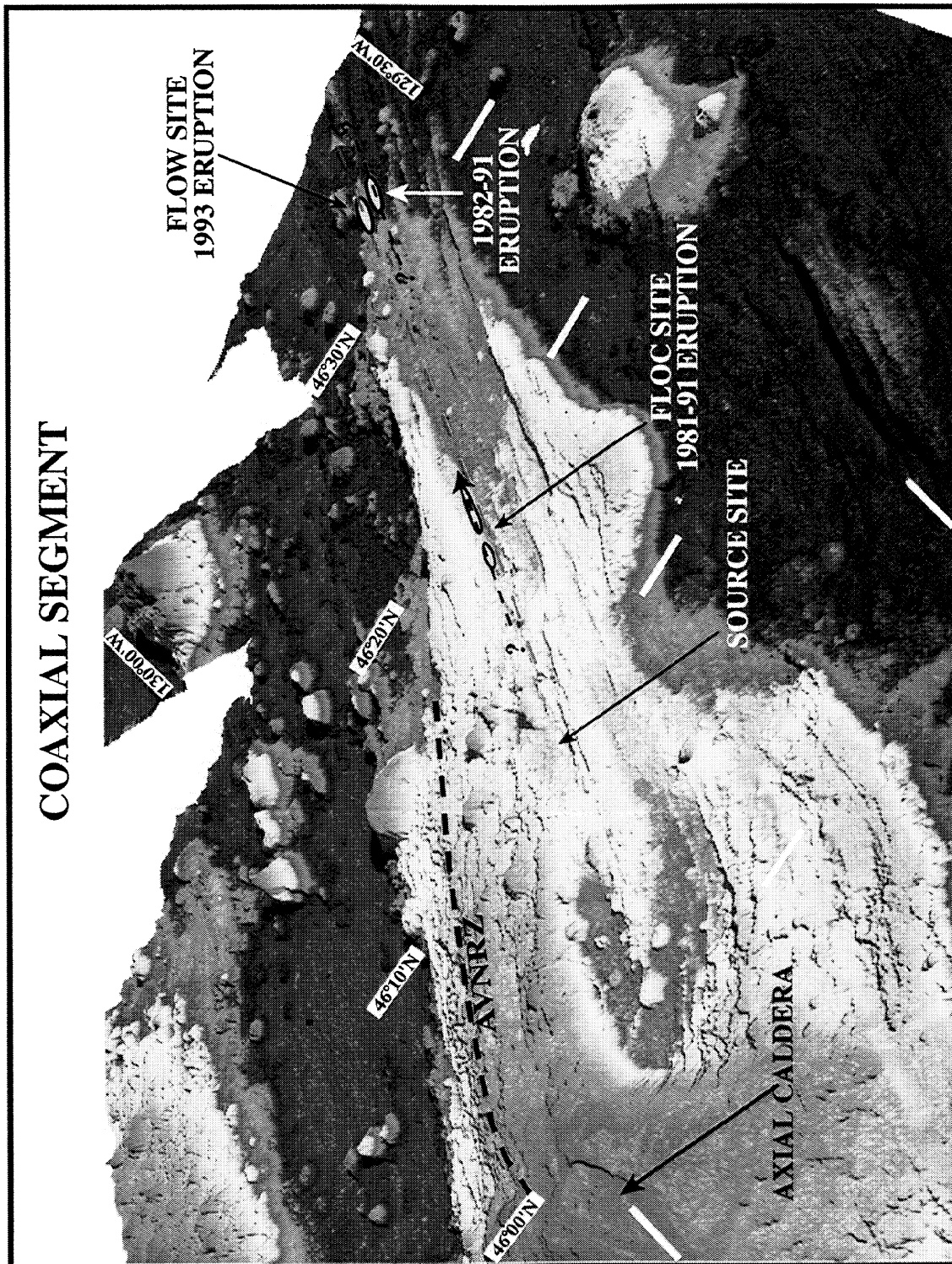


Plate 1. Perspective side-lit SeaBeam bathymetry of CoAxial segment of Juan de Fuca Ridge with locations of major features discussed in text. View is looking northwest from eastern side of Axial Volcano. Latitudes and longitudes are only approximate because of foreshortening of image. Dashed lines with arrows are orientations and extent of diking based on geologic evidence for 1993 (red) and 1981-93 dikes.

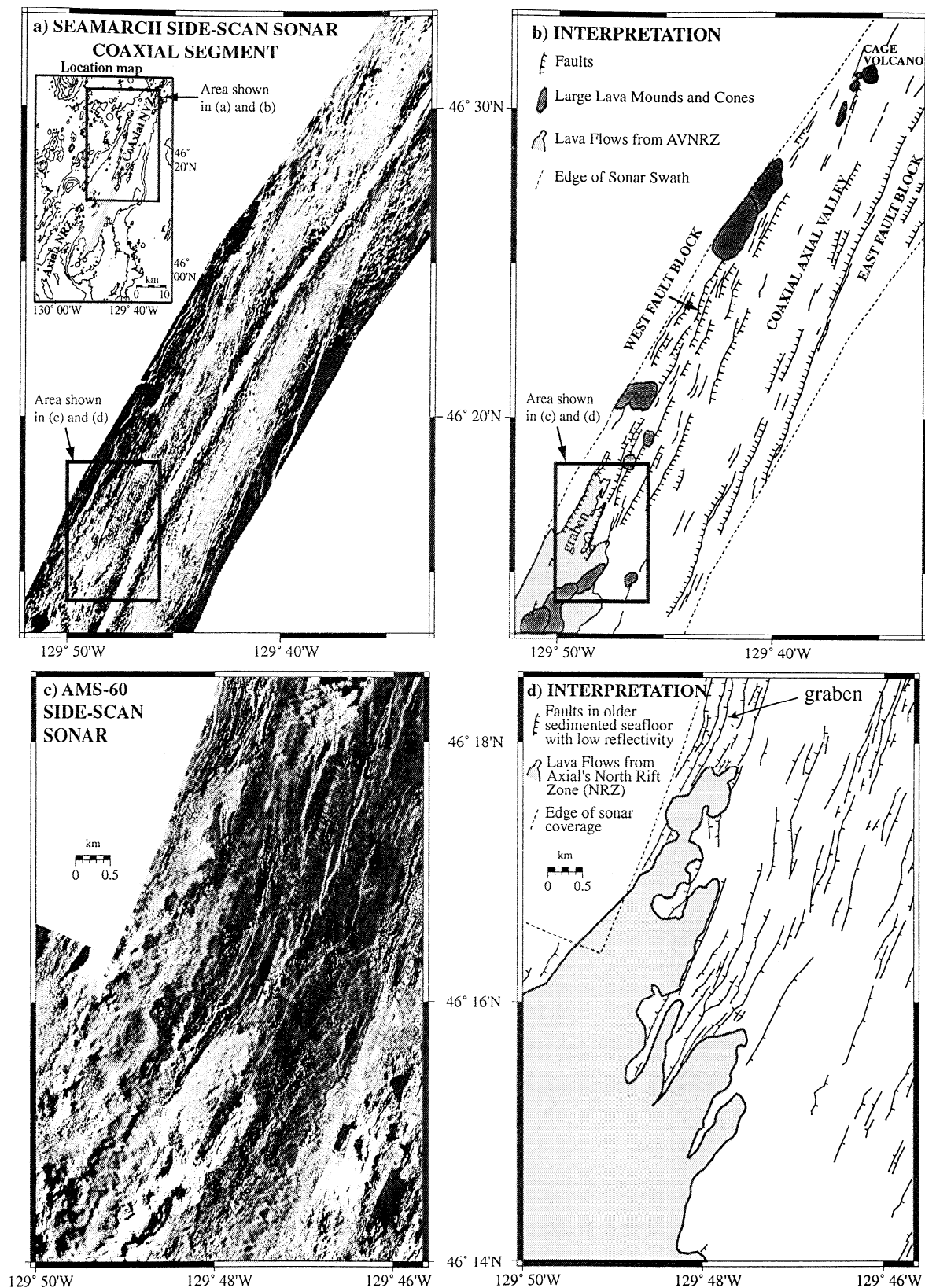


Figure 3. (a) SeaMARC II swath of Coaxial segment and (b) interpretation. Note distinct graben containing northernmost young lavas. (c) AMS-60 side-scan mosaic of junction of AVNRZ and CoAxial axial valley and (d) interpretation. Note high backscatter lavas erupted along AVNRZ covering older (lower backscatter) fissured lavas.

and the Cobb segment, respectively. These curvilinear ridges are interpreted to be formed by crack interaction between overlapping spreading segments such as those described at faster spreading centers [Macdonald and Fox, 1983; Sempere and Macdonald, 1986]. A set of oblique ridges on older crust found northeast of Axial Volcano (Figure 2) could be traces of an older overlapping zone.

A striking feature in Figure 2 is the asymmetric distribution of volcanic cones and lava flows on the west side of the ridge and the concomitant apparent lack of faulting. Sediment cover is thinner on the west side of the ridge because the ridge blocks the sediments from the continent, so this asymmetry in faulting is not caused by sediment cover. It is probably due either to burial of the faults by more active off-axis volcanism and/or because faulting has been less developed on the west side, possibly due to the shoaling of isotherms in the vicinity of the hotspot. Although there are a few large volcanos on the east flank of the ridge axis, most of the recent off-axis lava flows are confined to the flank of Axial Volcano and Rogue Volcano. An exception is one isolated but well-defined off-axis lava flow at 46°40'N, 129°20'W (Figure 2).

4. CoAxial Segment and Its Relation to Axial Volcano

The neovolcanic zone of a ridge segment is the narrow zone within which recent volcanic eruptions have been focused; it is essentially the present axis of accretion and spreading. Although the exact location of the neovolcanic zone along the CoAxial segment and the AVNRZ is not always clear from bathymetry alone, it is well-defined from a combination of side-scan and camera data. The CoAxial segment extends from the Helium Basin at the base of the steep northeast flank of Axial Volcano (~46°00'N; 129°57'W) to about 46°40'N where it overlaps with the southern end of the Cobb segment (Figures 1 and 2). The shoalest portion of the neovolcanic zone of the CoAxial segment lies between 46°03'N and 46°15'N along a ridge that bisects the bowl-shaped Helium Basin. The segment deepens to the northeast by 425 m over 60 km, from 2125 m at 46°08'N to 2550 m at 46°40'N. This relatively steep topographic gradient probably reflects a decrease of the long-term magma supply away from the hotspot.

Morphology of the neovolcanic zone along the CoAxial segment exhibits considerable along-strike variability (Figure 2 and Plate 1). The southern portion of the axial valley (46°00'–15'N) contains a series of prominent ridges and conical volcanos. From about 46°15'N to 46°30'N, the center of the axial valley consists of an alternating series of low-relief depressions, small volcanos, and ridges with no well-defined central neovolcanic ridge. North of 46°30'N, a series of narrow volcanic ridges are again prominent. These curve eastward in the overlap zone with the Cobb segment north of

about 46°33'N. Small circular volcanic cones (<1 km in diameter) are found within the axial valley for its entire length, but most of the largest cones lie along the southern portion of the segment.

Between 46°12'N and 46°25'N the CoAxial segment is bounded on both the west and east sides by large, fault-bounded ridges, which have outlines in map view like two halves of a pear split along the axis of the segment (Figure 2 and Plate 1). We interpret that these "fault-block ridges" initially formed on-axis at CoAxial by magmatic processes and were then split apart by subsequent plate spreading, as in the model proposed by Kappel and Ryan [1986] for the southern JdFR. The western fault-block ridge physically abuts, and is aligned with, the AVNRZ to the south. Some investigators [Sohn *et al.*, 1997] have assumed that the western fault-block ridge is an extension of the AVNRZ and therefore that the *T* wave epicenters tracked the 1993 dike as it intruded from AVNRZ to the eruption site on the CoAxial segment. However, side-scan, towed camera, and geochemical data show that this would have been unprecedented. Those data clearly show that the lavas erupted from the AVNRZ do not extend farther north than about 46°18'N. South of this boundary, the hummocky morphology of constructional volcanism is clearly present in the side-scan imagery (Figures 2, 3a, and 3c), young lavas are photographed in camera tows, and the lavas have a geochemical affinity with basalts recovered from Axial Volcano [Smith, 1999; Smith *et al.*, 1997]. North of this boundary, the recent volcanism abruptly ends and gives way to much older seafloor with numerous fissures and faults and a lower acoustic backscatter value (Figures 3a, 3b, 3c, and 3d) probably caused by increased sediment cover of up to 80–100% in this area as seen on bottom photos. The northern termination of young lavas from AVNRZ occurs within a 3-km-wide graben extending from 46°16'N to 46°19'N that bisects the top of the western fault block ridge (Figure 3). Our interpretation of these relationships is that the AVNRZ and CoAxial segment behave as separate but overlapping ridge segments, with separate shallow magma supplies, and the young volcanic constructions of the AVNRZ have been superimposed upon the older western fault block ridge.

Geochemical data are key to evaluating the level of interaction between the neovolcanic zones of Axial Volcano and the CoAxial segment. Isotopic ratios are one of the most effective tools for discriminating different parental magmas and their mantle sources because of their geochemical transparency to melting and most shallow level crustal processes. Assuming crustal assimilation has been negligible, significant differences in radiogenic isotopic ratios (e.g., ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd) of two basalts indicate that their mantle sources were different [Rogers and Hawkesworth, 1999]. However, covariation between incompatible element abundances and isotopic ratios in MORB from many portions of the MOR, including the JdFR, suggests that some of

the isotopic variability is a consequence of mixing of melts from distinct mantle domains (i.e., enriched versus depleted) or that it is a result of variable extents of melting of heterogeneous mantle [White *et al.*, 1987]. Although the Sr and Nd isotopic values of MORB from the JdFR do not vary much in comparison to other MOR segments affected by hot spots, the data allow us to distinguish a few spatial domains along the length of the JdFR. In particular, MORB from the CoAxial segment have distinctly non-radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, suggesting they were derived from long-term depleted mantle that has not been recently “enriched” by another component. A plot of $^{86}\text{Sr}/^{87}\text{Sr}$ of basalts against latitude (Figure 4) reveals that the recent source for the CoAxial segment is geochemically distinct from both Axial Volcano and the rest of the JdFR. This distinction is particularly clear when comparing the youngest samples from the AVNRZ and CoAxial segment. The lack of any overlap between the fields that encompass the CoAxial segment and Axial Volcano/AVNRZ provide compelling evidence that the magmatic plumbing systems beneath Axial Volcano and the CoAxial segment are separate and that although these ridge segments overlap, they do not interact magnetically.

5. The 1993 Eruption Site (“Flow Site”)

The dives made at the 1993 eruption site (“Flow site”) with the *ROPOS* and the submersible *Alvin* mapped out the extent of the fresh lava flow and diffuse hydrothermal venting associated with a zone of fissures and narrow grabens extending several kilometers to its north and south [Chadwick *et al.*, 1995; Embley *et al.*, 1995] (Figures 5–7). The eruption took place along an older volcanic ridge that extends north of Cage Volcano, a prominent 1-km diameter volcanic cone (Figure 6).

Differencing of SeaBeam bathymetric grids from surveys made in 1982, 1991, and 1993 shows a well-defined

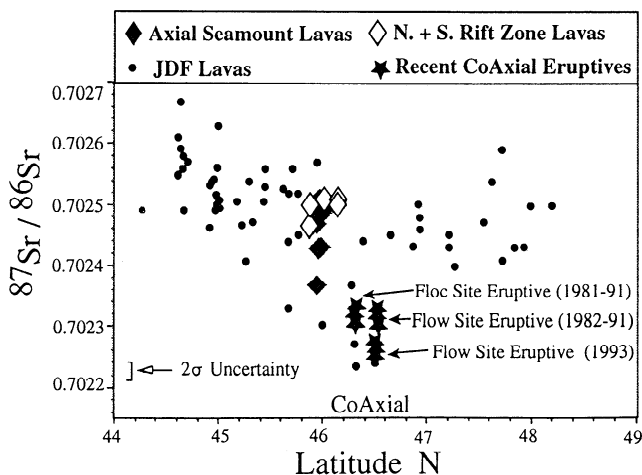


Figure 4. Sr isotopes versus latitude, central Juan de Fuca Ridge.

positive depth anomaly coinciding with the glassy, un-sedimented lava observed (Figure 6 and Plates 2a and 2b) [Chadwick *et al.*, 1995]. One of the thicker (~30 m) portions of the lava flow centered at $46^{\circ}32.4'N$ (Figure 6) coincides with an area of intense hydrothermal activity observed during *ROPOS* and *Alvin* dives in 1993 (Figure 6 and Plate 2c). Seafloor observations made during *ROPOS* dives (e.g., R219, Figure 6) in August 1993 (probably less than 2 weeks after the eruption) showed that the crestal region of the lava flow was emitting an extensive flow of warm water up to 50°C from an area of drained-out flattened pillow lavas. Fe-Si precipitates coated large areas of the crestal area where active venting was taking place (Plate 2c) [Embley *et al.*, 1995; Juniper *et al.*, 1995].

High-resolution near-bottom bathymetric surveys using an AMS-60 deep-towed side-scan sonar and a Mesotech scanning sonar mounted on *Alvin* mapped well-defined narrow (~20 m wide) grabens at both the southern and northern ends of the 1993 lava flow (Figure 6). Chadwick and Embley [1998] propose that these structures formed above the 1993 dike that fed the eruption. In this paper we use the terms “fissure” and “graben” as by Chadwick and Embley [1998]. A fissure is a fracture whose walls have moved apart by pure extension. A graben is a linear topographic depression created by subsidence along inward facing normal faults. Small grabens are distinguished from fissures in that they have a well-defined downdropped center block.

Surveys and seafloor observations using the *ROPOS* and *Alvin* mapped at least three small patches of lava north of the main lava flow (the northernmost is at $46^{\circ}32.5'N$) that erupted out of narrow grabens. Low-level diffuse venting was observed within the northern graben in August 1993, but none was observed in July 1994. An *Alvin* dive within the graben at the southern end of the main lava flow (Figure 6) in October 1993 found extensive diffuse hydrothermal venting and bacterial mats along its eastern wall, but venting had ceased by September 1995. Extensive venting was also found southwest of the 1993 flow on the plateau south of Cage Volcano in August 1993 at sites extending for 5 km SSW (~ $N202^{\circ}E$) of the main lava flow (Figure 5 and Plate 2d). All six *ROPOS* transects, including the southernmost one at $46^{\circ}28.4'N$, crossed a narrow zone of venting associated with small grabens and or fissures that cut through pre-1993 lavas (Figure 5). No recently erupted lava was observed on any transect south of the main lava flow.

Camera tows in 1994 and *Alvin* dives in 1995 (Figure 5) did not detect any active hydrothermal venting south of the lava flow where *ROPOS* observed it in 1993, but *Alvin* transects at two sites revealed “fresh” appearing fissures and small grabens characterized by bright white and yellow staining on the broken rock faces (Figure 5). At $46^{\circ}29'N$, *Alvin* (dives 2990 and 2992) encountered a very unusual fractured zone characterized by brecciated

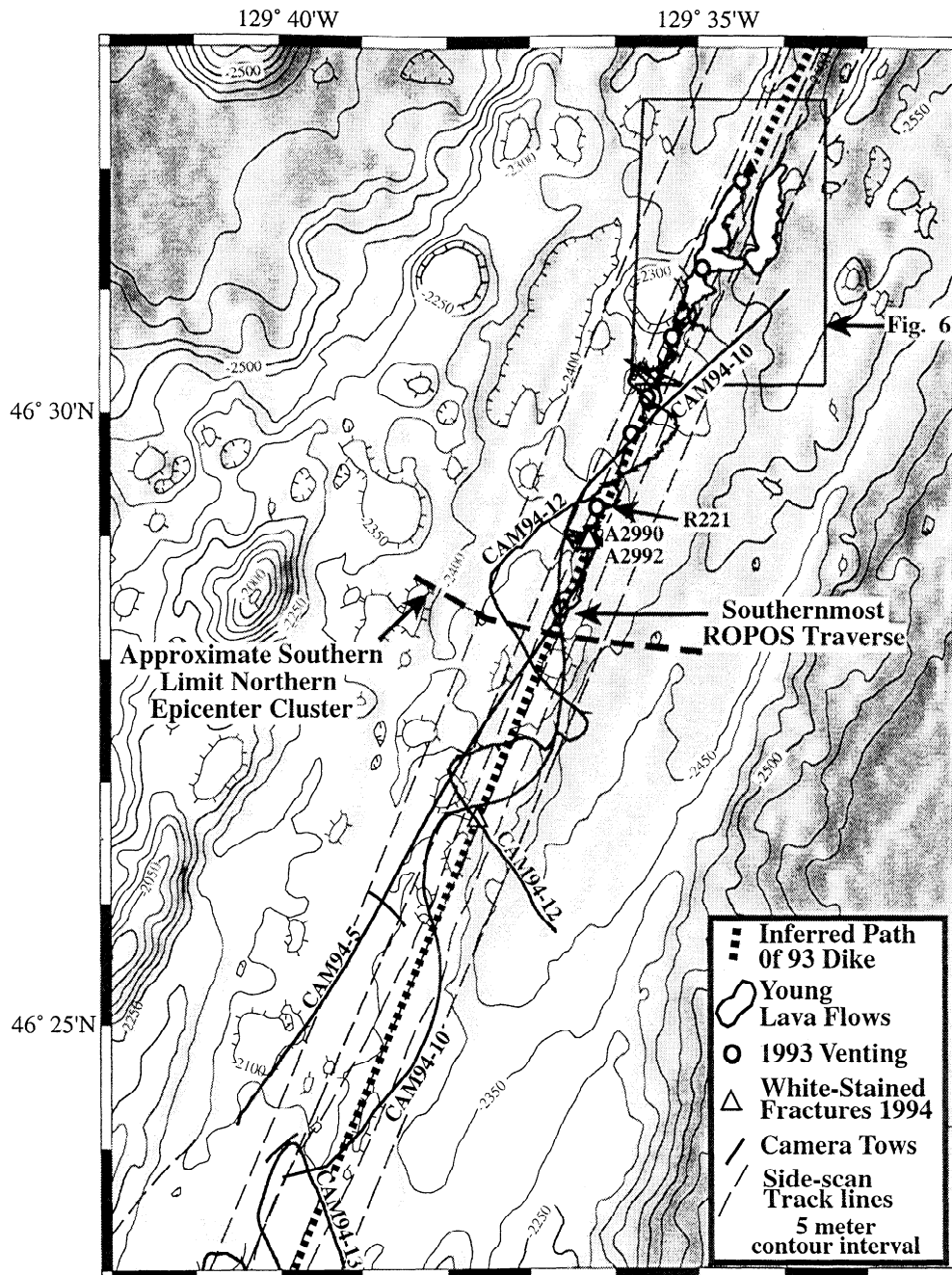


Figure 5. Bathymetric map of northernmost portion of CoAxial segment, including the Flow site. Bathymetry is side-lit from west with 50-m contours superimposed. Darker shades are deeper. Box shows area of Figure 6. Location on regional bathymetry shown in Figure 1.

ciated, pervasively stained basalt lying within a shallow graben up to 10 m wide (Plate 2e). Careful observation from *Alvin's* viewports confirmed that this rubble was generated in situ, not tectonic talus generated from a nearby scarp. The zone appeared to be continuous for at least 500 m along strike and located along the line of (apparent) continuous venting observed by *ROPOS* in 1993.

In summary, the 1993 CoAxial eruption site consists of a 3.8-km-long, (up to) 500-m-wide lava flow, a zone of grabens and fissures extending at least 1 km northward which fed several small eruptions, and a zone ex-

tending at least ~ 4.5 km to the south characterized by grabens, fractured seafloor, and extensive diffuse venting (in 1993), but no fresh lavas. This entire active zone is at least 8.4 km in length. A plot of the T wave epicenters (Figure 1) shows that the events in the second half of the swarm(s) (after JD184) form a "bull's-eye" pattern at the eruption site that has approximately the same diameter (~ 8 km) as the length of known along-axis venting and eruption (southern limit shown on Figure 5). The character and geometry of these structures as well as the short duration of hydrothermal venting along them are all consistent with the interpretation

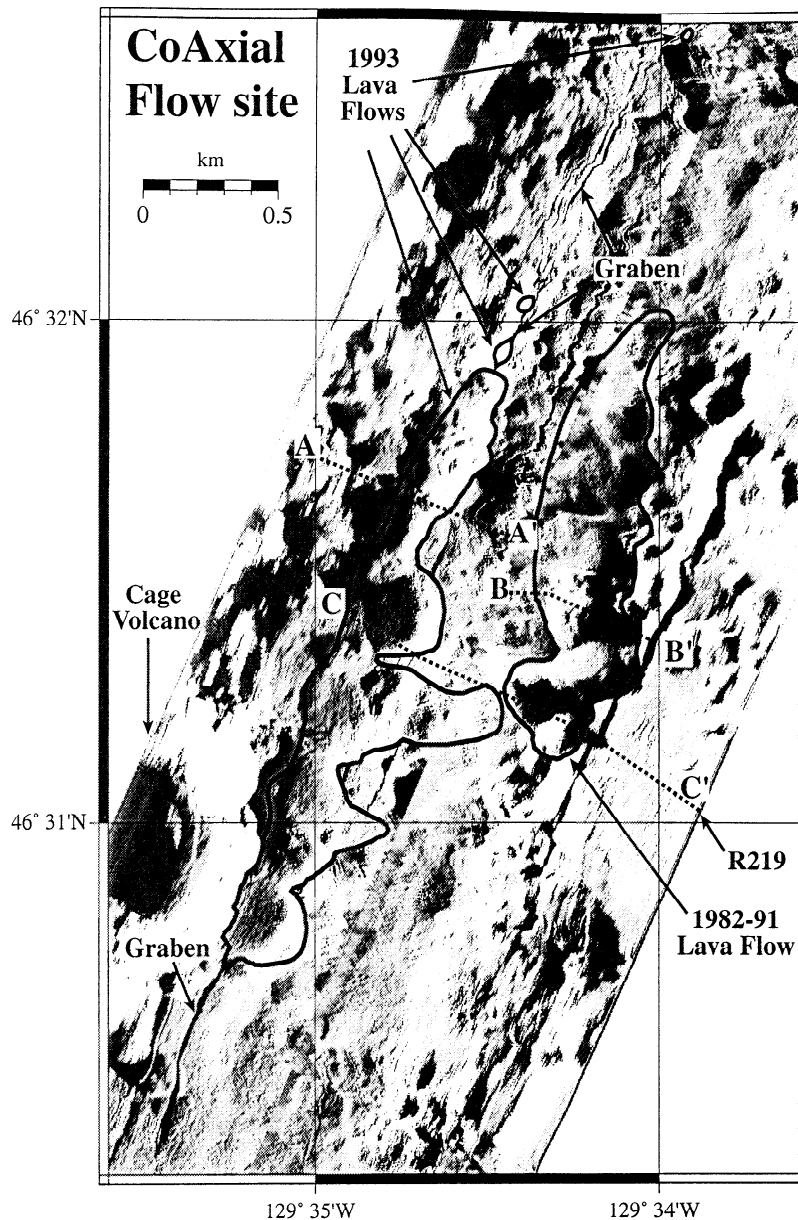


Figure 6. AMS-60 side-scan mosaic (two swaths) of 1993 and 1982–1991 lava flows at the Flow site, CoAxial segment. White lines are boundaries of young lavas determined by SeaBeam differencing anomalies and *ROPOS* and Alvin dives [Chadwick *et al.*, 1995]. Dotted lines denote depth cross-section locations shown in Figure 7. Location shown in Figure 5.

that they formed directly above the 1993 dike and thus reveal the path that the dike took along this section of the CoAxial segment. There is no evidence for any other 1993 eruption sites, but repeat SeaBeam surveys and camera tows have identified two pre-1993 eruption sites along the CoAxial segment, which are described in sections 6 and 8.

6. The 1982–1991 Lava Flow at the Flow Site

The first dive by *ROPOS* at the Flow site in August 1993 crossed over a largely sediment-free, glassy lava flow lying about 700 m east of the 1993 flow (Figures

5, 6, and 7). Subsequent comparison of SeaBeam surveys clearly showed that this lava was erupted between 1982 and 1991 [Chadwick *et al.*, 1995]. This older flow appears to be morphologically similar to the 1993 flow, consisting of mostly pillow lavas (Plate 2f) but with a distinct zone of flattened and partially drained-out pillow flows along the crest of the mound. The crest of the 1982–1991 lava flow has a veneer of dull yellow Fe-Si sediment (Plate 2g), which is likely the Fe-Si precipitates observed forming during the cooling phase of the 1993 lava flow (Plate 2c). Similar precipitates were also found on the crest of the lava mounds on the northern Cleft segment that erupted in the mid-1980s [Chadwick and Embley, 1994], so the presence of these deposits is

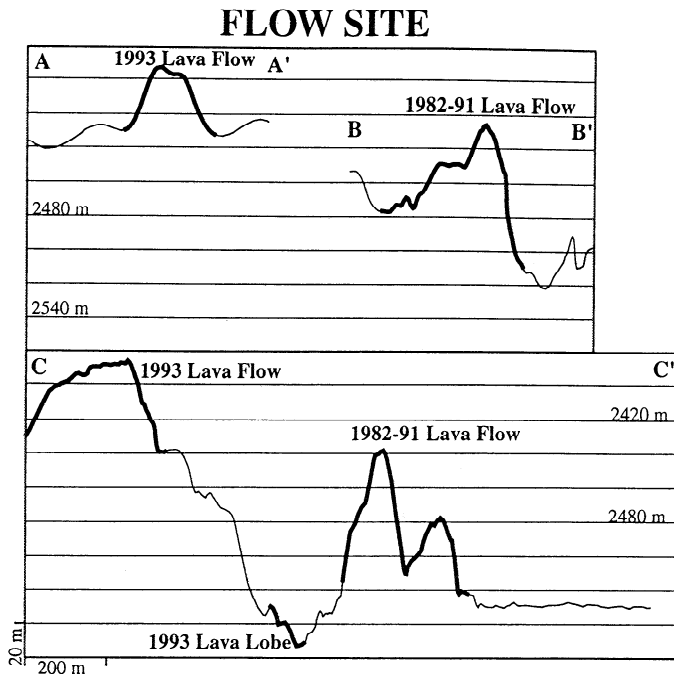


Figure 7. Depth cross-sections along submersible traverses of young lava flows at the Flow site, CoAxial segment. Young lavas are highlighted by thicker lines. Locations shown in Figure 6.

now a well-documented indicator of the cooling phase of recent pillow lavas and their feeder dikes. The northern extent of this flow is currently unknown due to lack of near-bottom photographic coverage. The separation between this eruptive mound and the 1993 mound is ~ 800 m (centerline to centerline).

7. Floc Site

The July/August 1993 CTD (conductivity, temperature, depth, light transmission) profiles showed high light attenuation values in the plumes located around $46^{\circ}18'N$ and centered above the CoAxial neovolcanic zone in the middle of the axial valley [Baker et al., 1995; Embley et al., 1995]. This area became known as the "Floc site" (Figures 1, 8, and 9). It should be noted that at the latitude of the Floc site, almost all of the epicenters in the 1993 *T* wave swarm are west of the CoAxial neovolcanic zone. The Floc site is where a mismatch between the *T* wave locations and seafloor geology becomes clear. A *ROPOS* dive at the Floc site in 1993 observed large white particles up to 200 m above the bottom and "snowdrifts" of these flocculent particles on the seafloor (Plate 2h). After localizing the source area with the Scripps Deep-Tow system in August [Spiess and Hildebrand, 1993], *Alvin* dives in October 1993 documented extensive diffuse venting along a fissure and graben system, including some places where vent fluid was so laden with large white particles that the sites became known as "snow blower" vents (Plate 2i) [Haymon et al., 1993]. Taylor and Wirsén [1997] propose

that production of these particles is controlled by direct excretion of filamentous sulfur from sulfur oxidizing bacteria. A high production of sulfur-rich particles was produced at the $9^{\circ}45' - 52'N$ East Pacific Rise site [Haymon et al., 1993], and there is photographic evidence (Embley, unpublished data, 1987) for a large particle accumulation on the seafloor following the mid-1980s eruption at the north Cleft site [Embley and Chadwick, 1994]. Hyperthermophilic Archaea (with optimal growth ranges of $90^{\circ}C$) were cultured from vent fluids sampled from the Floc site in October 1993 (but not subsequently), strongly implying the presence of a viable, substantive subsurface microbial biomass at this site in the months following the 1993 dike intrusion [Delaney et al., 1998; Holden et al., 1998].

Observations from the *Alvin* dives and camera tows presented here and from the plume surveys [Baker et al., 1998] show that diffuse venting was occurring over >5 km along strike from $46^{\circ}16'$ to $46^{\circ}19'N$ (between Mkr 18 and Mkr 5 on Figure 9). *Alvin* dives in the fall of 1993 observed only bacterial mats at these vent sites (Plates 2i and 3a), but subsequent dives in 1994 and 1995 to the same marked sites documented a rapidly evolving macrofaunal community [Tunnicliffe et al., 1997] (Plates 3b and 3c). By 1995, visible venting had declined to just a few isolated sites, notably at the Huge Diffuse Vent (HDV) and marker 18 sites (Figure 9) and by 1996, observations (using *ROPOS*) of extensive predation by crabs marked the rapid decline in the macrofaunal communities at the HDV site (V. Tunnicliffe, personal communication, 1996) (Plate 3d). Time series observations of hydrothermal plumes for the same period also show a rapid decline. By 1996, heat and particle content above the Floc and Flow sites had returned nearly to background levels [Baker et al., 1998]. These observations are consistent with the interpretation that the 1993 dike intruded close to the surface beneath the Floc site but by 1996 had cooled to the point that it was no longer producing enough H_2S flux to support chemosynthesis at the seafloor/rock interface. The rapid contraction of hydrothermal/biological sites above a dike intrusion was also observed at the Cleft segment following its mid-1980s eruption [Embley and Chadwick, 1994; Embley et al., 1994].

Structural control of the venting at the Floc site is revealed by side-scan imagery, which shows a braided and anastomosing fracture system 100–200 m wide cutting through low-relief seafloor from about $46^{\circ}16'N$ to $46^{\circ}19.5'N$ (Figures 9 and 10). This zone probably consists largely of preexisting structures that were reactivated during the 1993 intrusion (in contrast to the Flow site where the structures hosting active venting appeared to be new [Chadwick and Embley, 1998]). The southern part of the zone was apparently an eruptive vent in the recent past; submersible observations showed extensive drainback of young sheet flows between $46^{\circ}17.5'N$ and $46^{\circ}18.5'N$. An old sequence of pillow lavas was observed to be partly "coated" with a ve-

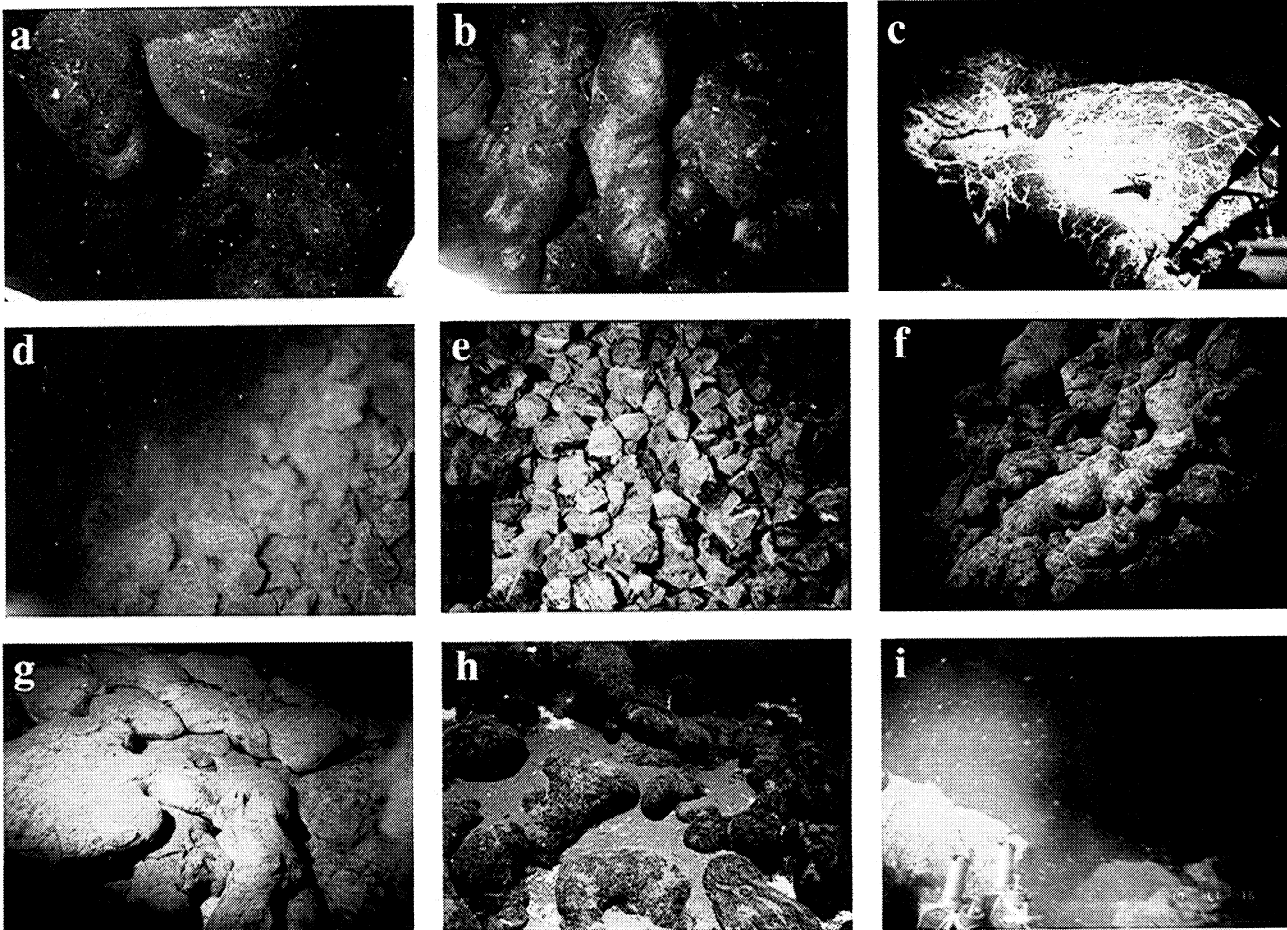


Plate 2. A series of 35-mm photographs from *ROPOS* (R) and *Alvin* (A) of lava flows and vents on CoAxial segment. Origin and year of photograph are given by, e.g., R93: (a) Lobes of pillow lavas on east flank of 1993 flow. Darker bands on pillow (~0.75 m diameter) in upper middle right are very delicate veneer of glass which sloughed off on contact. White particles are fallout in water column (Figure 6, *ROPOS* Dive 219, R93). (b) Sediment-free glassy tubes and pillows on east flank of 1993 eruption mound (R93). Pillow tube in center is ~0.5 m across (Figure 6, *ROPOS* Dive 219, R93). (c) Crest of 1993 lava flow showing extensive coating of Fe-Si deposit probably precipitated by Fe-oxidizing bacteria. Temperature probe (~1 m long) at lower right measured exit vent fluid temperatures as high as 51°C in the vicinity of this site (R93). (d) Extensive venting along fissure south of 1993 eruption (R93). (e) Brecciated zone along path of venting south of 1993 eruption site (Figure 7, *Alvin* Dive 2990, A95). Pieces are ~0.25 m across. (f) Flank of 1982–1991 lava site lying 500 m east of the 1993 flow (A93). (g) Crest of the 1982–1991 lava flow; note duller color than Plate 2c (A93). (h) “Floc” drifts amidst older pillow lavas (note thick sediment pockets) along center of axial valley at about 46°19.4'N (R93). (i) Turbid vent fluid rising out of fissure near Huge Diffuse Vent (HDV) at Floc site (Figure 9) (A93). Fissure is ~1 m wide.

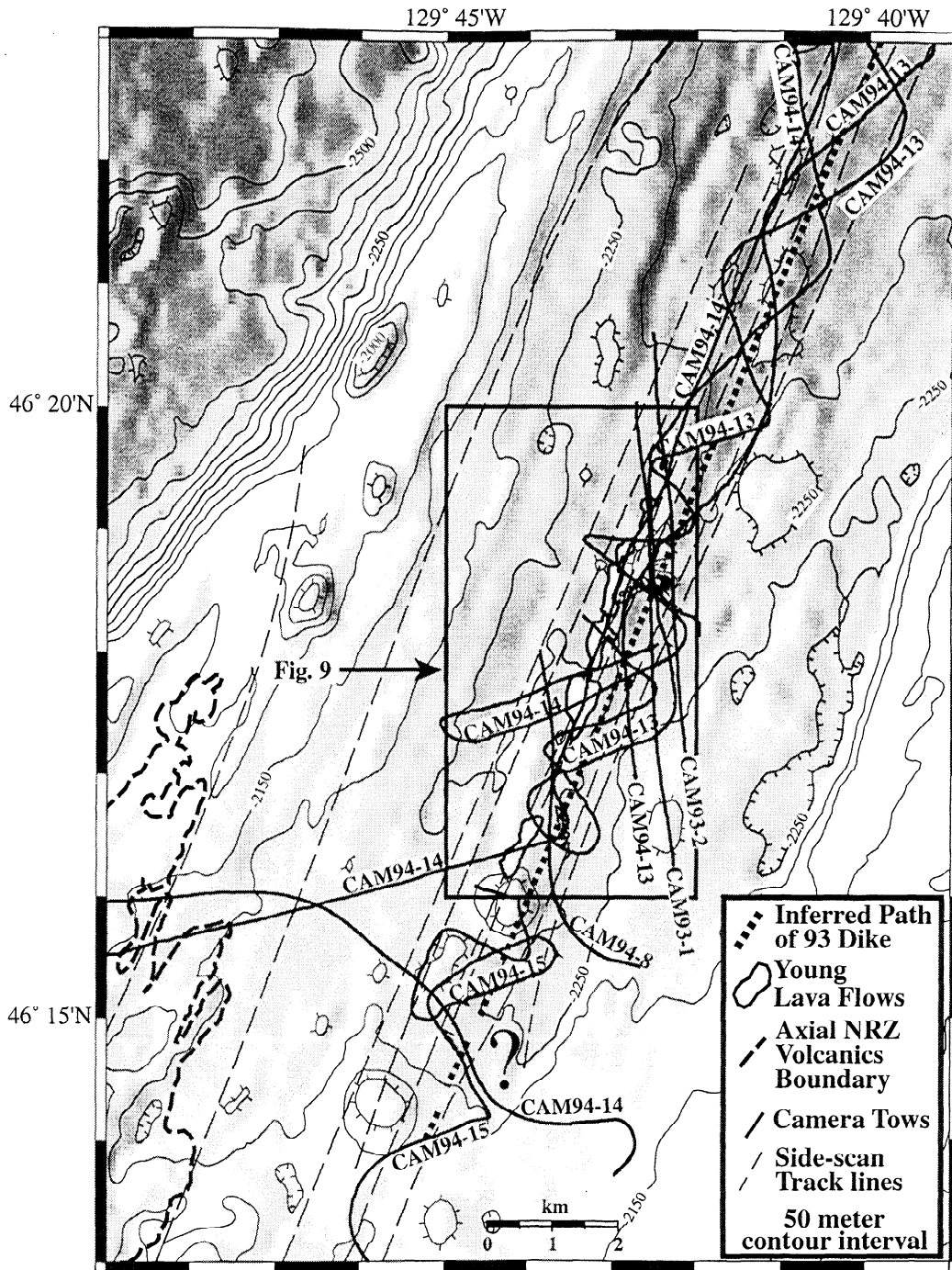


Figure 8. Bathymetric map of central CoAxial segment, including the Floc site. See Figure 5 caption for details.

neer of younger sheet flows characterized by “bathtub rings” (Plate 3e). Such drainback features are characteristic of eruptive fissures observed (mostly) on intermediate to fast portions of the MOR. An interesting aspect of the venting at the Floc site is that while it was located within a zone that consists of many individual structures, the venting at any particular location was always localized along a single fissure or graben, usually the westernmost structure in the swarm. Hydrother-

mal fluids vented from the floor, walls, and rims of the structures.

Sohn et al. [1998] located nine microearthquakes at the center of the CoAxial axial valley between 46°13'N and 46°17'N during a 1-month deployment of an ocean bottom seismometer array in 1994, 1 year after the eruption. *Sohn et al.* [1998] attribute this activity to post diking tectonic adjustments, which is consistent with the geologic evidence presented here.

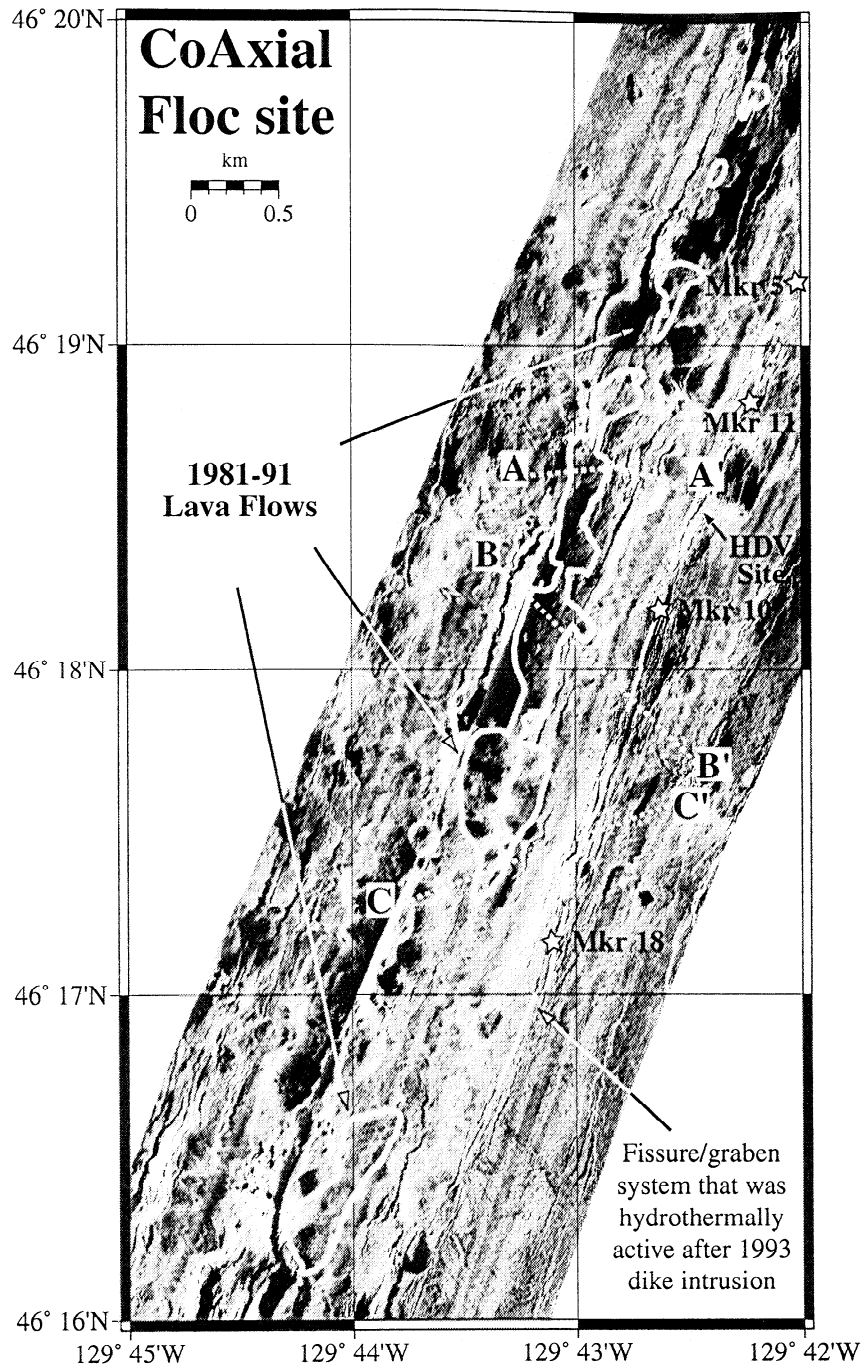


Figure 9. AMS-60 side-scan mosaic of fissure swarm (solid white lines) and 1981–1991 lava flows (white outline) at the Floc site. Boundaries of young lavas, extent of venting along fissure, and vent sites (e.g., Mkr 18) determined from camera tows (Figure 8) and *Alvin* dives. Location of map shown by box in Figure 8. Dotted lines are depth cross-sections shown in Figure 10.

8. The 1981–1991 Lava Flows at the “Floc Site”

The 1994 deep-towed camera survey delineated a series of young, glassy lava flows extending for 7 km along a ridge ~500 m west of the actively venting fissure swarm at the Floc site (Figures 8–10). The lava erupted along a preexisting ridge; in some locations it flowed down the east side of the ridge and at other

places down the west side (Figure 10). Application of the SeaBeam differencing technique revealed a small but distinct depth difference anomaly (up to 25 m) between the 1981 and 1991 surveys which coincides exactly with the young lava mound delineated by the towed camera centered at 46°17.5'N; 129°43.3'W. Note that this SeaBeam anomaly is different than the “southern 1981–1991 SeaBeam anomaly” tentatively identified at 46°26.2'N by *Chadwick et al.* [1995], which our

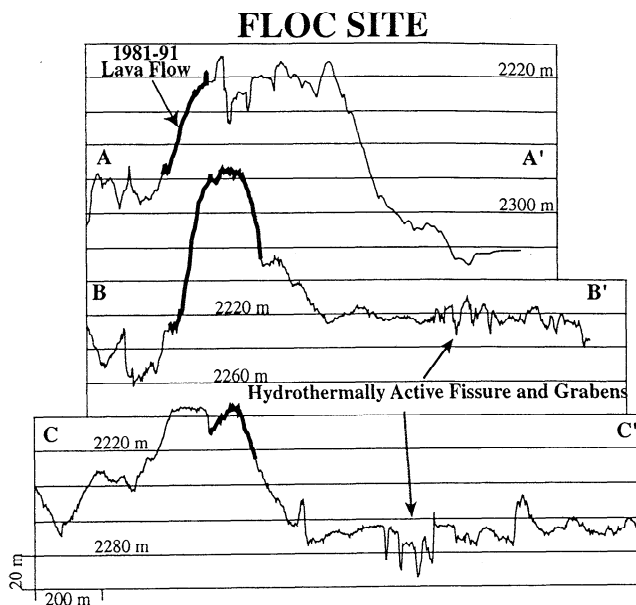


Figure 10. Depth cross sections of Floc site. Locations shown in Figure 9.

1994 camera tows revealed to be false. The Floc site anomaly discussed here was assumed to be an artifact [Chadwick *et al.*, 1995] because it was relatively small in area and did not have any photographic groundtruthing at the time. The absence of additional SeaBeam difference anomalies coinciding with the other areas of glassy lavas mapped by the towed camera suggests that most of the 1981–1991 lava flows at the Floc site are thinner than ~5–15 m, which is the vertical resolution of this technique [Fox *et al.*, 1992]. The SeaBeam differencing results do not allow age discrimination between the 1982–1991 lava flow at the Flow site and this one at the Floc site. However, close examination of *Alvin* hand-held photographs of the two sites suggests that the Floc site pillow mounds are slightly older because they have small sediment pockets and do not have as vitreous a luster as the northern lavas (compare Plates 2f and 3f). The towed camera imagery and video traverses made with the submersible *Alvin* show that neither of the 1981–1991 flows were fractured, nor were they colonized with sessile organisms.

9. Southern CoAxial Segment and the “Source Site”

The southern third of the CoAxial axial valley (south of about $46^{\circ}14'N$) is characterized by a distinct median volcanic ridge (Plate 1 and Figure 11). The ridge summit is covered with young pillow lavas with small pockets of sediment and small areas of sheet flows at its southern end ($\sim 46^{\circ}07'N$) where it broadens. Seafloor between the median ridge and the AVNRZ (dashed line on Figure 11) consists of heavily sedimented sheet flows (Plate 3g). A young pillow mound on the axis of the AVNRZ centered at $46^{\circ}10'N$, $129^{\circ}55'W$ (Figure

11) mapped by the towed camera probably represents a single eruption from a recent diking episode originating at or near the summit of Axial Volcano. No SeaBeam anomaly was found at this site, so it apparently precedes all of the historic CoAxial eruptions.

C'TDT tows along this part of the CoAxial segment in October 1993 encountered a hydrothermal plume centered around $46^{\circ}09'N$ (Figure 11) that was clearly separate from the plumes originating at the known Floc and Flow sites to the north [Baker *et al.*, 1998]. The high-temperature vent site subsequently discovered on *Alvin* dive 2681 in October 1993 became known as the “Source site” because it was postulated that this site may have represented the magma source region that generated the 1993 dike injection [Butterfield *et al.*, 1997].

The Source vent field is located on the west side of the neovolcanic ridge of the CoAxial segment (Figure 12) along a fissure/fault system. This ridge is the shallowest part of the CoAxial neovolcanic zone, rising to ~ 2100 m in the vicinity of the vent site and thus is the most likely position of a long-term hydrothermal system on this segment [Ballard and Francheteau, 1982; Crane, 1985]. The vent site consists of four major vents aligned at about $N022^{\circ}E$ along a west facing scarp (Plate 3h). The chimneys are spaced ~ 10 – 20 m apart and the entire vent field is <100 m in length. Less vigorous venting also occurs on small chimneys west of and slightly deeper than the large ones. The small chimneys are oriented along trends about $N040^{\circ}W$ and intersect the primary vents (Plate 3i). This pattern suggests that the locations of the vents may be controlled by intersection of two structural trends such as has been documented at the Endeavour Main Field [Delaney *et al.*, 1992]. The metal-poor vents emit a clear or grayish “smoke” with a maximum temperature of $294^{\circ}C$. Butterfield *et al.* [1997] concluded that these fluids have a relatively long crustal residence time compared to other hydrothermal systems on the JdFR, but the mechanism for this is unclear.

The only other active hydrothermal activity found nearby was an area of diffuse venting a few tens of meters on a side about 3.5 km to the south (Figure 12). Small mounds of iron oxides had a fluid temperature only $\sim 4^{\circ}C$ above ambient. A line of extinct sulfide chimneys was found several hundred meters northwest of the diffuse vent. These Zn-rich chimneys lie along a small fault aligned along $N020^{\circ}E$ and extend for at least 100 m along the same trend as the active high-temperature vent field to the north (Figure 12). The presence of these older chimneys indicates that this site has had a long-term history of high-temperature venting. To date, no other high-temperature activity (either past or present) has been found along the length of the CoAxial segment.

Several observations lead one to the conclusion that the Source site predated and was probably not affected by the 1993 seismic swarm. First, the initial seismic activity was to the north and northwest of the site (Figure

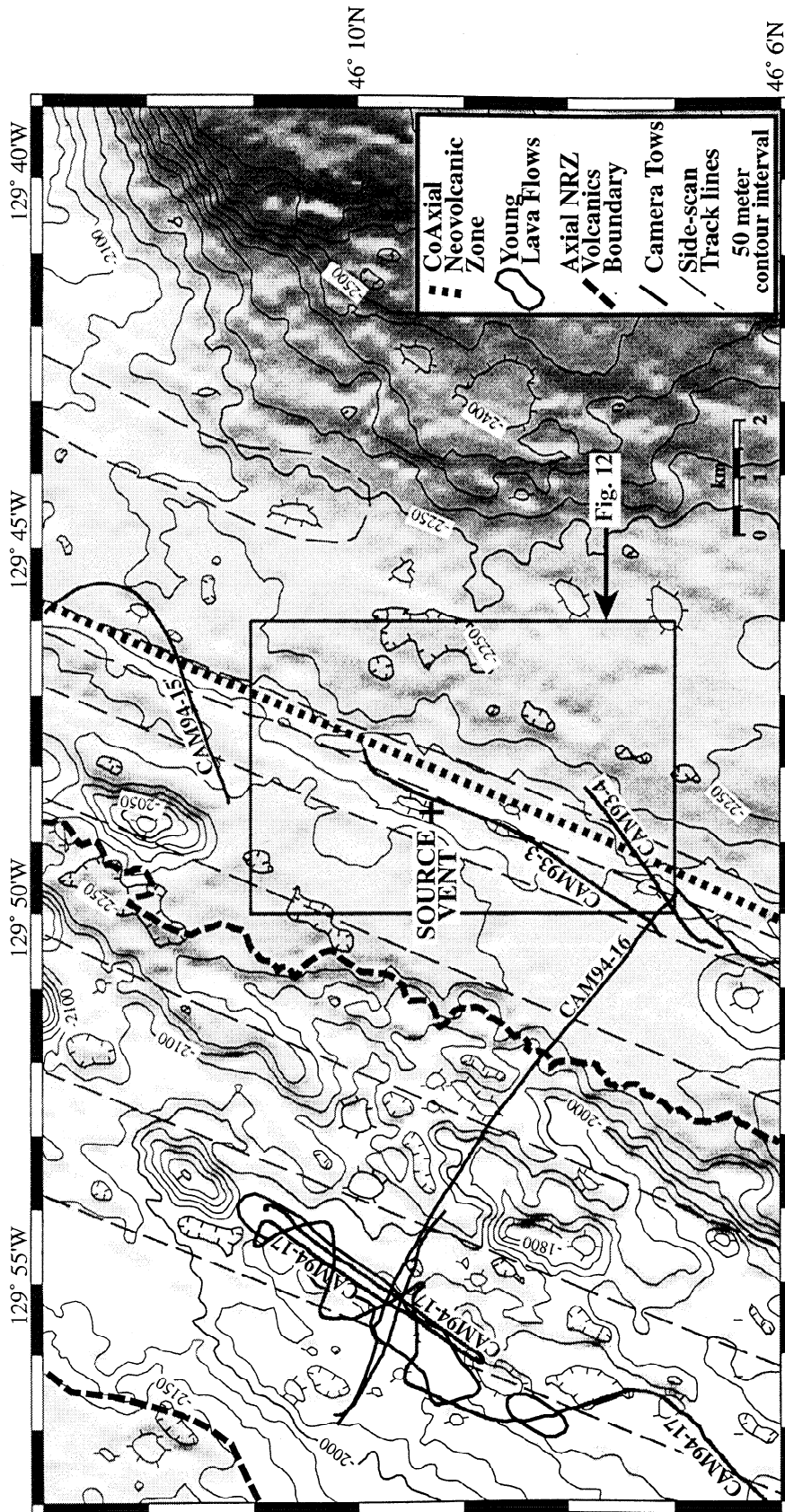


Figure 11. Bathymetric map of southern CoAxial segment including the Source site. See Figure 5 caption for details. Location of Figure 12 is shown by box.

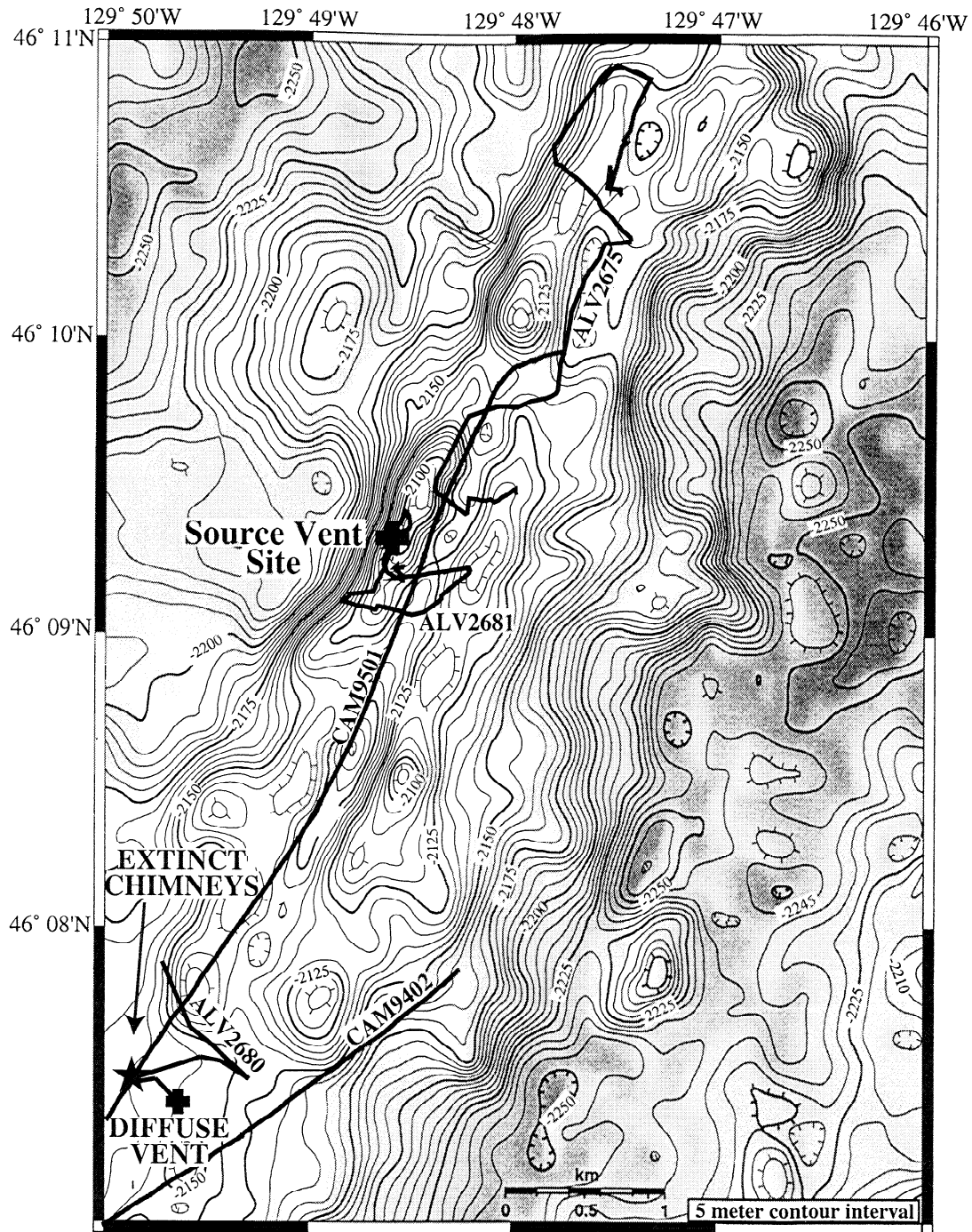


Figure 12. Bathymetry of "Source" site with camera, dive tracks, and locations of sites discussed in text. Side-lit from west. Contour interval is 5 m.

1); there were no SOSUS-detected events located along this ridge. Second, the submersible dives and camera tows across and along the ridge yielded no geologic or biologic evidence of very recent tectonic events or young venting such as observed at the Floc site. Last, analyses of a time series of vent fluid samples from this site taken in 1993, 1994, and 1995 [Butterfield *et al.*, 1997] do not show the rapid changes in temperature and chlorinity that characterize other recent eruption sites [Butterfield *et al.*, 1997; Butterfield and Massoth, 1994; Von Damm

et al., 1995]. Considering these data, it now seems unlikely that the Source site was significantly perturbed by the 1993 event.

10. Discussion

10.1. Relationship of *T* Wave Seismicity to Seafloor Structure and Geologic Observations

Where did the 1993 dike originate and how does the spatial pattern of the 1993 *T* wave swarm relate to the

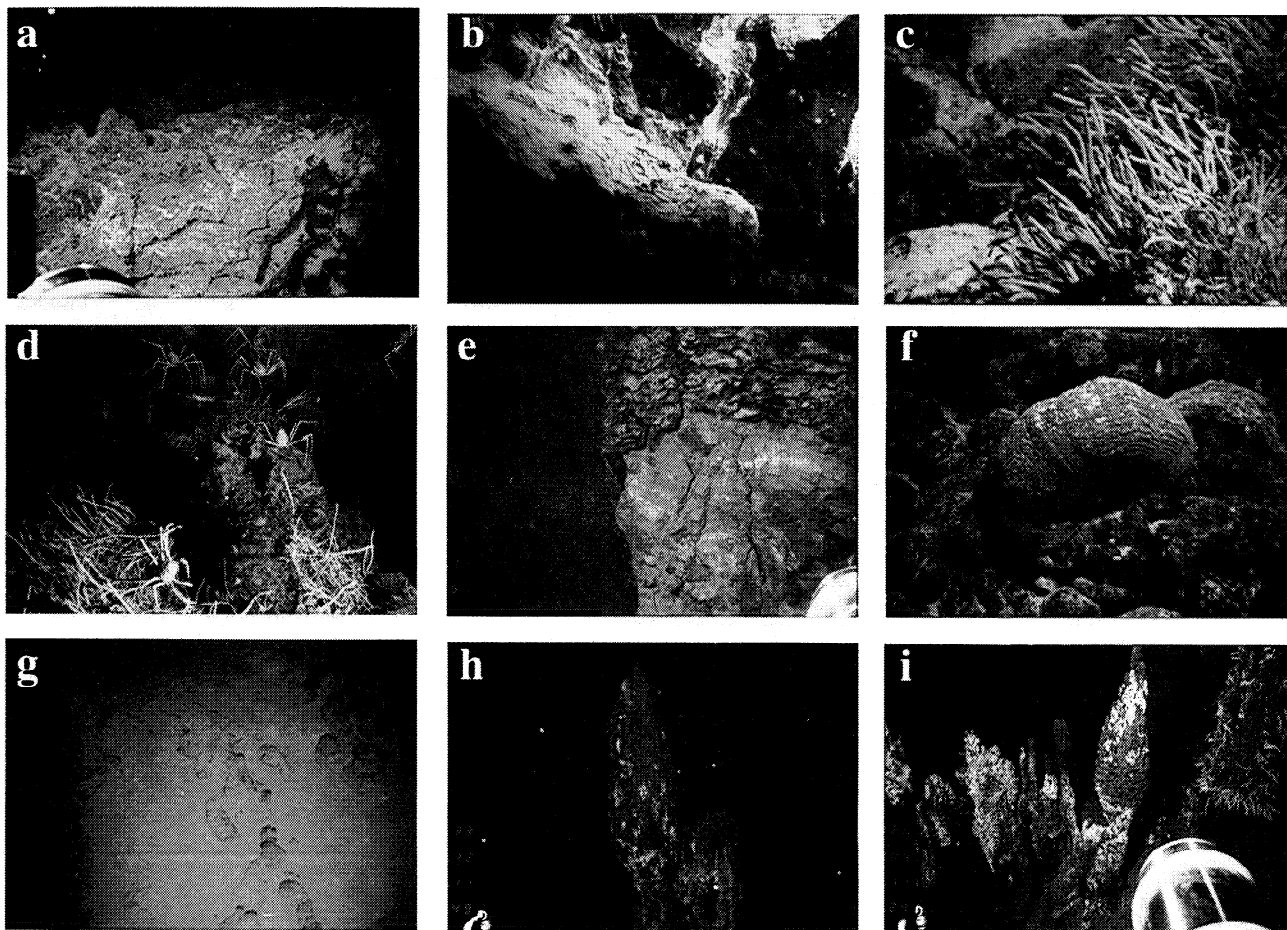


Plate 3. A series of 35-mm photographs from *ROPOS*, *Alvin*, and towed camera of Floc and Source sites: (a) Bacterial mats coating wall of fissure at Floc site (A-1993). (b) Nemertean worms (each ~3 cm in length) on bacterial mats on wall of fissure at southern Floc site near marker 18 (Figure 9) (A95). (c) Tubeworms (~0.3 m long) at HDV vent, Floc site (A95). (d) Crabs feeding on remnants of tubeworm community at the HDV vent at the Floc site (R96). (e) Young lavas (upper) coating wall of older lavas in fissure at Floc site near marker 18 (A95). (f) The 1981–1991 pillow lavas at the Floc site. Note small but distinct sediment pockets in these lavas (A95). Pillow is ~1 m across. (g) Photo from USGS towed camera of sediment-covered lavas between the AVNRZ and the CoAxial neovolcanic zone. Photo is ~5 m across. (h) Top (~2 m) of 7-m chimney (“Mongo”) at Source site. (i) Small chimneys (~0.5–1.0 m high) at Source vent lining up on structure oblique to primary chimneys.

physical manifestations of the 1993 dike intrusion on the seafloor? A puzzling problem has been the discrepancy between the trend of the 1993 *T* wave swarm and the trend of the neovolcanic zone at CoAxial as defined by geologic mapping. We think that the 1993 dike intruded from a magma source beneath the southern CoAxial segment and propagated northward along the CoAxial neovolcanic zone and that Axial Volcano was not involved in the 1993 event, for the following reasons:

1. Hydrothermal plumes related to the 1993 dike intrusion were located over the neovolcanic zone of CoAxial segment, not along the trend of *T* wave epicenters [Baker *et al.*, 1998].
2. Time series measurements of hydrothermal plumes at both the Flow and Floc sites show a power law decline of temperature and rise height, consistent with the expected thermal decline during the cooling of a dike [Baker *et al.*, 1998; Cherkaoui *et al.*, 1997].
3. Venting sites on the seafloor were located directly under the hydrothermal and exclusively along the neovolcanic zone of CoAxial. The evolution of the vent sites on the seafloor at the Flow and Floc sites, including a rapid bacterial bloom followed by rapid cooling of the system, is consistent with a geothermal response to an intruded dike. Geothermal perturbations associated with dike intrusions in volcanic rift zones on land generally appear directly over the axis of the dike [Björnsson *et al.*, 1979].
4. SeaBeam bathymetry of the central JdFR is consistent with Axial Volcano and its rift zones effectively behaving as one of many independent spreading segments along the ridge, with overlapping (but not intersecting) relationships with the adjacent ridge segments (Vance and CoAxial).
5. Side-scan imagery and bottom photography delineate the neovolcanic zones of AVNRZ and CoAxial segment and show that they are separate from one another. The northern limit of the AVNRZ only extends to 46°15'–18'N, where it merges with the western fault block ridge, an older tectonized feature hypothesized to have formed along CoAxial. There is no evidence from geologic mapping that dikes have propagated in the past from the AVNRZ into and along the neovolcanic zone of CoAxial. Although dikes intrude at variable directions over a period of time on a given rift zone [Gudmundsson, 1990], it is difficult to envision how a dike could propagate across structure from one volcanic rift zone to another and then along structure on the second rift zone.
6. An ocean bottom seismometer deployment made around the Floc site detected small earthquakes

tightly clustered at the Floc site along the trend of the neovolcanic zone [Sohn *et al.*, 1998].

7. Geochemistry of lavas from Axial Volcano and its rift zones is distinct from lavas collected from CoAxial segment, particularly with relation to Sr isotopic signatures. Geochemical signatures of the 1993 lava flow and the two 1981–1991 flows indicate that they all came from CoAxial magma sources, not from Axial Volcano.
8. Detailed geologic mapping of the low-temperature hydrothermal vent sites on the seafloor associated with the 1993 intrusion shows that the vents are localized along fissures and small grabens which are interpreted to have formed or were reactivated directly over the 1993 dike while it was intruding. These structures which trace the path of the dike are located within the CoAxial neovolcanic zone.

Therefore all of the geologic and geochemical evidence leads to the conclusion that the 1993 dike originated within the CoAxial segment and intruded northward along its neovolcanic zone and did not follow the path suggested by the *T* wave epicenters from AVNRZ to CoAxial. What could explain the oblique trend of the *T* wave swarm, particularly since the *T* wave epicenters cluster perfectly above the 1993 eruption site at the northern end of the swarm? There are two hypotheses that could explain this discrepancy. One hypothesis, suggested by Fox *et al.* [1995], is that the first half of the *T* wave swarm consisted of deeper earthquakes [Schreiner *et al.*, 1995] and the relatively shallow seafloor to the west of the central CoAxial segment may have radiated more of the acoustic energy and so added a systematic location error to the epicenters in the southern part of the swarm. A second hypothesis is that the early *T* wave events might have been associated with faulting along the boundary of the western fault block ridge rather than directly associated with the dike itself, located on-axis. Intruding dikes have triggered normal faulting in volcanic rift zones on land [Rubin, 1992; Sigurdsson, 1980], and several normal fault earthquakes located on the bounding faults of the summit caldera of Axial Volcano were triggered during the early stages of the 1998 dike injection there [Dziak and Fox, 1998, 1999].

10.2. Implications for Stress Release During Accretion Events on the Mid-Ocean Ridge

Three separate eruptions have occurred on the CoAxial segment within the 12-year period from 1981 until 1993 (Plate 1). The two younger eruptions occurred near the northern end of the segment, and the oldest event occurred at the midpoint of the segment at 46°15'–21'N.

How much strain has been released during this time period and what are the implications for the space-time

pattern of strain and volcanism for the rest of the ridge system? It seems reasonable to assume that the two 1981–1991 eruptions represent diking events similar to the 1993 event because (1) all the lava flows are similar in volume and are elongated along the axis of the neovolcanic zone, and (2) all of the other known historical eruptions documented to date along the northeast Pacific spreading centers [Chadwick *et al.*, 1998; Dziak and Fox, 1998; Dziak *et al.*, 1995; Embley and Chadwick, 1994] have been associated with dikes that have intruded over tens of kilometers along axis. The T wave epicenters suggest that the 1993 dike was injected from a latitude between the Floc and Source sites ($\sim 46^{\circ}12'N$), so presumably a magma reservoir exists beneath the axis of CoAxial around this location. If we assume that all three recent eruptions were fed by dikes that intruded northward from this area, this may have interesting implications for the pattern of stress accumulation and release from this section of the ridge. At a spreading rate of 5.5 cm/yr, each meter thickness of intruded dike relieves about 18 years of accumulated stress. Although we cannot directly estimate the thickness of any of the dikes intruded during the CoAxial events, estimates of dike widths from sections of oceanic crust exposed in ophiolite sections are typically 0.5–1.5 m [Gillis, 1995]. The three documented eruptions occurring over a 12-year period represent only a minimum number of diking events because additional events may have taken place without producing eruptions in the 1981–1991 period prior to SOSUS monitoring and after the initial SeaBeam survey. Also, the lack of teleseismic events ($M \geq 4$) along this portion of the ridge (R. Dziak, personal communication, 1999) in the 1966–93 time period suggests that faulting was not a significant factor in stress release for this period. Nevertheless, the record of recent eruptions at the CoAxial segment represents the first direct evidence of the style of stress release over the timescale of about a decade along a portion of the MOR. The CoAxial diking events of 1981–1993 must have relieved a significant amount of stress along the segment. No diking events have been detected by SOSUS in the 1993–1999 period.

Although the period of observation is very short, this pattern could be analogous to the behavior of Icelandic central volcanos. The long-term record of volcanism in Iceland shows that the central volcanos release accumulated stress in a series of major rifting/volcanic events about every 100–150 years [Björnsson *et al.*, 1979]. During the latest of these episodes, the Krafla Volcano produced 20 diking/rifting events between 1975 and 1984, only about half of which erupted lava at the surface [Björnsson, 1985]. Whether the CoAxial “rifting episode” has ended remains to be seen, although at the time of this publication, the segment has been seismically quiet for 6 years. Geodetic monitoring of the Krafla episode suggests that as each diking event relieves some of the regional stress, it becomes more

difficult to inject additional dikes into an increasingly compressive stress field [Ewert *et al.*, 1991].

10.3. Implications for Magma Delivery Systems at Intermediate Spreading Rates

How magma is delivered along segments of the MOR is poorly known because of the lack of direct measurements of 3-D seismicity patterns and deformation during diking events. Models of magma delivery systems have been mostly inferred from surface morphology, lava geochemistry, and geophysical measurements [Batiza, 1996]. Even in Iceland, where a rifting episode was monitored in 1975–1984 at the Krafla Volcano and where there has been extensive geologic mapping, there remains some controversy as to how magma is delivered to the upper crust. The seismicity patterns during the Krafla rifting events showed that at least some of the dikes were propagated laterally from beneath Krafla caldera [Einarsson and Brandsdóttir, 1980], and this led Sigurdsson [1987] to propose that lateral propagation of dikes is an important process on Icelandic central volcanos. On the other hand, Gudmundsson [1995] concludes that many of the long dikes generated during episodes on Icelandic central volcanos are propagated primarily vertically from deeper magma sources. Another source of information about magma delivery systems in mid-ocean ridge settings comes from ophiolites. Interestingly, a study of flow directions in the dikes of the Troodos ophiolite [Varga *et al.*, 1998] showed a significant lateral component of magma transport during diking.

Embley *et al.* [1994] proposed that the dike(s) that produced the 1980s eruption(s) at the north Cleft segment had a significant lateral component. This was based primarily on the observation that hydrothermal cooling proceeded more rapidly at the end of the dike even though that is where the largest eruption occurred. Their preferred interpretation of this observation was that the distal end of the dike is “rootless”; that is, it did not erupt vertically from a local magma source but was fed laterally from a more robust magma source. The longer-lasting high-temperature venting associated with a sheet flow eruption to the south was assumed to be over the location of the primary magma source.

What was the mode of dike injection during the 1993 event? The northward propagation of the T waves during the 1993 CoAxial event is certainly consistent with a lateral dike injection [Dziak *et al.*, 1995]. Also, Butterfield *et al.* [1997] concluded that the chemistry of the 1993 pillow mound site vent fluids could be explained by the cooling of the dike and lava flow alone (i.e., “rootless portion”), whereas the chemistry of the fluids at the Floc site constrained them to a larger and hotter source. Although there were no observations of active venting on the older pillow lava eruptive mounds at the CoAxial site, the presence of the yellowish sediments on the 1982–1991 mound is consistent with a low-temperature

reaction zone of a rapidly cooling dike and lava flow. *Smith* [1999] explained a decrease in MgO content in the lavas at the Floc site 1981–1991 eruption mounds as crystal fractionation within a northward propagating dike. Finally, two of the CoAxial eruptions and the north Cleft eruption [*Chadwick and Embley*, 1994] were characterized by 80–100% of the eruption by volume being emplaced at the deep end of the segments. This pattern is also consistent with a lateral dike injection in that it is [*Fialko and Rubin*, 1998] hydraulically easier to erupt lava as the seafloor deepens.

Thus the spatial and temporal patterns of eruption and hydrothermal cooling and the lava geochemistry of the 1993 and older events are consistent with a dike that had a significant lateral component of injection. Admittedly, this conjecture is largely circumstantial, unfortunately; there are very few data (e.g., seismic reflection) on the along-axis melt supply of the Juan de Fuca Ridge. However, some new and more direct evidence for lateral dike injection on a segment of the Juan de Fuca Ridge was the 3-m drop in the caldera of Axial Volcano (Figure 1) measured by a seafloor pressure gauge coupled with eruption of lava on the rift zone during the seismicity episode in 1998 [*Fox*, 1999; *Embley et al.*, 1999]. Clearly, monitoring of diking events (at a range of spreading rates) with arrays of seismometers and instruments to measure vertical and horizontal strain is needed to provide more definitive data on the geometry of MOR crustal level magma plumbing systems.

11. Conclusions

1. The 1993 CoAxial eruption on the Juan de Fuca Ridge is the third well-documented eruption to occur on this segment since 1981. These closely spaced events probably released decades of accumulated stress along this segment.
2. These three eruptions were generated by dike injections from within the CoAxial segment. The alternate hypothesis that the 1993 dike propagated from Axial Volcano appears unlikely, both because the Sr isotopes of the most recent extrusives from Axial Volcano and the CoAxial segment are different and because the surface manifestations of the 1993 dike at the Floc and Flow sites (short-term hydrothermal venting along dike-related structures) clearly line up along the axis of the CoAxial segment.
3. The epicenters from the early, southern part of the 1993 *T* wave swarm must either be systematically biased to the west or were related to faulting along the western fault block ridge induced by the dike intrusion on-axis.
4. On the other hand, the 1993 lava flow and the along-axis extent of intrusion-related venting at the Flow site coincide very well with the diameter of the cluster of *T* wave epicenters that occurred during the later, northern part of the seismic swarm.
5. The venting at the Floc site occurred along a pre-existing, 5- to 6-km-long fissure system between about 46°16'N and 46°19.5'N. This fissure system did not produce eruptions during the 1993 event, but sheet flows had been erupted from the system in at least two locations in the recent past.
6. The fact that hydrothermal activity lasted 1–2 years longer at the Floc site than at the Flow site means that the Floc site had a larger source of heat to mine, probably due to the 1993 dike being wider and/or extending deeper beneath the site.
7. The Source site was apparently a preexisting high-temperature hydrothermal system and was unaffected by the 1993 dike intrusion.
8. The source area of the dike(s) that fed the 1993 eruption on the CoAxial segment (and possibly the two 1981–91 eruptions) appears to be located somewhere between the Source and Floc sites (~46°12'N), the latitude at which the *T* wave swarm started.
9. The three diking events that occurred along the CoAxial segment between 1981 and 1993 must have relieved a significant amount of strain along at least a portion of the segment and the lack of any more events since 1991 makes a comparison to the behavior of Icelandic central volcanos tempting.
10. The available observations of the patterns of extrusion and hydrothermal cooling and of the geochemistry of the lavas and vent fluids venting for these 1981–1993 CoAxial eruptions are consistent with that predicted from a dike having a significant lateral component of injection.

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