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Initial results of the rapid response to the 1993 CoAxial event: Relationships between hydrothermal and volcanic processes

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Abstract. Between June 26 and July 10, 1993, swarms of "T-wave" events occurred over a 40-km portion of the CoAxial segment on the northern Juan de Fuca Ridge. A rapid response utilizing a CTD/rosette/chemical scanner and a remotely operated vehicle occurred in the month following the T-wave swarms. The pattern of T-wave events and water-column anomalies (including several event plumes) are remarkably coincident. The only known eruptive area is at the northern swarm area, where a very fresh pillow lava ridge was discovered, mapped, and sampled with the remotely operated vehicle ROPOS. A vent area about 22 km south of the lava flow was emitting large quantities of bacterially generated floccular material. The temporal pattern of T-wave events and the coincidence between the T-wave swarms, the young lava flows, and hydrothermal plumes suggests that there is a close analogy between this activity and lateral dike injections such as have been closely monitored at Icelandic central volcanoes.

Background

On June 26, 1993, the first of several swarms of seismic events accompanied by a low frequency background signal began near 46°15'N, 129°53'W on the northern portion of the Juan de Fuca Ridge. Although undetected by continental seismometers, the water-borne tertiary waves, or "T-waves," were detected by a just-implemented realtime monitoring system that analyzes signals from the U.S. Navy's SOSUS hydrophone arrays [*Fox et al.*, this issue; *Dziak et al.*, this issue]. Over the next 2 days, the seismicity migrated northward as far as ~46°36'N within the axial valley of the spreading center and was mostly localized at the northern end for the next 3 weeks [*Fox et al., Dziak et al., Schreiner et al.*, all in this issue]. Within days of the event detection, CTD casts conducted by the Canadian research vessel *Tully* revealed significant hydrothermal plumes centered at depths ranging from 200 to 700 meters above the seafloor over the axial valley. On July 8, the NOAA Ship *Discoverer* left Seattle carrying a CTD/Rosette, the PMEL SUAVE chemical scanner, a Sea Beam sonar system, and the ROPOS, a 5000-m HYSUB remotely operated vehicle [*Embley and Franklin*, 1993].

Description of CoAxial Segment

The swarms of T-wave events occurred along an 80-km ridge segment offsetting (in a right-stepping sense) the northern rift zone of Axial Volcano from the Cobb Segment to the north (Figure 1). This previously unnamed segment is henceforth called CoAxial Segment because of its geographic relationship to Axial Volcano. The shoalest portion (2050 m) of its neovolcanic zone occurs between 46°03'N and 46°15'N along a constructional ridge bisecting the southern portion of its 9-km-wide axial valley. The neovolcanic zone is not topographically well-defined along its northern portion, but appears to follow a diffuse series of isolated volcanic hills, ridges, and shallow depressions. The crest of the neovolcanic zone deepens by more than 350 m from south to north.

Hydrothermal Plumes-Initial Observations

The *Discoverer* arrived at the CoAxial Segment on the evening of July 9th. Analysis of the *Tully* data and continued analysis and locations of the T-wave data by that time indicated that: (1) all the later T-wave events were concentrated in the center of the northern CoAxial Axial Valley (Figure 1); and (2) deep currents were carrying plumes in an easterly direction. After conducting a CTD cast to confirm that the plumes were still active, the CTD/rosette package was "tow-yowed" (i.e., the CTD package is cycled vertically in a saw-toothed pattern as it is towed through the water) from 46°36'N to 46°08'N along a N200°E line about 1 km east of the centerline of the Axial Valley (Figure 2). Detailed hydrographic and chemical results from this and subsequent tows and casts are discussed in *Baker et al., Lupton et al.*, and *Massoth et al.* in this issue. Two kinds of plumes were mapped—a lower plume that was 150–200 m above the seafloor, and several upper plumes that were up to 800 m above the seafloor. In the early July tow-yo, the lower plumes extended for 39 km along the axis from 46°34'N to 46°14'N (approximately the latitudinal extent of the T-wave activity) and were characterized by temperature anomalies as high as 0.07°C (Figure 2). The two upper plumes (EP2 and EP3, Figure 2), which were well-defined both by temperature and light attenuation anomalies, were present for about 17 km along axis and were approximately centered above the northern T-phase swarm. Their rise height (up to 800 m), temperature distribution (max. anomaly of .20°C), chemistry [*Massoth et al.*, this issue; *Lupton et al.*, this issue] and ephemeral nature (they were no longer found over the axis 2 weeks later) indicate that they are event plumes [*Baker*, 1994; *Baker et al.*, this issue].

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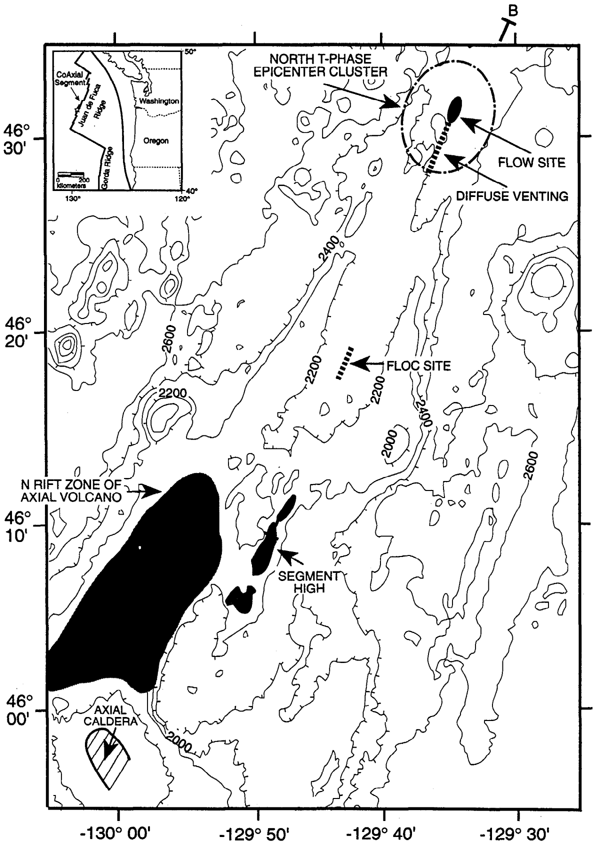

Figure 1. Simplified Sea Beam bathymetry of CoAxial Segment. A-B shows endpoints of CTD tow-yo profile shown in Figure 2. Thick dashed line south of lava flow site is southward extend of venting seen on ROPOS dive R221. Large stippled area shows limits of lave flows from north rift zone of Axial Volcano as interpreted from Sea Beam bathymetry and Sea MARC II sidescan sonar [*Davis and Currie,* 1993]. Stippled areas labelled Segment High show location of shoalest portion of CoAxial neovolcanic zone. Inset shows location of CoAxial Segment on Juan de Fuca Ridge.

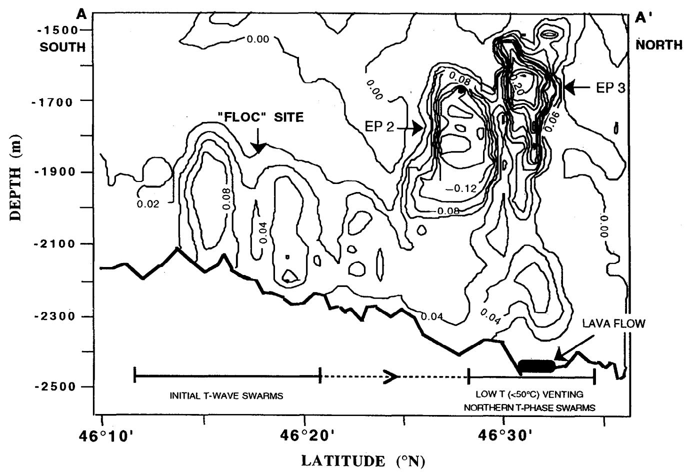

Figure 2. Along-axis temperature anomaly (see *Baker et al.* [this issue] for details) from CTD tow-yo along the CoAxial axial valley. EP2 and EP3 are terminology of *Baker et al.* [this issue]. Location shown in Figure 1. Latitudinal range of major T-wave swarms and location of lava flow are shown below.

Event plumes have been hypothesized to result from the expulsion of hydrothermal fluids due to a rapid permeability increase such as that induced by dike injections [*Baker et al.*, 1987; *Lowell and Germanovich*, 1994].

Seafloor Observations from ROPOS

Because of the spatial coincidence of the northern T-wave swarms and the EP2 and EP3 event plumes (Figure 2), a concentrated effort was undertaken with ROPOS to locate, map, and sample recent eruptive areas and/or hydrothermal systems at the site. The first dive (R219) traversed the valley floor from east to west and encountered sediment-free, glassy lava on the west-facing slope of a ridge just north of a small, older volcano (Cage Volcano) (Figure 3, bottom left). A slightly older flow that was determined from Sea Beam resurveys to have erupted between 1982 and 1991 was encountered about 700 m east of this ridge [*Chadwick et al.*, this issue]. Basalt samples recovered by ROPOS from the new flow are iridescent, glassy, lobate-to-pillowed flows with upper glass selvages up to 2.5 cm thick (Figure 3, bottom left). Subsequent video traverses and sampling (Dives R219, R221 and R234) revealed fresh lava in a band about 2.5 km long, oriented in a 020° direction, and up to 300 m wide (Figure 3). Up to a 50-m-wide zone centered over the crest was venting warm water (up to 51°C) through the interstices of the pristine, unfractured lava flows (Figure 3, bottom right). The young lava flow was devoid of sessile organisms, whereas adjacent, older lavas hosted many non-vent macro-organisms. The diffuse venting was nearly continuous along the axis of the young lava flow and ended abruptly at its northern termination. Initial analyses of vent fluid samples from the ROPOS dives indicate the presence of dissolved Mn and Fe at concentrations of >50 μmol/kg [see *Massoth et al.*, this issue], depleted Mg, elevated Ca, Si, and Li concentrations, and undetectable H_2S (<1 μmol/kg). These measured properties are consistent with subseafloor dilution of a higher temperature endmember (>150°C). SEM-EDS analyses of the yellow-orange precipitates coating portions of the flow (Figure 3) reveal the presence of chlorite and kaolinite, which form from water-rock reactions of 250°C and above. This also suggests that, at least initially, vent fluids emanating from the lavas had formed at higher temperatures.

Traverses made during ROPOS Dive 221 showed that hydrothermal venting continued at least 4 km south of the lava flow (Figure 1). The venting usually occurred along fractures within a 20- to 40-m-wide graben that cut through older lavas and was presumably formed or enlarged during the eruptive event. We speculate that the vent fluids are exiting from a continuation of the same graben/fracture system beneath the lava flow, but that the permeable pillow lavas allow the vent fluids to diffuse the vent fluids over a broader zone.

The purpose of the final ROPOS dive (HYS235) at 46°19.4'N (Figure 1) was to investigate an intense near-bottom plume signal centered at about 46°19'N (Figure 1). At about 200 m above the seafloor, ROPOS began passing through an intense floccular cloud composed of irregularly shaped clumps of whitish material. The floc, which is bacterial in origin (Juniper, personal communication), was forming small drifts on the seafloor hundreds of meters west of the center of the axial

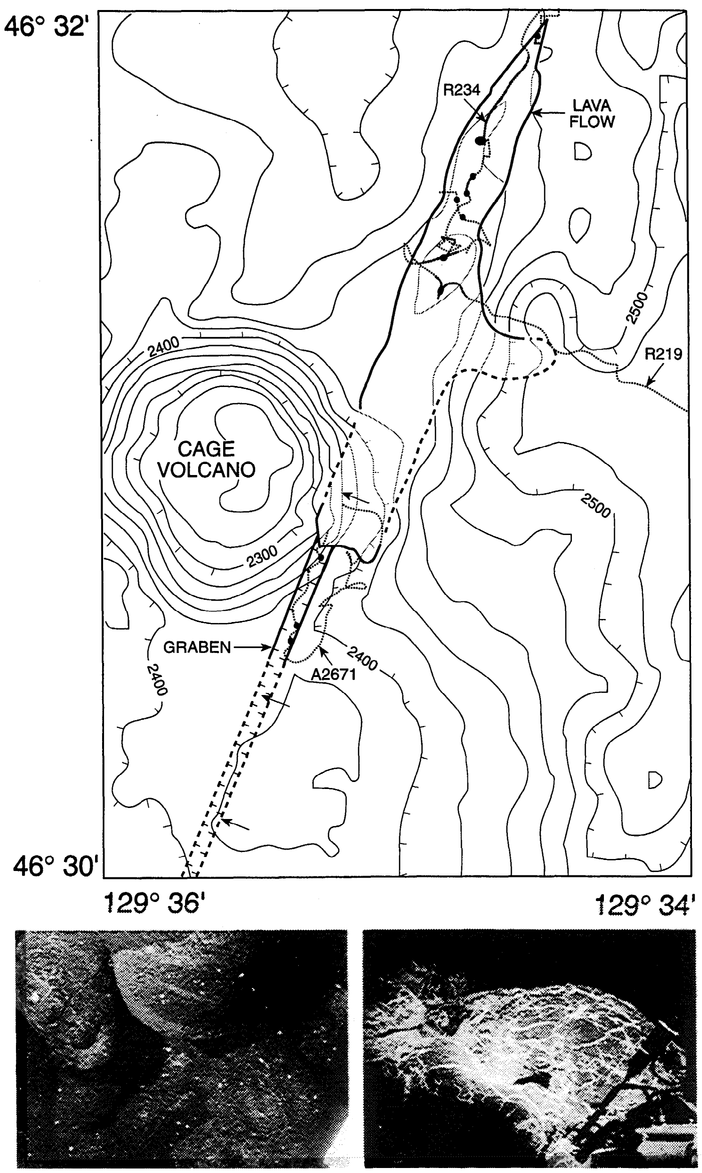

Figure 3. Top: Sea Beam bathymetry of lave flow site (see Figure 1 for location). Contour interval is 20 m. Outline of lava flow determined from Sea Beam difference anomaly and the video imagery of the ROPOS remotely operated vehicle and an *Alvin* dive (tracks shown by light lines). Solid-filled areas are locations of active hydrothermal venting and labelless arrows show approximate location of venting found during bottom traverse made on R221, which was not transponder navigated. Dark gray highlighted tracks indicated presence of hydrothermal precipitate. Bottom: Left: Pristine pillow lavas of new lava flow showing delicate outer skin of glass. Right: Lobate lavas at crest of new flow with hydrothermal precipitates.

valley. Subsequent investigations with the Scripps DEEPTOW vehicle [*Spiess and Hildebrand*, 1993] and the *Alvin* revealed a diffuse flow of floc-rich water exiting from fractures in older basalt centered around 46°18'N; 129°42.5'W (Delaney and others, unpublished data, 1993) (Figure 1).

Discussion and Speculation

The pattern of T-wave events, water-column anomalies, fresh lava, and seafloor vent sites is remarkably coincident. Hydrothermal plume activity was present over the length of the segment that was affected by the T-phase activity, and the EP2 and EP3 event plumes were hovering over the fresh, vigorously venting lava flow. The propagation of seismicity down rift [*Dziak et al.*, this issue], its correlation with the hydrothermal plumes, and the striking correspondence between the eruption and the northern swarm area are all consistent with the effects of lateral dike injection events commonly monitored on Hawaiian and Icelandic volcanoes. In the Icelandic events [e.g., *Bjornsson et al.*, 1979], an injection of magma into the upper crust beneath the central volcano triggers an along-axis dike propagation of up to 80 km along the rift zone, which is often accompanied by eruptions and rapid changes in geothermal activity at the surface. The initial southern T-wave swarms on the CoAxial segment could represent the initial injection from below, with subsequent rapid migration of T-phase activity following the path of dike propagation.

The pattern of T-waves observed at the CoAxial segment also matches the proposed scenario for the mid-1980s events at the southern Juan de Fuca Ridge, where megaplumes were probably associated with an eruption of pillow mounds [*Embley and Chadwick*, 1994; *Chadwick et al.*, 1991, 1994]. The injection at the northern Cleft Segment produced eruptions over a 17-km line, with the largest mound at the northern end. The CoAxial event appears to follow a similar pattern, with the largest (and probably the only) eruption near the northern end of the injection path. This suggests a hydraulic control on the eruption, i.e., in both cases, the longest sustained eruption occurred at the point farthest "downhill" from the source. It is also interesting to note that the CoAxial eruption occurred at a place where the depth suddenly increased slightly (just north of Cage Volcano), allowing the shallowing dike to break the surface. An alternate model to the lateral dike injection is that the sudden release of stress along the segment was accompanied by magma injection from a deep source along its entire length, with eruptions taking place where the vertical dike reaches the surface. Although the existing data from the CoAxial event does not uniquely choose between these hypotheses, we believe that the data are more consistent with the lateral dike injection model. First, the T-phase migration rate is very similar to proven cases of subaerial lateral dike injection [*Dziak et al.*, this issue]. Second, the rapid falloff of heat flux over the year following the eruption (*Alvin* dives made in July 1994 revealed a significant diminishment in venting over the lava flow) is consistent with the cooling of a shallow-rooted intrusion and lava flow in contrast to a deeper, more extensive crustal magma lens. This scenario is consistent with that proposed for the North Cleft intrusion/eruption event(s). In that case, hydrothermal venting along a 17-km line of lava mounds had shut off within 8 years (and probably much earlier) [*Embley and Chadwick*, 1994].

It is clear that the CoAxial Event was a short-lived crustal accretion event. Since rifting/intrusion events will result in both a transfer of heat and mass into the upper crust, and a sudden increase in permeability, the "event" should have a finite lifetime which can be monitored. Little is known of the spatial and temporal distribution of crustal accretion events, but, if this phenomenon is similar to other natural phenomena, there should be a negative correlation between size and frequency, i.e., the CoAxial-size events would be fairly common. The now-realized ability to remotely detect mid-ocean ridge volcanic events will provide ideal opportunities to conduct geophysical, hydrothermal (both water-column and seafloor), geological, and biological time series of a crustal accretion event where time zero is known.

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