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1998 Eruption of Axial Volcano: Multibeam anomalies and seafloor observations

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Abstract. Lava flows erupted during the January/February 1998 seismic swarm at Axial Volcano on the Juan de Fuca Ridge have been identified by differencing of pre- and post-event multibeam bathymetric surveys and by seafloor observations. A sheet flow more than 3 km in length and 500-800 m wide erupted from the uppermost south rift is the site of a robust hydrothermal system. 1998 lavas occur over about 9 km of the upper south rift zone, or about 20% of the along-axis length of the seismicity event (~50 km). The estimated volume of lava erupted is 18-76 x 10^6 m^3 for the extrusion and 100-150 x 10^6 m^3 for the intrusion. The total volume is consistent with the volume from modeling of seafloor strain measurements recorded during the event.

Introduction

An intense swarm of earthquakes began on 28 January, 1998 at the summit of Axial Volcano on the central Juan de Fuca Ridge (JDFR) at 46°55'N; 130°00'W [*Dziak and Fox*, this issue] (Fig. 1). Within 6 hours of initiation, the seismicity began to migrate down the south rift zone, and by the second day, the seismicity had moved 50 km to the end of the rift zone. Over the next 10 days, swarm activity continued at the southernmost zone and at the summit. Initial CTD (conductivity, temperature, depth) casts in February 1998 measured large increases in the heat and chemical flux emitted from the summit area [*Baker et al.*, this issue], implying that an eruption had taken place; this eruption was later confirmed by imaging and sampling of the seafloor in July-September 1998. Some of the questions raised by the 1998 event were: (1) what is the spatial pattern of the eruption and associated hydrothermal activity and how does it compare to that of previously documented accretion events?; (2) How does the spatial pattern of extrusion compare to the seismicity?; and (3) what is the morphology of the eruption (sheet flow vs. pillow lavas) along the path of the dike injection?

Background

Axial Volcano rises more than 700 meters above the adjacent ridge crest at 46°N, 130°W, where the Cobb-Eickelberg hotspot volcano chain intersects the JDFR (Fig. 1)[*Delaney et al.*, 1981]. Multibeam bathymetric maps show that this volcano is an elongate feature characterized by NE-SW-trending rift zones and a summit rising to less than 1500 meters capped by an 8 x 3-km horseshoe-shaped caldera. Extensive hydrothermal activity and young lavas are found on the shallow portions of the rift zones within and near the summit caldera [*Embley et al.*, 1990]. Frequent earthquake swarms since 1991 [*Dziak and Fox*, in press] and a caldera deflation event recorded by a bottom pressure gauge in 1988 [*Fox*, 1990] indicated that Axial Volcano was in an "active" stage leading up to the 1998 seismicity episode.

Following the 1998 seismicity event, there were several opportunities to investigate the site to determine the extent and nature of extrusions. A quantitative bathymetric comparison technique [*Fox et al.*, 1992] was used to compare the initial multibeam bathymetric survey made in 1981 (and additional ones from 1991 and 1996) with a dedicated Simrad EM300 survey collected in May 1998, several months after the event. *Alvin* made several dives in the caldera in July 1998, and an expedition using the *ROPOS* remotely operated vehicle conducted an extensive mapping and sampling campaign at the site in August-September 1998.

Multibeam Sonar Comparison Results

There were three multibeam sonar surveys over Axial Volcano conducted prior to the early 1998 eruption. The original 1981 survey by the NOAA Ship *Surveyor* covered the rift zones and summit of Axial with nearly 100% coverage. The other data sets were a 1991 survey conducted by the NOAA Ship *Discoverer* and a 1996 Hydrosweep survey conducted by the R/V *Sonne* that covered the summit and the upper portions of the rift zones. After gridding all the data sets at 50 m, we applied the grid-differencing technique described by *Fox et al.* [1992] to process the data and produce difference maps between the post-event 1998 EM300 survey and the older surveys (1981-98, 1991-1998, and 1996-1998). The grid-differencing technique was applied to the summit and south rift zone affected by the earthquake swarms (Fig. 1). The only significant positive depth change anomalies were found on the south rift zone at 45°52'N and on the summit at 45°54.5'N. The northern of the two anomalies has a maximum depth change of 13 meters, which is near the 5-15-m

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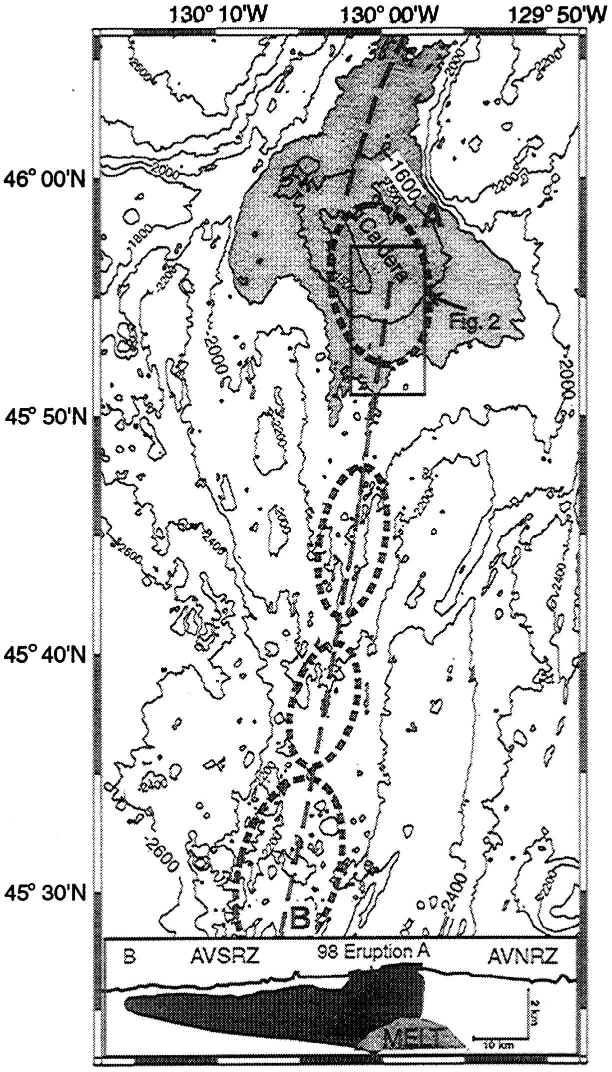

Fig. 1: Sea Beam bathymetry (200-m contours) of the summit and south rift zone of Axial Volcano. Light gray encloses area less than 1800 m. Dashed ovals represent main clusters of T-wave epicenters [*Dziak and Fox*, this issue] from 1998 event. Dashed line represents approximate axis of neovolcanic zone. A-B are endpoints of schematic cross-section (bottom). Inset at bottom is schematic cross-section of dike and eruptions. Box is location of Figure 2.

detection limit of the technique [*Fox et al.*, 1992]. It is only clearly seen in the 1981-98 comparison because of problems with the data coverage and quality of the other two surveys. The southern anomaly is larger, with a maximum change of 26 meters. It was found in the 1996-1998 comparison (as well as the others) and thus is constrained to have formed during that time period.

Seafloor Mapping and Observations

The boundaries of the northernmost portion of the new lava flow at 45°55-57'N were mapped (Fig. 3) by submersible and ROV in July-September 1998. The lava flow in this area has a thickness of at least 4-6 meters (measured at the edges of drain-back pits), below the resolution of the multibeam depth difference technique, and is 500-800 m in width. The western side of the northern depth difference anomaly was reached on *Alvin* dive 3247 (Fig. 3, 'a'), but the dive ended before the eastern side was crossed. The northernmost area of new lava appears to have erupted along a fissure system at least 3 km long in the form of a drained-out sheet flow and is superimposed on older sheet-flow eruptions. The very recent age of this lava was verified by the partial burial of a seismometer/pressure gauge (Fig. 3, 'b') and a mooring line (Fig. 3, 'c') deployed in 1997 and [*Embley and Baker*, 1999].

Camera tows and submersible dives in the 1980s and 1990s found numerous vent communities over several kilometers along the uppermost south rift near the eastern wall of the caldera (Fig. 3). The *ROPOS* dives revealed dramatic changes in these hydrothermal systems on the southeast part of the caldera [*Embley and Baker*, 1999], including: (1) the partial or total burial of pre-existing mature vent communities (Fig. 3, 'd' and 'e'); (2) nascent vent communities on the new lava either uncolonized by tubeworms or undergoing initial stages of colonization; and (3) a subsurface bacterial bloom manifested by "snowblower" vents [*Delaney et al., 1998*].

The southern Sea Beam difference anomaly centered at 45°52'N was investigated during *ROPOS* dive 465. The eastern and western boundaries of the anomaly very closely matched the contacts between black, glassy lavas and the older, sedimented lavas. The lavas at this site were primarily pillows and lobate morphologies. The eruption apparently occurred at the crest of the rift zone, flowed down its eastern slope, and accumulated in a thick pile. Probing the lava interstices with a chemical scanner and CTD (G. Massoth, pers. commun.) mounted on *ROPOS* did not detect any thermal or chemical anomaly, so it appears that either hydrothermal cooling proceeded much more rapidly here than at the caldera site, or that this was actually an older lava erupted between 1996 and 1998. However, there were no significant earthquake swarms in this area prior to 1998, so it is highly likely that the eruption occurred during the 1998 seismicity event.

The extent of new lava between the summit zone and the 45°52'N anomaly is not yet clearly defined. However, no multibeam depth difference anomalies were found here, so any lava in this region would probably average less than the 5 m detection limit. To estimate the volume of lava erupted we start with the quantified volumes of the northern and southern multibeam depth changes, 3.4 x 10^6 m^3 and 6.2 x 10^6 m^3 , respectively. To these volumes, the parts of the 1998 lava flows that are undetected by the multibeam comparison are added based on their mapped area and an assumed average thickness of 2-10 m (7.6 and 0.7 x 10^6 m^3, respectively), yielding a combined volume estimate of 18-50 x 10^6 m^3. On the other hand, if we assume the two anomalies are connected by a narrow band (~500 m wide) of 2-10 m thick lava with a volume of 5-26 x 10^6 m^3, the total volume estimate increases to 23-76 x 10^6 m^3.

The total estimated volume of extrusion (18-76 x 10^6 m^3) plus the volume of magma in the dike (100-150 x 10^6 m^3)[*Chadwick et al.*, in press] is 118-226 x 10^6 m^3. This is consistent with the magma volume of 207 x 10^6 m^3 calculated from modeling the strain measurements made during the event [*Chadwick et al.*, this issue].

Discussion

The 1998 dike injection and eruption of Axial Volcano was probably the most significant magmatic event on the Juan de Fuca Ridge in the past decade. The earthquakes occurred

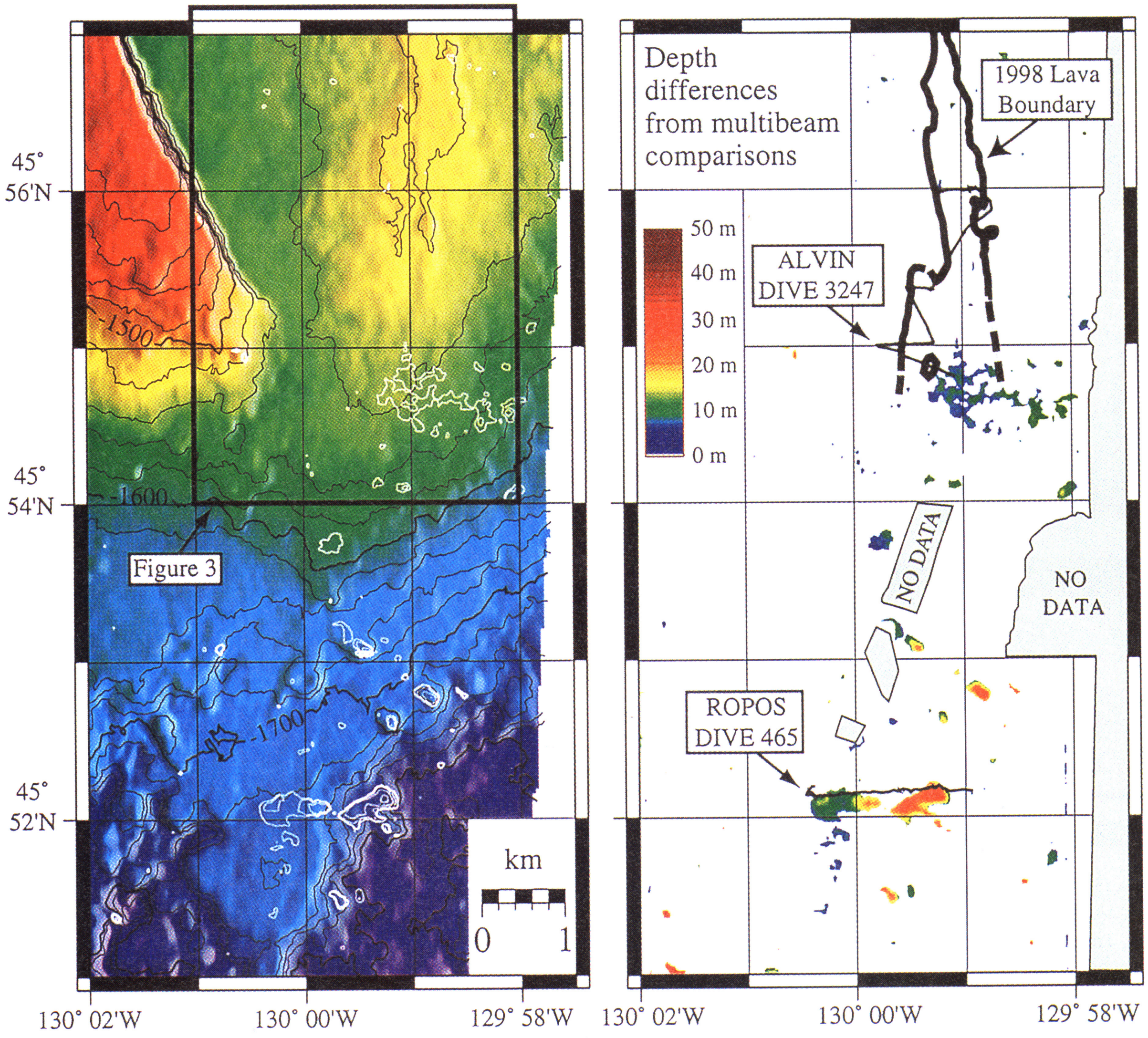

Fig: 2: Left: May 1998 EM300 multibeam bathymetry and difference anomalies (white lines are 5-m contours) for the northern (centered at 45°54.7'N) and southern (centered at 45°52.1'N) areas. Right: Multibeam difference anomalies for same areas. Shown are the 1981-1998 anomalies for the northern area and the 1991-1998 anomalies for the southern area. Box is location of Figure 3.

along a 50 km trendline extending between the summit of Axial Volcano and the southernmost end of the south rift zone of the volcano. The 1998 summit eruption and concomitant hydrothermal activity is roughly coincident with the most recent volcanism and venting mapped prior to 1998. This long-term hydrothermalism in association with young lavas is consistent with the presence of a shallow melt zone beneath the summit, the likely source of the 1998 dike. Eruptions from the 1998 dike were found along a 9 km zone extending south from the caldera, although the seismicity extended for more than 40 km further south. The persistence of seismicity at the extreme southern end of the rift zone is consistent with the pattern observed for the 1993 CoAxial event [*Dziak et al.*, 1995], which produced an eruption at the distal site. However, *Dziak and Fox* [this issue] concluded from a study of the rise times of the hydroacoustic signal envelopes of the 1998 events that the southernmost end of the Axial south rift did not erupt. Also, neither a multibeam difference anomaly nor a hydrothermal plume (E. T. Baker and J. Cowen, unpub. data) were found here, so it seems unlikely that an eruption occurred here. This (apparent) lack of an eruption at the distal end of the seismicity trend is surprising. Both the CoAxial segment [*Embley et al.*, 1995] and the Cleft segment diking events [*Embley et al.*, 1994] events produced all or most of their extrusives at or near the end of the segment, a pattern that may have been influenced by the along-axis topographic gradient, a significant factor in driving lateral dike injection [*Fialko and Rubin*, 1998]. However, if the seismicity pattern observed during the 1998 event does represent a lateral dike injection, it occurred under a larger lateral topographic gradient than is present either at the Cleft or the CoAxial segments (by a factor of 2 or more). However, an equally important factor is the magmatic pressure, and the dike would not have erupted if this dropped below some critical limit. For example, the summit eruption may have relieved some of the excess magmatic pressure after the initial injection, so that the pressure at the distal end was never enough to break the surface in an eruption.

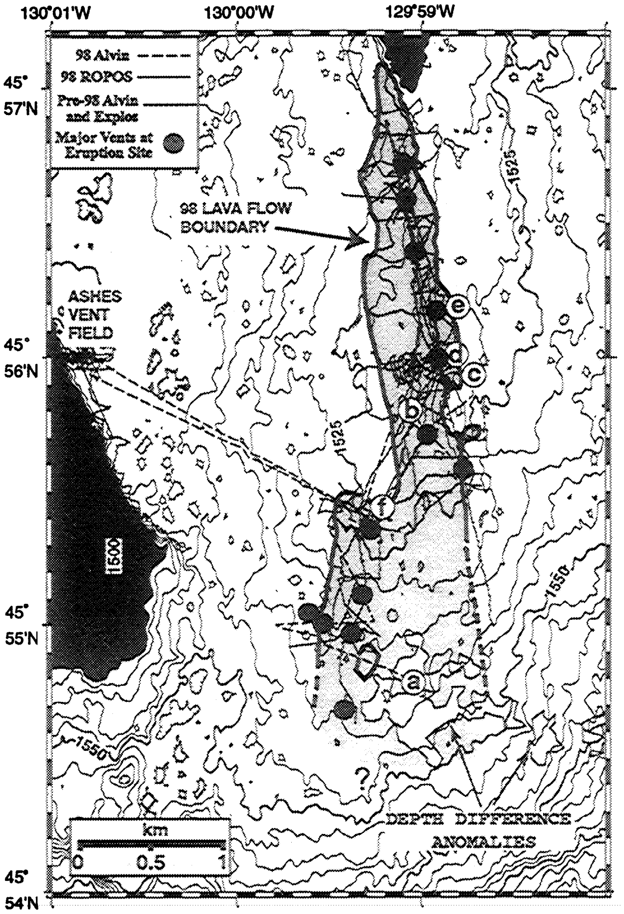

Fig. 3: EM300 multibeam bathymetric map of southern portion of caldera showing caldera walls (dark shading), 1998 lava flow (medium gray shading), and multibeam difference anomaly (light gray shading). Major vents (filled circles), tracklines of *ROPOS*, *Alvin*, and 1996 towed camera tracks are shown. Small letters refer to sites discussed in text.

The dike erupted sheet flows at the summit and primarily pillow lavas further downrift. The 1993 CoAxial dike erupted a pillow mound at the end of the segment and extensive new hydrothermal venting but no eruption over the presumed magma source [*Embley et al.*, 1995]. The mid-1980s dike injection(s) at the Cleft segment erupted a sheet flow at the shallow end in a zone of long-lived hydrothermal activity (over the presumed magma source) and a chain of pillow mounds extending north to the end of the segment [*Embley and Chadwick*, 1994]. In any case, the overall pattern of a rapidly cooling pillow eruption downrift from a longer-lasting, higher temperature hydrothermal system and associated high-effusion rate lava flow is similar to both the Cleft and the CoAxial patterns and is consistent with a lateral dike injection model [*Embley and Chadwick*, 1994].

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