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Evidence for deformation associated with the 1998 eruption of Axial Volcano, Juan de Fuca Ridge, from acoustic extensometer measurements

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Abstract. Acoustic extensometer instruments capable of making precise daily measurements of horizontal distance were deployed across the north rift zone of Axial Volcano in June 1996 and were in place when a submarine eruption began on Axial's south rift zone in January 1998. The instruments recorded a gradual 9-cm extension over a 405-m baseline leading up to the eruption, and then an abrupt, 4-cm contraction at the time of the eruption. An elastic point-source deformation model shows that deflation of Axial's summit can explain both the 4-cm distance decrease at the extensometer array and a 3.2-m subsidence measured by another instrument in the caldera, if the pressure source is located at a depth of 3.8 km below the center of the caldera. The 9-cm distance increase may represent pre-eruption spreading across the rift zone.

1. Introduction

The surfaces of active volcanoes deform in response to subsurface movements of magma. One of the techniques used in volcano deformation monitoring on land is the repeated precise measurement of horizontal distances between fixed points. Such measurements have been used to detect magma movements and quantify the geometry of buried magma bodies [*Dvorak and Dzurisin*, 1997]. In the last decade, there has been an increasing effort to adapt volcano monitoring technologies to the deep ocean floor to increase our understanding of how the mid-ocean ridges behave as volcanic systems and how they might differ from those on land.

In June 1996, five acoustic extensometer instruments were deployed across the north rift zone of Axial Volcano (Figure 1a), an active hotspot seamount with a large summit caldera on the Juan de Fuca Ridge [*Embley et al.*, 1990]. Axial is believed to behave somewhat like Kilauea Volcano, Hawaii, in that magma accumulates and is stored within a summit reservoir beneath the caldera and periodically is injected laterally into the rift zones [*Embley et al.*, 1990]. The extensometers were deployed at a site 7 km from the physical center of the caldera (Figures 1a–c). In January 1998, while the instruments were still deployed and recording data, a dike intrusion and volcanic eruption occurred at Axial along the south rift zone [*Dziak and Fox*, this issue; *Embley et al.*, this issue]. In this paper, we report on the acoustic extensometer results, the first horizontal distance measurements made in the vicinity of a submarine eruption on the mid-ocean ridge.

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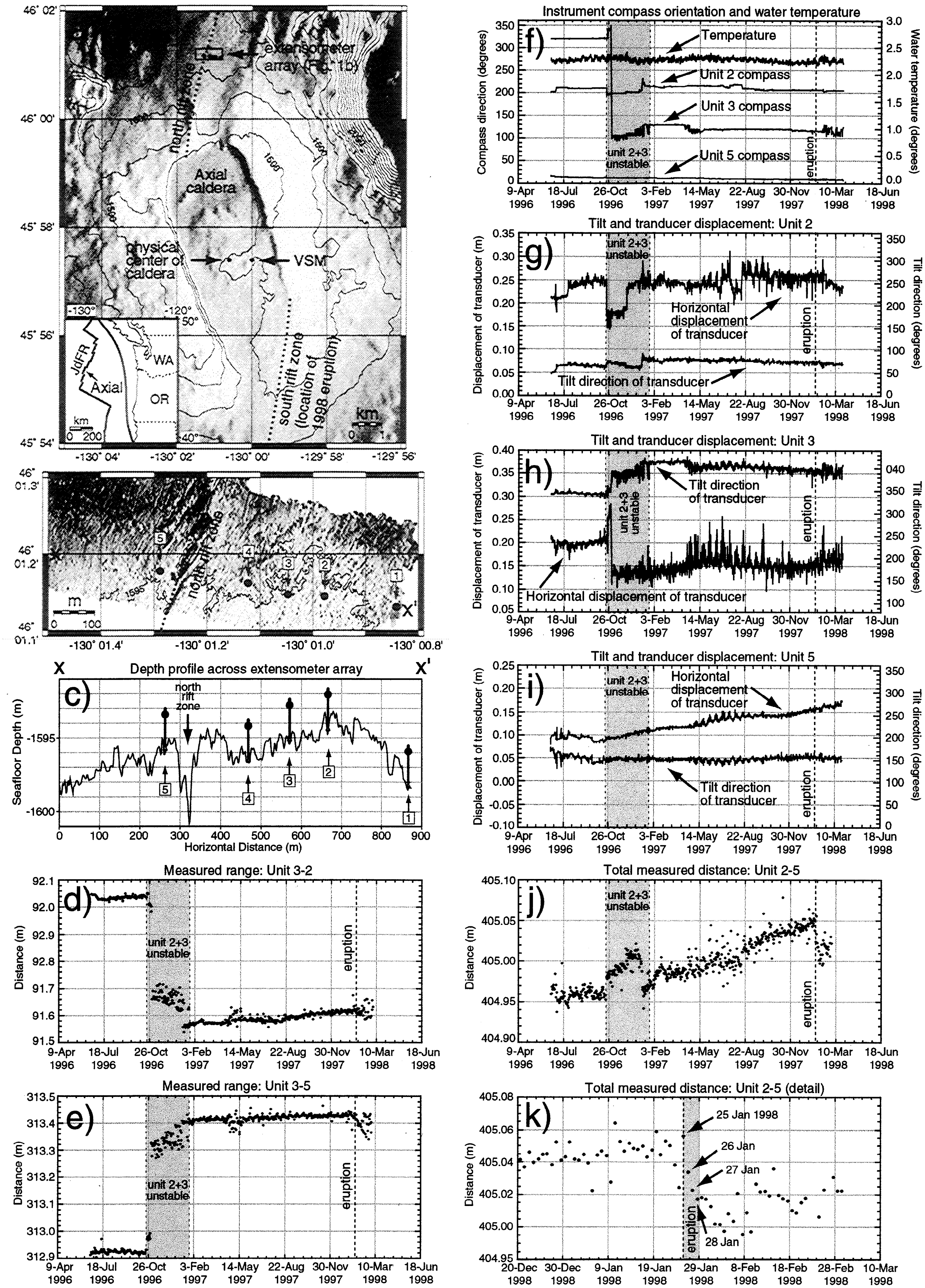
2. Instrument Design and Results

Methods commonly used to make precise horizontal distance measurements on land (GPS, lasers, etc.) are generally impossible in the deep ocean. The acoustic extensometers measure distances from the round-trip travel time of acoustic pulses between pairs of instruments separated by 100–200 m. In order to span larger cumulative distances, multiple instruments are deployed along a straight line in an array, oriented perpendicular to the spreading axis (Figures 1b-c).

The instruments that were deployed at Axial Volcano are prototypes of a more advanced system currently being developed. The prototype instruments [*Chadwick et al.*, 1995] consist of a conformable monopod anchor, a narrow, 3-m tall pressure case for batteries and electronics with an acoustic transducer at the top, and weigh ~20 pounds in water. This design was chosen to allow the instruments to be deployed in relatively rough seafloor terrain while keeping the transducer well above local microtopography, since the instruments require acoustic line-of-sight to their neighbors. A ball of syntactic foam flotation is attached to the top of the pressure case to keep the instruments upright. Although this design allows the instruments to sway slightly due to bottom currents, internal tiltmeters and a compass allow the ranges to be corrected as if the instruments were vertical. Each instrument measures the distance to its two nearest neighbors in both directions within the array once a day; in a line of 5 instruments, unit 3 will range to all the other 4 units. To make a range measurement, one instrument sends out a burst of five cycles at 50 kHz to one of its neighbors, which then replies with an identical burst (after a 2-second delay), and finally the first instrument records the round-trip travel time after it detects the reply. The clock-oscillator in each instrument measures the travel times to the nearest 500 nanoseconds, which corresponds to a distance resolution of 0.4 mm for each range. However, our effective resolution between each pair is about ±1 cm, due to limitations in the tilt and compass sensors (discovered in hindsight).

We had intended to deploy the instruments in June 1996 with the ROPOS remotely operated vehicle (ROV), to carefully pick bottom sites and to ensure acoustic line-of-sight, but the ROV was unusable at the last minute and we were forced to deploy them by simply dropping them from the surface. The instruments were recovered in September 1998 with ROPOS at the locations shown in Figures 1a–c. One of the five instruments (unit 4) failed, and another (unit 1) landed in a depression and did not have acoustic line-of-sight with the others, so only units 2, 3, and 5 were able to range to one another. The instruments were designed for 1-year deployments, but have enough battery power and physical memory for almost 2 years. The units recorded ranges from June 20, 1996 to March 2, 1998 (20.5 months), and recorded temperature, tilt, and compass data until March 26, 1998.


extensometer array (Fig. 1b)
north rift zone
Axial caldera
physical center of caldera
VSM
south rift zone (location of 1998 eruption)
JdFR
Axial
WA
OR
km
Instrument compass orientation and water temperature
f)
Temperature
Unit 2 compass
Unit 3 compass
Unit 5 compass
unit 2+3 unstable
eruption
Compass direction (degrees)
Water temperature (degrees)
Tilt and tranducer displacement: Unit 2
g)
Horizontal displacement of transducer
Tilt direction of transducer
Displacement of transducer (m)
Tilt direction (degrees)
Tilt and tranducer displacement: Unit 3
h)
Tilt and tranducer displacement: Unit 5
i)
Depth profile across extensometer array
c)
north rift zone
Seafloor Depth (m)
Horizontal Distance (m)
Measured range: Unit 3-2
d)
Distance (m)
Measured range: Unit 3-5
e)
Total measured distance: Unit 2-5
j)
Total measured distance: Unit 2-5 (detail)
k)
25 Jan 1998
26 Jan
27 Jan
28 Jan

The raw acoustic travel times are converted to ranges by calculating a sound speed, which is a function of salinity, depth, and temperature. Of these, temperature is the most variable and has the biggest influence, so the average temperature recorded by the two ranging units is used in the calculations, and the salinity and depth are assumed constant (salinity = 34.54 ppt and depth = 1600 m at this site). The effect of these three parameters on a 100-m range measurement (if uncorrected) would be: 3.0 mm for every 0.01°C of temperature change; 0.9 mm for every 0.01 ppt of salinity change; and 1.0 mm for every 1 m change in depth.

The acoustic ranges from unit 3 to units 2 and 5 (after temperature, tilt, and clock corrections) are shown in Figures 1d–e. The most obvious features in the measurements are two major offsets that appear in both ranges, beginning on October 23, 1996, and ending on January 21, 1997. These changes were not associated in time with any of the pre-1998 earthquake swarms detected at Axial (R. Dziak, personal communication). The offsets are such that the unit 3–5 range increased by about the same amount that the unit 3–2 range decreased (Figures 1d–e). At the same time as these range offsets, major changes were recorded in the compass direction, tilt magnitude, and tilt direction of units 3 and 2 (Figures 1f–i). We interpret that these changes were simply due to unit 3 physically moving, rather than any real ground deformation, because when the two range legs are added to show the total distance between units 2 and 5, the offsets almost disappear (Figure 1j). Indeed, unit 3 was recovered at the base of a small basalt pedestal, ~1 m wide and ~0.3 m high. We speculate that when unit 3 landed on the seafloor it set down on top of this pedestal, but part way through the deployment it fell off (toward unit 2) in two separate slips. During the time between these two slips the total distance ranges are offset from the trend established before and after, probably because unit 3's orientation was more variable, leading to higher than usual tilt/compass correction errors. After the second of the two slips, unit 3 became stable again on the bottom, and there is little net offset in the total distance ranges from the point before the first slip (Figure 1j). This episode shows that the tilt and compass sensors are good indicators of instrument instability and their records indicate that the instruments were stable for the remainder of the deployment (Figures 1f–i).

Besides these major offsets obviously due to instrument movement, there are two other features in the total distance data that may be related to the January 1998 eruption at Axial. The first is a long-term distance increase, gradually accumulating over the deployment and amounting to ~9 cm over the 405-m baseline by the time of the eruption (Figure 1j). The second is a short-term decrease in distance of ~4 cm (Figures 1j–k) that is associated in time with the eruption. Other sources of data help constrain the timing of events near the eruption onset. The T-wave data show that the earthquake swarm started at the summit of Axial at ~1133Z on January 25, 1998, the epicenters started to migrate down the south rift zone by ~1700Z on January 25 (interpreted as the intrusion of a dike), and the migration had ended by 1200Z on January 27 [*Dziak and Fox*, this issue]. Temperature records from moorings near the eruption site suggest that the eruption had started on the uppermost south rift zone by 1330Z on January 25 [*Baker et al.*, this issue]. A Volcanic System Monitor (VSM, Figure 1a), an instrument package with a precision pressure sensor, that was deployed near the center of the caldera, showed that the caldera floor subsided 3.2 m during the intrusion and eruption, beginning at 1500Z on January 25 and ending by 2400Z on January 30, although the subsidence was 90% complete by 2400Z on January 28 [*Fox*, this issue]. The acoustic extensometer distance measurements were made at ~1330Z each day, thus the measurement on January 25 was made just as the eruption was beginning and before the caldera had begun to subside. The short-term distance decrease of 4 cm accumulated progressively from January 25–28, the same time that subsidence was measured in the caldera (Figure 1k).

3. Modeling Results And Possible Implications

We interpret that this short-term distance decrease is real because there are no associated unusual temperature, tilt, or compass changes that might indicate sound velocity errors or instrument instability. The fact that the distance decrease takes place abruptly and within a few days after the onset of the eruption, and is coincident with other independently measured deformation, also lends credibility to the measurements. Clearly, no magma was intruded into the north rift zone at the time of the eruption (which would have caused extension across the extensometer baseline), consistent with the concentration of T-wave epicenters within the caldera and along the south rift zone [*Dziak and Fox*, this issue]. Instead, the short-term distance decrease may have been due to a general deflation of Axial Volcano as magma was drained from the summit reservoir and intruded into the south rift zone.

To test this idea, we used a simple elastic point-source model employed in many previous volcanic deformation studies [*Mogi*, 1958; *Dvorak and Dzurisin*, 1997]. The model relates vertical and horizontal surface displacements to the depth and volume change of a buried pressure source. This model shows that the length of the extensometer line would indeed decrease by 4 cm at the same time that the VSM subsided by 3.2 m, if we assume that the pressure source is centered below the physical center of the caldera at a depth of 3.8 km. Other model solutions consistent with the observed displacements are possible if different source locations and depths are chosen. For example, if the pressure source is moved 500 m north, the source depth decreases to 3.3 km, or if it is moved 500 m south, its depth increases to 4.3 km. We chose the center of the caldera for the location of the pressure source, because the caldera is the long-term structural and morphologic expression of previous deflation events, and because it seemed the simplest assumption. According to this preferred model, each extensometer instrument would have moved horizontally toward the caldera center by 68 cm (and subsided by 37 cm), and it is this inward radial displacement that caused the measured distance to decrease. The observed contractions are approximately proportional to the baseline lengths, as would be expected from the model. The maximum vertical subsidence would have been 3.4 m at the caldera center (0.8 km west of the VSM, Figure 1a). The volume change at

Figure 1. (a) Bathymetric map of Axial Volcano showing caldera and rift zones (VSM = Volcanic System Monitor instrument). (b) High-resolution bathymetry of the extensometer deployment site. Dots are instrument locations (unit numbers 1–5) and X and X′ are endpoints for profile in Figure 1c. (c) Depth profile across extensometer array, showing instrument locations. In Figures 1d–j, major divisions on x-axis are 100 days apart; 10 days in Figure 1k. (d) Measured range between units 3–2. (e) Measured range between units 3–5. (f) Compass orientation from units 2, 3, and 5, and water temperature from unit 3. (g–i) Tilt direction and horizontal displacement of the transducer for unit 2, 3, and 5, respectively. (j) Total distance measured between units 2–5 (the sum of ranges in Figures 1d and 1e). (k) Detail of Figure 1j showing contraction of total distance by 4 cm directly after the eruption onset.

the source is calculated by the model as 207×10^6 m^3, consistent with the sum of the estimated volume of lava erupted, 18–76 $\times 10^6$ m^3 [*Embley et al.*, this issue], plus the magma in the dike that intruded into the south rift zone, 100–150 $\times 10^6$ m^3 (or 118–226 $\times 10^6$ m^3, total). This rough estimate of the dike volume assumes a thickness of 1.0 m, a height of 2–3 km, and a length of 50 km (the length of the T-wave swarm [*Dziak and Fox*, this issue]). The model depth of the pressure source for the Axial eruption (3.8 km) is also consistent with previous modeling of deformation on basaltic volcanoes on land which have found magma reservoirs at ~2–4 km depth [*Dvorak and Dzurisin*, 1997], previous gravity surveys at Axial [*Hildebrand et al.*, 1990], and the maximum hypocentral depths of earthquakes beneath Axial caldera recorded after the eruption [*Sohn et al.*, this issue].

What is the implication of these model results for the long-term extension of 9 cm leading up to the eruption? If it were due to inflation from the same pressure source, the elastic model would predict an associated maximum uplift of 7.8 m at the center of the caldera over the 2-year deployment. The VSM instrument was deployed in Axial caldera on October 2, 1997, giving it only enough time to measure 1.7 m of this hypothetical inflation, but still well above the 20–50 cm/yr drift rate of its pressure sensor [*Fox*, this issue]. However, the VSM recorded no such uplift. Therefore, the 9-cm expansion recorded before the eruption is either, 1) real, but due to local deformation, such as rift zone widening instead of inflation of a sub-caldera reservoir, 2) due to instrument movement instead of ground deformation, or 3) due to some source of measurement error. Which of these is most probable?

The long-term distance increase does not appear to be due to instrument instability or tilt/compass correction errors because the tilt and compass signals are quite stable (except for the obvious period of movement discussed earlier). It is unlikely that the distance increase could be due to errors in data processing, because there are no errors that are cumulative; each distance measurement is computed independently of all others. The magnitude of changes in the variables that affect sound velocity (temperature, salinity, depth) that would be required to explain 9 cm of extension are too large to be plausible (1 ppt for salinity, for example). One potential source of error in the prototype extensometers is a "cycle slip," in which the incoming acoustic signal is sometimes detected on the second cycle of the pulse instead of the first, since the first cycle is smaller in amplitude than subsequent ones. This can occur at neither, one, or both instruments when a pair are ranging. At 50 kHz, each cycle slip adds 1.5 cm to a given range, or 3.0 cm at most. However, such an error should occur randomly and not accumulate linearly with time over a deployment. The internal clock in the extensometers has an accuracy of 1.5 ppm per year (based on years of experience with this same clock in other seafloor instruments), which would translate into 1.0 cm/yr of distance error over the 405-m baseline, in the worst case. However, because unit 4 failed and we lost its independent measurement of the unit 2–5 baseline, we cannot rule out the possibility that the clock in unit 3 had an anomalously high drift rate. Measurement of the clock frequencies after the next deployment will test this unlikely possibility. Therefore, until we gain more experience monitoring horizontal distances on the seafloor we will not know for sure, but at this point it seems possible that this long-term distance increase was real extension across the north rift zone preceding the eruption. If so, it means that magma may have been leaking into the rift zone during the months before the eruption, or alternatively modest pre-eruption summit inflation (comparable in magnitude to the drift rate of the VSM) was structurally accentuated across the rift and caused larger displacements there than would be predicted by the elastic point-source model. On the other hand, the extension across the unit 3–5 baseline is only half that measured on the shorter unit 3–2 baseline (Figures 1d–e), which is the opposite of what one would expect, perhaps indicating that the structural axis of the north rift zone is actually east of where we mapped it based on surface morphology (Figures 1b–c).

After servicing, the prototype extensometers (except unit 4) were redeployed at the same site on Axial's north rift zone, to be recovered in summer 1999. Many of the problems and ambiguities in this dataset that are inherent to the design of the prototype instruments will be avoided with our next-generation instruments, currently under development and testing. An array of these benchmark extensometers will be deployed at the Cleft segment of the Juan de Fuca Ridge in summer 1999, and we hope to deploy additional arrays on both the north and south rift zones of Axial Volcano within the next few years.

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