GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 2, PAGES 167-170, JANUARY 15, 1995

SeaBeam depth changes associated with recent lava flows, CoAxial segment, Juan de Fuca Ridge: Evidence for multiple eruptions between 1981–1993

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Abstract. After a swarm of earthquakes was detected on the CoAxial segment of the Juan de Fuca Ridge in June–July 1993, the area was resurveyed with SeaBeam multibeam sonar to search for depth changes associated with a submarine volcanic eruption. Quantitative comparison of the 1993 SeaBeam survey with surveys in 1981/82 and 1991 shows one area of seafloor depth change (up to 29 m) between 1991–93 exactly where a pristine lava flow was discovered. In addition, two other depth anomalies (up to 37 m and 20 m) are identified between 1981–91, evidence that other recent eruptions have occurred along this spreading ridge segment.

Introduction

The Juan de Fuca Ridge (JdFR) is a mid-ocean ridge about 400 km west of Washington and Oregon (Figure 1). Historically, the JdFR has been seismically quiet, but the detection threshold for earthquakes from land-based seismometers is about magnitude 4, above the level of most volcanic earthquakes [*Fox et al.*, 1994]. Recently, however, the National Oceanic and Atmospheric Administration (NOAA) has developed a new surveillance system that lowers the detection threshold to about magnitude 2, by monitoring for water-borne, acoustic T-waves generated by earthquakes [*Fox et al.*, 1994]. An unusual swarm of earthquakes was detected by this system beginning on June 26, 1993, along the CoAxial segment of the JdFR [*Dziak et al.*, this issue; *Fox et al.*, this issue]. The swarm migrated 60 km northward along the neovolcanic zone of the segment during the first 2 days and then became localized at the northern end for the following 2 weeks, suggesting that it might be associated with active dike intrusion and possibly seafloor volcanism [*Dziak et al.*, this issue]. An interdisciplinary response effort was quickly mounted to determine what effect this activity may have had on the seafloor and the overlying ocean [*Embley et al.*, this issue].

One of the response efforts was to resurvey the area of the earthquake swarm with SeaBeam multibeam sonar from the NOAA ship *Discoverer*. The purpose of this resurvey was to search for depth changes that may have occurred if new lava flows were erupted during the swarm. SeaBeam resurveys had previously documented depth changes associated with a volcanic eruption in the mid-1980s on the Cleft segment of the JdFR [*Fox et al.*, 1992; *Chadwick and Embley*, 1994]. The 1993 bathymetric survey extended from 46°06′ to 46°39′N along the ridge (Figure 1), and included the CoAxial segment and the adjacent north rift of Axial Volcano, since some of the T-wave epicenters were located between these overlapping ridge segments [*Dziak et al.*, this issue; *Fox et al.*, this issue].

There were two prior SeaBeam surveys over the CoAxial segment: one in 1991, and the original survey in 1981/82 (since it extended over 2 years, the earliest data will be 1981 in some areas and 1982 in others). Having a total of three surveys allows us to constrain any depth changes to be within 1 of 2 time

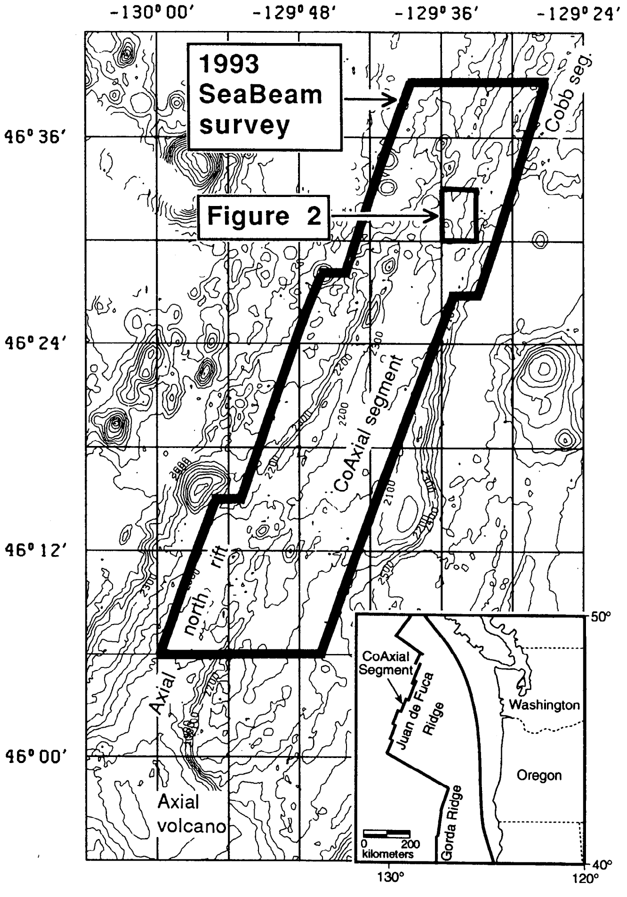


Figure 1. Bathymetric map of the CoAxial segment, Juan de Fuca Ridge (contour interval 100 m), showing areas of 1993 SeaBeam survey and Figure 2.

Paper number 94GL01895
0094-8534/95/94GL-01895$03.00

intervals (either 1981–91 or 1991–93), and it gives us increased confidence in our results because any real changes appearing in one of these intervals would also have to appear in the combined time interval (1981–93).

To objectively identify areas of significant depth change between SeaBeam surveys, we have applied a quantitative comparison technique which was previously developed and used to document the eruption on the Cleft segment. The method is explained in detail by *Fox et al.* [1992], and will only be summarized here: 1) the raw sonar data from the two surveys to be compared are mathematically gridded, 2) the two bathymetric grids are co-registered—one grid is shifted relative to the other to minimize their relative navigation errors, 3) the grids are then subtracted, one from the other, yielding raw depth differences, 4) the raw differences are weighted as a function of seafloor slope—false depth differences due to misregistration are larger over steep slopes than over a flat seafloor, and 5) a significance threshold is applied to separate significant depth changes from noise. To be detected by this method, a new seafloor feature must be at least 5–15 m in thickness and 200–300 m in diameter [*Fox et al.*, 1992; *Chadwick and Embley*, 1994].

Results from the CoAxial Segment

The quantitative comparison revealed only one area of significant depth change between the 1991 and 1993 SeaBeam surveys, near the northern end of the CoAxial segment. This depth change is centered near 46°31.4′N, 129°34.8′W, exactly where a fresh pillow lava flow was discovered and mapped within weeks of the earthquake swarm by the remotely operated vehicle *ROPOS*. The flow is 2.5 km long and 0.3 km wide, and was obviously new when first observed because it was pristine and still venting warm water [*Embley et al.*, this issue]. In addition, however, we found two areas of depth change between the 1981/82 and 1991 surveys, evidence that there have been other recent eruptions along the CoAxial segment.

Bathymetric maps of the area where the new lava flow erupted, made from the three different SeaBeam surveys, are shown in Figures 2a, 2b, and 2c. Qualitatively, the depth contours look about the same in most of the mapped area, but there are some apparent changes near the center, along the ridge that extends NE of the small seamount named Cage volcano. With three SeaBeam surveys, three separate quantitative comparisons can be used to determine which depth changes are real and when they appear (Figures 2d, 2e, and 2f). In the center of Figure 2e (the 1982–93 comparison) there are two well-defined positive depth anomalies that we interpret to be real, because both are located exactly where bottom observations have mapped very fresh lava flows. The western of these two anomalies is up to 29 m and is associated with the 1993 lava flow; the eastern anomaly is up to 37 m.

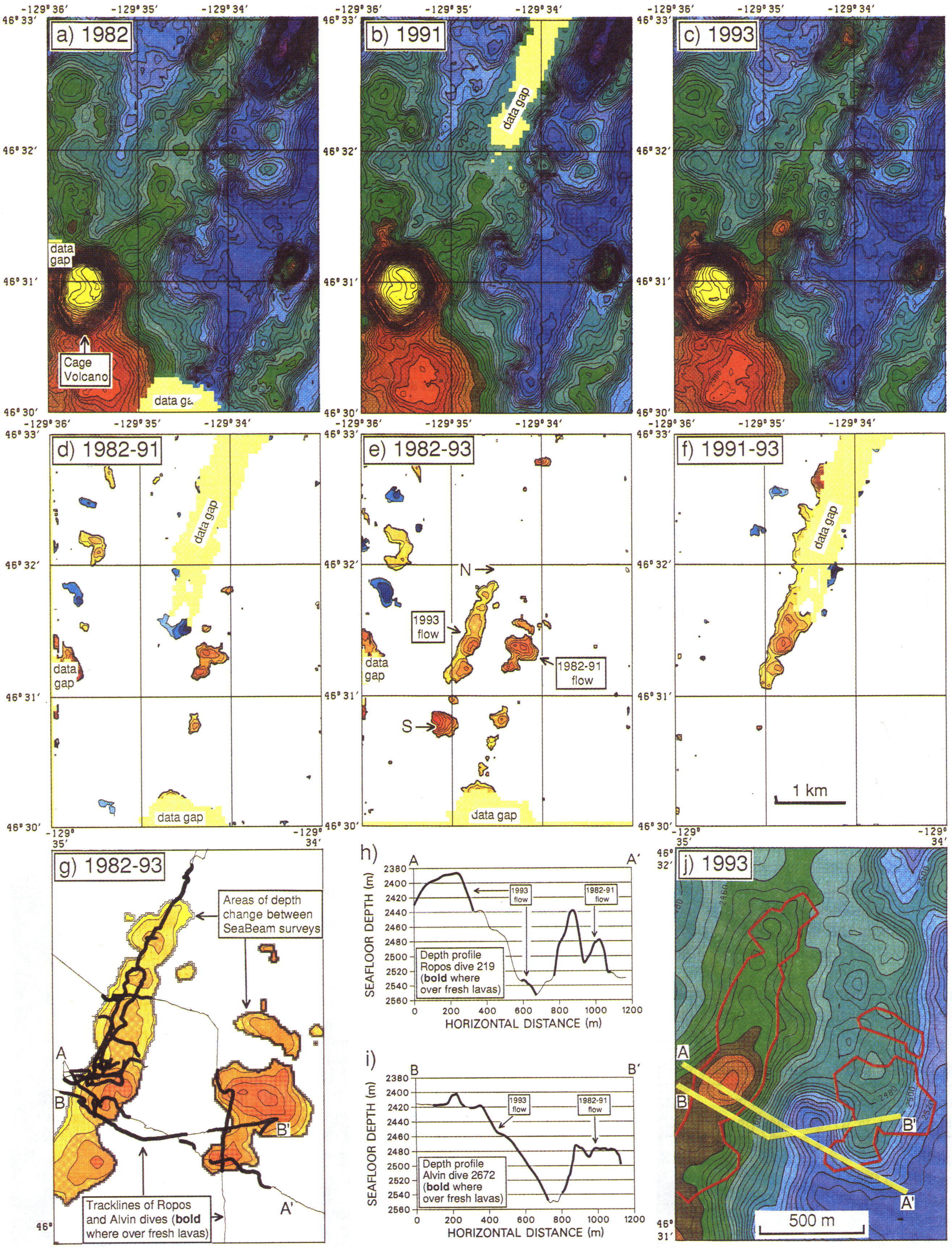
The anomalies in the NW of Figures 2d and 2e are not real, because they can be eliminated by slight changes in the grid registrations (the NW section of the grids is covered by a different SeaBeam swath and adjacent swaths sometimes have differing navigation errors). The largest anomaly (at the "S" in Figure 2e) is suspect, because if it were real, it would show up in one of the other comparisons, and it does not (Figures 2d and 2f). This large false anomaly is probably due to a combination of real and false depth differences; we know from bottom observations that the 1993 lava flow extends from the "N" to the "S" in Figure 2e, but this anomaly is also located on the very steep east slope of Cage volcano where false depth differences can be exaggerated by navigation errors.

The 1991 survey had a data gap just north of the 1993 flow (Figure 2b), but most of the 1993 flow is still well defined in the 1991–93 comparison (Figure 2f). The eastern of the two anomalies that we interpret to be real does not show up in the 1991–93 comparison (Figure 2f), but does appear in the 1982–91 comparison (Figure 2d). This is evidence for a separate volcanic event at least 2 years before 1993, that erupted another lava flow at the same latitude along the ridge segment, but offset to the east by ~700 m. We are very confident that these two anomalies are real because of the consistency of their size, shape, and character between the different comparisons, and because we have ground-truth observations in this area from *ROPOS* and the submersible *Alvin* [*Embley et al.*, this issue; J. Delaney, unpublished data, 1993].

The bottom observations show that both these areas of depth change are located exactly where *ROPOS* and *Alvin* mapped fresh lava flows (Figures 2g–2j). The depth profiles in Figures 2h and 2i cross both the 1993 and 1982–91 flows and show that their apparent thicknesses are consistent with the SeaBeam depth changes. The 1993 flow was erupted along a pre-existing ridge and a thin tongue of 1993 lava flowed down its steep east flank into a low area between the SeaBeam anomalies. *ROPOS* dive 219 (Figures 2g and 2h) crossed the lower end of the lava tongue, and *Alvin* dive 2672 (Figures 2g and 2i) followed its northern edge down the slope. The lava tongue appears as a positive anomaly in the raw difference grid (not shown), but is below the significance threshold in the final difference grid (Figure 2g), because it is apparently too thin and also because it is more difficult to resolve depth changes on steep slopes.

The bottom observations are consistent with the conclusion that there were two separate eruptions at this site. Although the two flows are both very young, they are noticeably different in appearance. The 1993 flow is pristine except near hydrothermal vents along its crest. The 1982–91 flow is also very fresh, but has no active hydrothermal venting, has a slight dusting of accumulated sediment, and its surface is not quite as dark and glassy. In addition, the 1993 flow and the 1982–91 flow have significantly different chemical compositions, and both are

Figure 2. (a–c) Bathymetric maps of 1993 CoAxial eruption site made from SeaBeam surveys in 1982, 1991, and 1993. (d–f) Maps showing areas of significant depth change between SeaBeam surveys for 3 comparisons: 1982–91, 1982–93, and 1991–93 (warm colors are positive, cool colors are negative). North and south ends of 1993 lava flow (from *ROPOS* dives) are labeled "N" and "S" in Figure 2e. (g) Tracks of 2 *ROPOS* and 3 *Alvin* dives overlain on center of Figure 2e, showing that SeaBeam anomalies are located exactly where fresh lavas are mapped. (h) Depth profile along *ROPOS* dive 219 between A and A′ in Figures 2g and 2j. (i) Depth profile along *Alvin* dive 2672 between B and B′ in Figures 2g and 2j. Tracks and profiles are bold where they cross fresh lavas. Depth profiles are 4 times vertical exaggeration. (j) 1993 bathymetric map of same area as Figure 2g, with SeaBeam anomaly outlines (red) and depth profiles (yellow). Contour interval of all maps is 5 m.


-129° 36′
-129° 35′
-129° 34′
46° 33′
46° 32′
46° 31′
46° 30′
a) 1982
data gap
Cage Volcano
data gap
b) 1991
data gap
c) 1993
d) 1982-91
data gap
data gap
data gap
e) 1982-93
N→
1993 flow
1982-91 flow
data gap
S→
data gap
f) 1991-93
data gap
1 km
-129° 35′
-129° 34′
g) 1982-93
Areas of depth change between SeaBeam surveys
A
B
B'
A'
Tracklines of Ropos and Alvin dives (**bold** where over fresh lavas)
46°
h)
A
A'
1993 flow
1982-91 flow
Depth profile Ropos dive 219 (**bold** where over fresh lavas)
SEAFLOOR DEPTH (m)
2380
2400
2420
2440
2460
2480
2500
2520
2540
2560
0
200
400
600
800
1000
1200
HORIZONTAL DISTANCE (m)
i)
B
B'
1993 flow
1982-91 flow
Depth profile Alvin dive 2672 (**bold** where over fresh lavas)
SEAFLOOR DEPTH (m)
HORIZONTAL DISTANCE (m)
46° 32′
46° 31′
j) 1993
A
B
B'
A'
500 m

different from the surrounding older lavas [*Smith et al.*, 1993].

A second depth change between the 1981/82–91 surveys was found along the ridge axis at 46°26.2′N, 129°38.7′W, about 10 km south of the 1993 flow. This anomaly is well-defined in both 1981–91 and 1981–93 comparisons, but it is relatively small (up to 20 m) and no ground-truth data has been collected in this area, so its confirmation will have to await further field work.

Fox et al. [1992] found no depth anomalies along the CoAxial segment when comparing these same 1981/82 and 1991 SeaBeam surveys. The two 1981/82–91 anomalies may not have been reported then because the northern one is near the data gap in the 1991 survey and the southern one is relatively small. We have increased confidence in our present results by having three SeaBeam surveys instead of two, and because we now have ground-truth data. In addition, the GPS navigation (dithered) of the 1993 survey may allow a slightly better comparison than the Loran-C navigation of the earlier surveys.

Discussion

These results are another example that SeaBeam comparisons can detect and quantitatively map seafloor eruptions of sufficient size. The 1993 SeaBeam resurvey of the CoAxial segment found only one lava flow associated with the 1993 earthquake swarm, located in the center of the most persistent part of the swarm [*Dziak et al.*, this issue; *Embley et al.*, this issue]. There is no evidence from the 1993 resurvey of any associated activity on the north rift of Axial volcano. The character of the 1993 anomaly shows that the 1993 flow is the product of a fissure eruption; it is long and narrow and its thickness varies along its length where the eruption apparently localized during its later stages, similar to the Cleft lava flows [*Chadwick and Embley*, 1994]. The area and volume of the depth change associated with the 1993 flow are 3.4×10^5 m^2 and 5.0×10^6 m^3, respectively. These values are minimums, but indicate that the volume of the 1993 CoAxial eruption is about an order of magnitude less than the volume of the Cleft eruption (Table 1). It is also probably 1–2 orders of magnitude less than the volume of the dike that intruded along the CoAxial segment during the earthquake swarm, which can be roughly estimated at $120–180 \times 10^6$ m^3. This volume estimate assumes that the dike is 60 km long (the length of the earthquake swarm [*Dziak et al.*, this issue]), 2–3 km high (the depth at which possible magma storage zones have been detected seismically elsewhere on the JdFR [*Morton et al.*, 1987; *Christeson et al.*, 1993]), and 1 m thick (the average dike thickness in ophiolites [*Kidd*, 1977]). The northern 1982–91 anomaly is about the same volume as the 1993 flow, and the southern 1981–91 anomaly is less than half that volume (Table 1).

The evidence for two eruptions between 1981–91 indicates that the 1993 eruption was not an isolated event. This could mean that the CoAxial segment experiences seafloor spreading events of this size about every decade, or alternatively the segment may be in the midst of a more infrequent but longer-lived spreading episode, perhaps lasting years or decades as in Iceland [*Björnsson et al.*, 1979].

Table 1. Areas and volumes of SeaBeam depth changes

SeaBeam anomaly (JdFR segment, year)	Maximum change (m)	Area ($\times 10^6$ m^2)	Volume ($\times 10^6$ m^3)
Cleft, 1983–87*	45	2.8	51.
CoAxial, 1993 flow	29	0.36	5.4
CoAxial, northern 1982–91 flow	37	0.25	5.1
CoAxial, southern 1981–91 flow	20	0.16	1.8

* from *Chadwick and Embley* [1994].

The remarkable proximity of the 1993 and northern 1982–91 flows suggests that the earlier eruption must not have relieved all the accumulated tensile stress along this part of the plate boundary. The east-west separation of the flows shows that the width of the active neovolcanic zone is at least 700 m wide at the CoAxial segment, and that successive eruptions at intermediate-rate spreading centers do not necessarily happen along the exact same line or structures, but can jump laterally within a zone of finite width.

Acknowledgments. This research was funded by the NOAA VENTS Program. NOAA's National Undersea Research Program helped fund the *Alvin* dives. We thank the officers and crews of the *Discoverer* and the *Atlantis II*, and the pilots of *ROPOS* and *Alvin*. Helpful reviews were provided by D. Fornari, J. G. Moore, P. J. Fox, and an anonymous reviewer. PMEL contribution 1533.

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(Received April 21, 1994; accepted May 25, 1994.)