JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B8, PAGES 12,689–12,696, AUGUST 10, 1990

Axial Seamount: An Active Ridge Axis Volcano on the Central Juan De Fuca Ridge

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INTRODUCTION

Axial Seamount (some of the manuscripts in this special section refer to the edifice with the more precise name of "Axial Volcano"), a large ridge axis volcano, is located on the central segment of the Juan de Fuca Ridge approximately 250 nautical miles west of the Washington/Oregon/British Columbia coast. Currently both volcanically and hydrothermally active, Axial lies directly at the intersection of the Cobb-Eickelberg Seamount Chain and the Juan de Fuca Ridge (Figure 1). The volcanic activity associated with the seamount formation strongly interacts with, and is affected by, the normal seafloor spreading processes at the intersection. Because of this unique geologic setting, its proximity to west coast ports and oceanographic institutions, and its shallow depth, Axial has become the focus of a large number of scientific investigations over the past decade.

Axial Seamount became an early target for study using the newly developed swath-mapping tools of Sea Beam, Sea MARC I and II, and GLORIA. During the entire decade of the 1980s, geologists and geophysicists from a wide variety of institutions, including the U.S. Geological Survey, NOAA, the Pacific Geoscience Centre, as well as the Universities of Washington, Victoria, and British Columbia, and Oregon State University, conducted extensive surveys and detailed sampling programs of both the summit and flanks of the volcano. Since 1984, the NOAA VENTS Program has devoted a major surface ship and submersible effort to high-density studies of the summit area and its hydrothermal systems. The shallow 1500-m summit depth of the seamount has allowed access with *Pisces* submersibles (both Canadian and Russian) as well as *Alvin*. This extensive sea-going effort has made Axial one of the most intensely studied and best characterized areas of seafloor in the world.

GEOLOGICAL SETTING

Axial Seamount is located astride the central segment of the Juan de Fuca Ridge, an intermediate spreading-rate ridge with a total opening velocity of 6 cm/yr. The Juan de Fuca Ridge is bounded on the south by the Blanco Fracture Zone and on the north by a triple junction formed by the ridge, the left-lateral Nootka fault and the Sovanco Fracture Zone [*Atwater*, 1970; *Hyndman et al.*, 1979]. Like the East Pacific Rise, the Juan de Fuca Ridge can be divided into six 50- to 100-km-long segments, with the Axial Segment being the third segment north of the Blanco Fracture Zone (Figure 2).

Axial Seamount represents a large mass excess associated with a "hotspot"-influenced spreading center. The term "hotspot" is used in quotations here since geochemical evidence (Desonie and Duncan, this issue; Rhodes et al., this issue) argues that Axial is not a geochemical hotspot in the traditional Hawaiian or Icelandic sense. Examination of the older, more distal portion of the Cobb-Eickelberg (C-E) chain (Figure 1) shows that it is a relatively thick "band" of seamounts, rather than a single bathymetric lineation. *Riddihough et al.* [1983] and *Davis and Karsten* [1986] observed that almost all of the seamounts formed at the C-E hotspot and smaller seamounts found in proximity to the Juan de Fuca Ridge north and south of Axial lie on the Pacific plate to the west, rather than on the smaller Juan de Fuca plate to the east [*Riddihough et al.*, 1983; *Davis and Karsten*, 1986].

The general setting of Axial Seamount in the eastern Pacific, and the overall morphology of the edifice, can be seen in Figures 1 and 2, and in the color Plates A and B of this issue. To the south, structures of the Vance Segment overlap with the South Rift Zone of Axial and interact with the seamount in the SE quadrant. This zone of interaction between the Vance and Axial segments is quite extensive, with at least 30 km of overlap. The farthest northward projection of spreading from the Vance Segment is a zone of intense fissuring (observed in Sea MARC I and II data) on the outer flank of the volcano [*Johnson and Holmes*, 1989; Appelgate, this issue].

Interaction of the Axial Segment with Northern Symmetrical (also named Cobb) Segment to the north is more complex. Both magnetics and morphology data show that the Axial Segment forms a "bent spreading center" connection zone between the two segments, an unusual intrasegment connection region that is apparently nonoverlapping at the present [*Johnson and Holmes*, 1989]. An elevated saddle of basement rock connects the west flank of Axial with the easternmost flank of Brown Bear Seamount (Plate A), the next oldest seamount in the C-E chain. The Son-of-Brown Bear Seamount, lying directly east of Axial Volcano, and three smaller volcanos just to the north and south (Plate A) are four members of the rare class of volcanos that formed near the ridge axis and ended up on the Juan de Fuca plate, rather than the Pacific plate.

STRUCTURAL COMPONENTS OF THE VOLCANO

Structurally, the edifice of Axial Volcano can be interpreted to represent a complex interplay of three usually distinct

Paper number 90JB01037.
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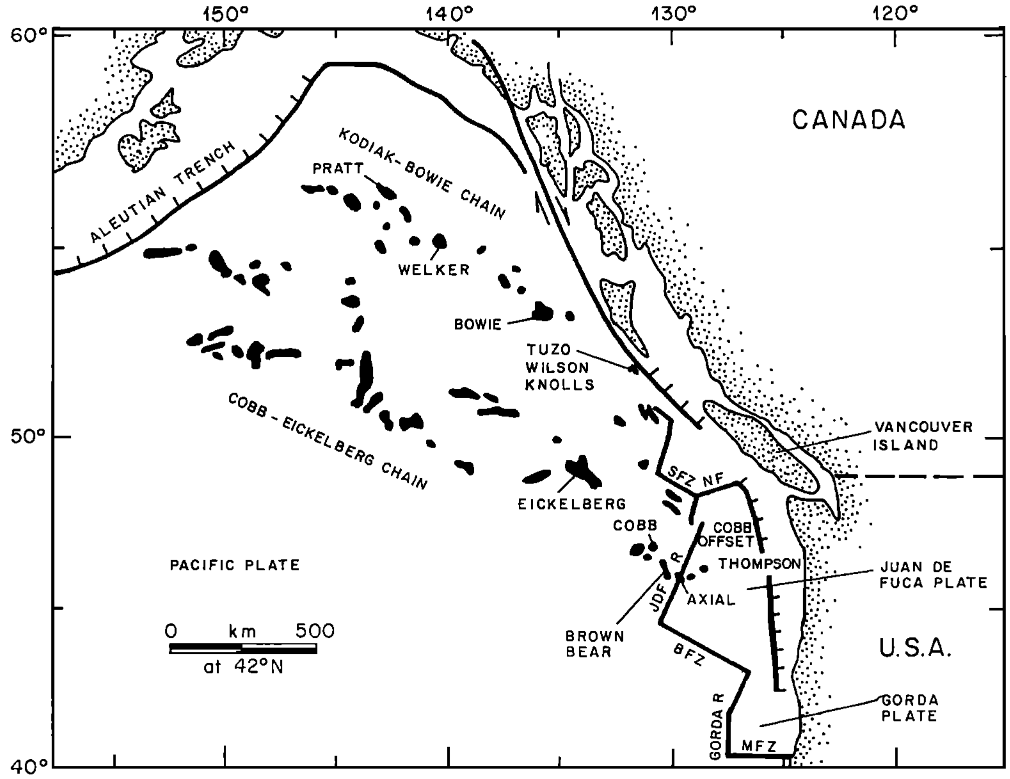

Fig. 1. Seamounts and spreading centers in the northeast Pacific, adapted from *Riddihough et al.* [1983]. Thick hachured lines are subduction zones. Note that the Cobb-Eickelberg Chain has a finite width and actually consists of a band of seamounts rather than a linear chain.

geological processes: seafloor spreading, seamount formation, and Hawaiian-style rifting. The elongate structure of the entire edifice (Plate A) appears to represent the distribution of an "excess" of magmatic activity along the entire Axial Segment. The elongate North and South Rifts show evidence of "rifting" or, more correctly phrased, longitudinal growth due to along-strike, near-surface magma transport. Finally, the dome-shaped summit and caldera argue for seamountlike formation processes, including eruption from (and subsequent collapse into) localized magma reservoirs.

The summit of Axial, with its well-defined, three-sided caldera (Figure 3 and Plate B) and associated active hydrothermal systems, has provided the focus of many of the studies in this volume. Floored with very recent lava flows, some of which are young enough to onlap actively venting hydrothermal deposits, this caldera is a potential natural laboratory. Because of the shallow 1500-m depth of the caldera floor, high-temperature hydrothermal systems can undergo "phase separation," a term used by water chemists when they are discussing "boiling" of the hydrothermal fluid (Butterfield et al., this issue). The influence of this "phase separation" on hydrothermal systems is profound and is a theme that runs through several of the manuscripts in this special section.

THIS ISSUE

The manuscripts in this issue can be divided into four broad categories: (1) the large view studies that look at Axial as an active submarine volcano; (2) the more focused summit geological and geophysical studies; (3) studies of the chemistry and movement of the water column above Axial; and (4) specific experiments and studies that focus on the active hydrothermal systems.

Axial as a Volcano

The large-scale context of Axial is presented in the papers by Desonie and Duncan and by Rhodes et al. Desonie and Duncan examine the age and chemistry of the Cobb-Eickelberg (C-E) seamounts, using dredge samples collected mostly from the distal members of the chain, and find a westward age progression away from the spreading center, consistent with the general assumption that Axial is the youngest member of the progressively older (to the west) seamount chain. The same study also shows an eastward decrease in age difference between the seamounts and the crust on which they are formed, arguing that the spreading center and the "mantle source" responsible for the seamounts have been approaching each other as the Juan de Fuca migrates toward the fixed C-E "hotspot." Desonie and Duncan, however, find that there is not a clear, mantle plume signature to the geochemistry of the surface rocks of these outer seamounts and call upon mixing between a weak mantle plume and normal spreading-center magmas to explain the observed compositions.

Rhodes et al., on the other hand, concentrating on samples from the summit and flanks of Axial volcano itself, find no evidence at all of any mantle plume influence in the geochemistry of the rocks. These authors argue that although the geochemical data (as well as the morphological evidence) appear to favor a very active and extensive magmatic plumbing system for Axial Seamount and one that is separate and distinct

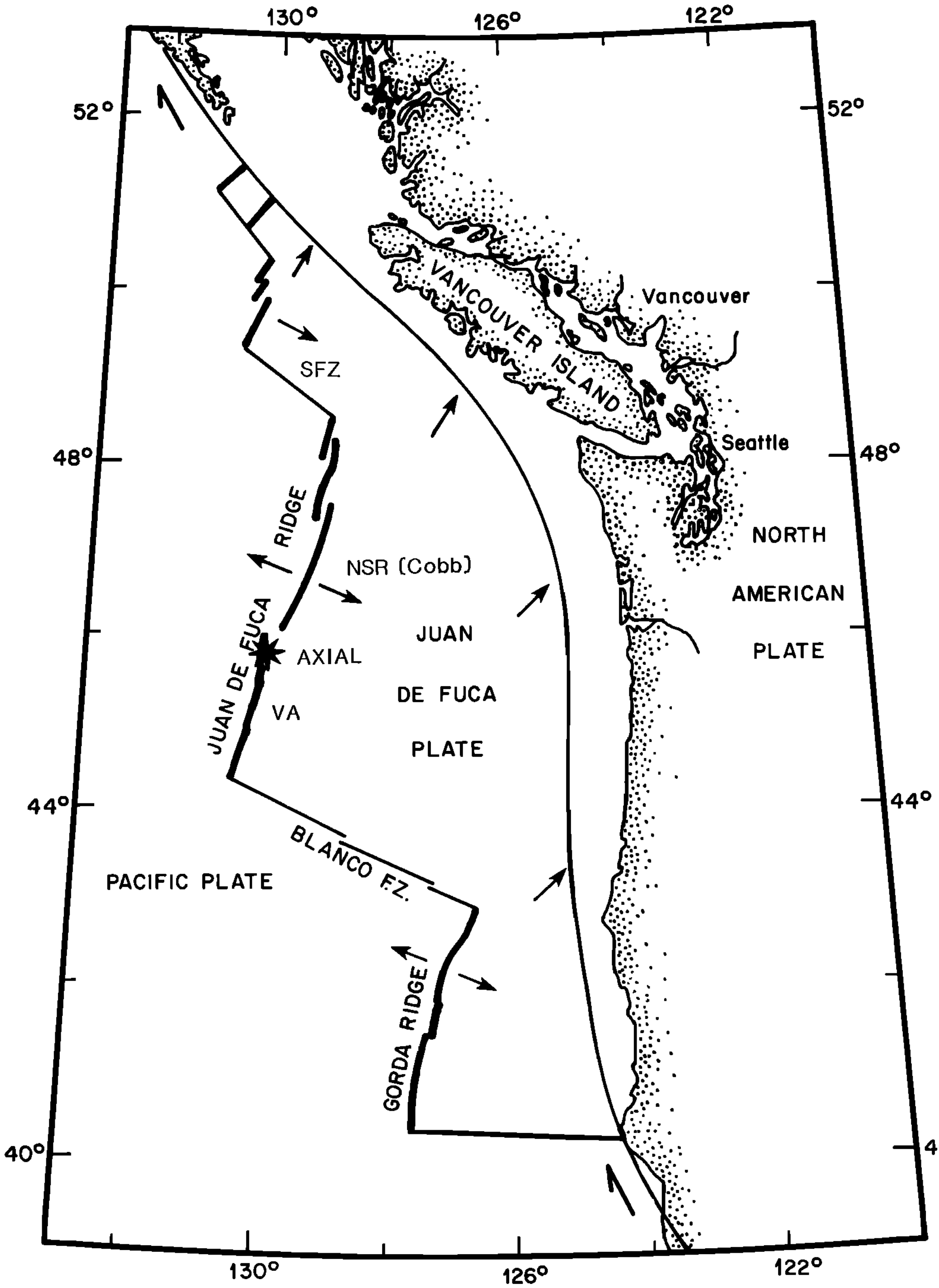

Fig. 2. Schematic diagram of the ridge segments of the Juan de Fuca Ridge, in the northeast Pacific. Thick lines indicate the spreading center segments; thinner lines indicate fracture zones and the location of the continental margin. The following abbreviations are used: SFZ, Sovanco Fracture Zone; NSR, Northern Symmetrical Ridge; AXIAL, Axial Seamount Segment; VA, Vance Segment (or segment B in the older literature).

from the rest of the Juan de Fuca Ridge volcanics, the volcano represents the surface expression of a thermal, rather that a geochemical, anomaly in the mantle.

Potential field measurements over Axial Seamount, including sea surface magnetics and both seafloor and sea surface gravity data, have provided some insight into the internal structure of the volcano. Tivey and Johnson, using the closely spaced sea surface magnetics data acquired during many years of cruises in the area, show that even though the seamount lies entirely within crust formed during the normally magnetized Brunhes epic, the edifice does not produce a simple positive anomaly that can be simply related to the bathymetry. Both inversion of the anomaly data and forward modeling coupled with rock magnetics measurements show that the seamount contains large zones of relatively low magnetization associated with the summit region. While the interpretation is inherently nonunique, the anomalies are best explained by a thinned (<700 m) source layer underlying the summit of the volcano.

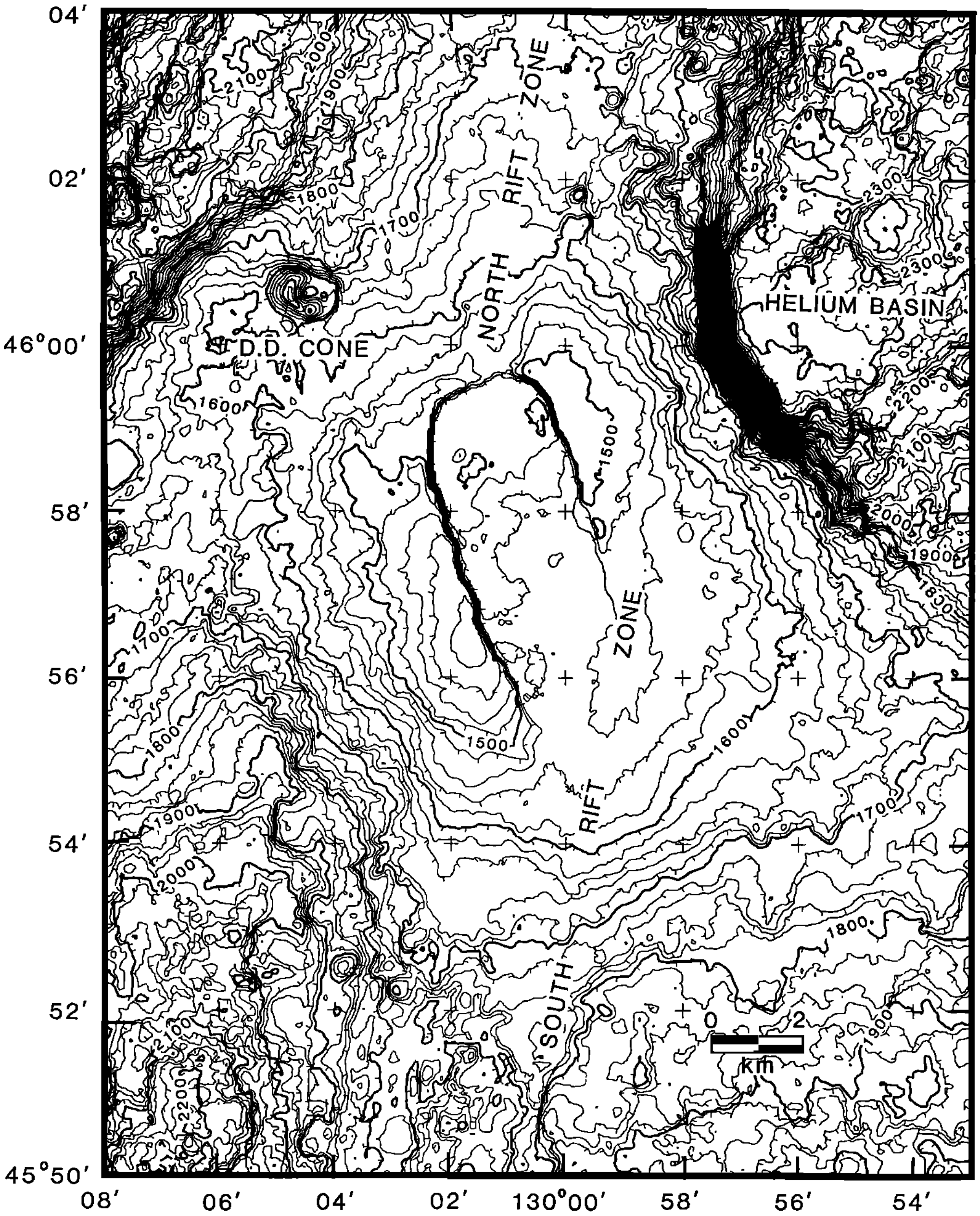

Fig. 3. Detailed bathymetry map of Axial summit and caldera, from the NOAA Sea Beam coverage in the area. Note the three-sided caldera, with an orientation that is oblique to all other tectonic trends in the region. Depths are calculated using a water velocity of 1500 m/s. Primary navigation was by LORAN-C, but was shifted to Global Positioning System base. Contour interval is 10 m.

The necessary thinning could be caused by the presence of a shallow, subcaldera magma chamber, residual heat in a transport pipe from previous eruptions, or a zone of extensive subsurface alteration.

Hildebrand et al., using both sea surface gravity anomalies and data from a new seafloor gravimeter, report evidence for a shallow, low-density region underlying the summit caldera, also suggesting a partially molten magma chamber at depth within the volcano. Away from the summit, the gravity data of Hildebrand et al. suggest that the North Rift Zone represents a tongue of high-density material at shallow depths, an interpretation that is consistent with a zone of cooled dike intrusions associated with Hawaiian-style rifting. A narrow, extremely high-amplitude magnetic anomaly over the North Rift Zone, described by Tivey and Johnson, is also consistent with this interpretation.

The process of rifting over the South Rift Zone is discussed at length in the paper by Appelgate. Using high-resolution Sea MARC I data, Appelgate shows that the surficial morphology of the South Rift Zone systematically changes from linear volcanic ridges near the summit to small cratered cones at the distal end. Furthermore, he shows that ridge-parallel faults along the South Rift are the sources for the most recent lava flows in this region and that the exposed faults are likely to serve as shallow conduits for the horizontal (southward) transport of magma. Finally, using processed side scan data in the Southern Rift Zone, Appelgate identifies a very large (48 km^2 in area; estimated 1.8 km^3 in volume) lava field east of the rift zone, which, he speculates, may have been a major contributor in the formation of the summit caldera.

Summit Geology

The summit of Axial Seamount represents a well-studied region of recent eruptive volcanics in the submarine environment and contains evidence of a variety of geological processes that are currently active. Embley et al., using Sea Beam and Sea MARC I swath maps, coupled with towed-camera and submersible observations, describe the basic geology of the summit area and the associated caldera; these data allow the compilation of maps of the summit area comparable in detail to those available for subaerial volcanos. Embley et al. show that much of the postcaldera volcanism and associated hydrothermal venting appears to be associated with South Rift Zone activity. The orientation of the 3 × 8 km summit caldera, with its roughly rectilinear sides that trend in the N160° direction, oblique to all other trends in the area, has been a major enigma in interpretation of the morphology of the seamount. Embley et al. discuss several of the factors that may be responsible for the caldera and favor a model based on a mobile "overlapping spreading center."

The current tectonic activity within the caldera is graphically demonstrated in this volume by Fox, who used a precision pressure sensor to infer movement of the caldera floor over a period of a year. Data from this recorder showed an abrupt 15-cm downward movement of the caldera floor over a period of several weeks during this period. Simultaneous hydrographic measurements showed the presence of a new water temperature anomaly and a change in bottom current velocities on the caldera floor occurring at the same time as the proposed vertical movement. Fox attributes this correlation to a period of active caldera deflation and a related thermal plume with associated cold water entrainment.

Water Column Studies

A structure on the seafloor the size of Axial Seamount can present a formidable barrier to the free circulation of seawater in the region. Positioned at the intersection of the C-E Seamount Chain, the bathymetric expression of Axial intensifies water circulation patterns in the region. Cannon and Pashinski discuss a series of year-long moored current meter measurements made both on the summit of the volcano and on the bathymetric saddle that connects Axial with Brown Bear Seamount (Plate A). The authors interpret these data to show that there is substantial long-term averaged southward flow along the entire east side of the seamount. West of Axial, in the saddle separating it from Brown Bear Seamount, lies a zone of convergence between southward and northward flowing currents. After converging, these two currents seem to merge and flow westward away from the ridge. In addition to being important in their own right, these current systems also determine the ultimate fate of the hydrothermal effluent that issues from the summit of the active volcano.

The hydrothermal vent systems on the summit of Axial Volcano make a detectable heat and chemical signal in the overlying water column. Lupton describes the data from hydrographic surveys over and near the volcano, taken between 1980 and 1987, which show complex patterns of ^{3}He- and Mn-rich plumes within the water column. These plumes represent regional concentrations, as well as local effects, over both the summit and a local topographic low known as Helium Basin (Figure 3). Although the plumes showed distinct ^{3}He and Mn signatures, there was no detectable thermal signature over the seamount, an observation attributed by Lupton to the high ^{3}He/heat ratios and low salinities of the fluids being vented within the caldera.

Thermal anomalies were, however, found by Baker et al., who focus on the results of hydrographic and chemical sampling of the water column directly over the summit. Here, they found temperature anomalies that were restricted to a 200-m-thick layer above the caldera. The summit water-temperature anomaly over Axial is significantly smaller than anomalies associated with other hydrothermal fields on the Juan de Fuca Ridge, perhaps a surprising result considering the tremendous amount of magmatic activity that must be associated with the formation of the volcano.

Feely et al. examine the chemistry of the particulates within the water column over the summit region and use the data to differentiate between distinct regions within the general summit plume. These three major regions include (1) a single buoyant plume, (2) an upper nonbuoyant plume, and (3) a lower nonbuoyant plume. Sediment trap data reported by Feely et al. also confirm that the integrated particulate fallout from the summit hydrothermal systems is not as large as some of the other vent fields from other segments (i.e., Endeavour Segment) on the Juan de Fuca Ridge.

Hydrothermal Vent Fields

Although low-level hydrothermal activity and deposits are found in several areas of the caldera (shown by Embley et al.), most of the studies in this issue focus on the ASHES vent field, which contains the only high-temperature vents in the caldera. Most of these investigations were supported by the NOAA VENTS Program. The site is ideal for short- or long-term experiments, being located on the flat, unobstructed caldera floor, away from the caldera wall. Hammond describes the vent field in detail, drawing from the results of *Alvin* and *Pisces* IV dives and deep-tow camera photographs. There is a variety of hydrothermal deposits in the ASHES field, and because of the intensity of interest in the region, the deposits are well-mapped and sampled for chemistry, geology, and biology. Hammond proposes that the largest field, the ASHES system near the southeast corner of the caldera, is controlled both by the faulting associated with the wall formation and by the permeability of the lobate pillow flows that make up the caldera floor in this region.

Butterfield et al. present the detailed chemical data from the ASHES vent field, which is the first well-documented example of a phase-separated deep-sea hydrothermal system. Using the extensive collection of water samples taken from the ASHES field in 1986, 1987, and 1988, they describe the geochemical effects of boiling on a hydrothermal system. They observe a wide range of fluid compositions from the field, including both gas-rich and gas-poor compositions and both high and low chlorinity values. Butterfield et al., however, propose that the entire range of observed compositions can be explained by the process of boiling and subsequent phase segregation of a hydrothermal fluid with a single original composition. Fox describes the physical separation of the brine and vapor phases that result from a "boiling" vent system and presents a relative permeability model within the fluid conduits as a possible mechanism to produce that separation. Little et al. discuss both the theoretical "noise" produced by hydrothermal systems in general and actual sound measurements of noise generated by vents at the ASHES field.

The natural distribution of hydrothermal fauna, and the impact of geological controls on this distribution, is described by Arquit. The major impact of submersible sampling on the hydrothermal fauna is discussed by Tunnicliffe, who points out that vent animals are very sensitive to disruption, in spite of living in the extremely harsh environment of a high-temperature vent.

CONCLUSIONS

Although detailed conclusions are not appropriate for an introductory manuscript, it is difficult not to make some final remarks regarding the current status of our understanding of the remarkable geological feature represented by Axial. Clearly, Axial Seamount is an active undersea volcano, with recent lava flows, active hydrothermal systems, and a caldera that may be presently undergoing inflation/deflation cycles. The gravity and magnetics data argue for either a shallow magma chamber underlying the summit caldera, or a warm and/or altered interior. The vigorous hydrothermal activity associated with the caldera, while (surprisingly) not of the same scale as the large fields found on the Endeavour Segment and Explorer Ridge to the north, still have a major impact on the regional water chemistry, biology, and perhaps hydrology. The detailed studies of the ASHES vent field have, for the first time, documented the chemistry of a phase-separation-dominated hydrothermal system. Presently only observed on Axial Seamount, this process has a major impact on the chemistry and geology of the vent field and will no doubt be seen on many of the shallow submarine volcanos of the western Pacific in the future.

Although, as stated earlier, Axial Volcano is already a remarkably well-studied piece of seafloor, the recent volcanic eruptions, the concurrent hydrothermal activity, and the proximity of the seamount to North American west coast ports virtually guarantee that Axial Seamount will continue to be an intensely interesting natural laboratory for a long time to come.

REFERENCES

Atwater, T., Implication of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull., 81,* 3513–3536, 1970.

Davis, E. E., and J. L. Karsten, On the cause of the asymmetric distribution of seamounts about the Juan de Fuca Ridge: Ridge-crest migration over a heterogeneous asthenosphere, *Earth Planet. Sci. Lett., 79,* 385–396, 1986.

Hyndman, R. D., R. P. Riddihough, and R. Herzer, The Nootka fault zone—A new plate boundary off western Canada, *Geophys. J. R. Astron. Soc., 58,* 667–683, 1979.

Johnson, H. P., and M. L. Holmes, Evolution in Plate Tectonics: the Juan de Fuca Ridge, in *The Eastern Pacific Ocean and Hawaii,* vol. N, *Decade of North American Geology,* edited by E. L. Winterer, D. M. Hussong, and R. W. Decker, pp. 73–92, Geological Society of America, Boulder, Colo., 1989.

Riddihough, R. P., M. W. Beck, R. L. Chase, E. E. Davis, R. D. Hyndman, S. H. Johnson, and G. C. Rogers, in *Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs, Geodyn. Ser.,* vol. 9, edited by R. Cabre, pp. 5–23, AGU, Washington, D.C., 1983.

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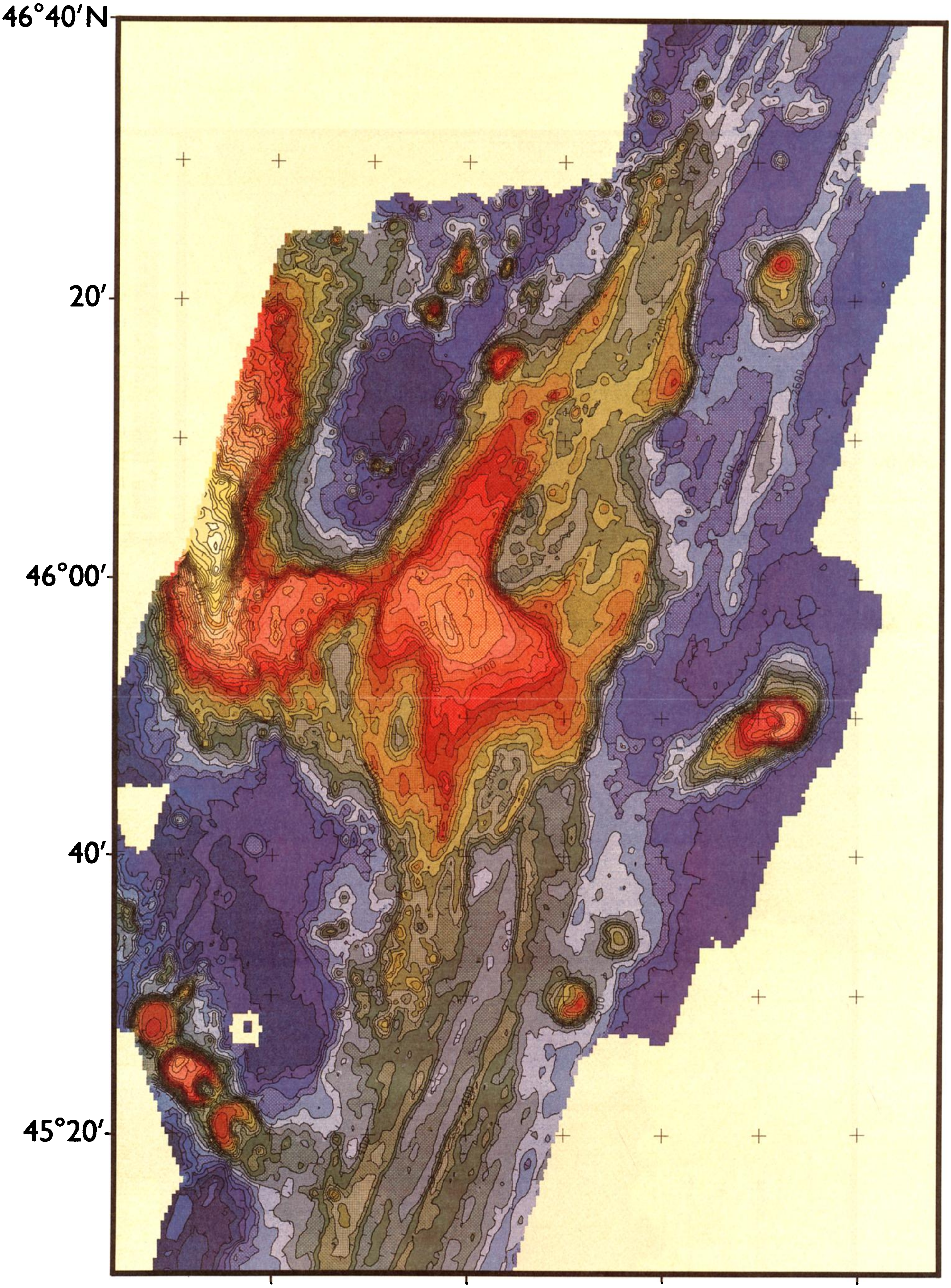
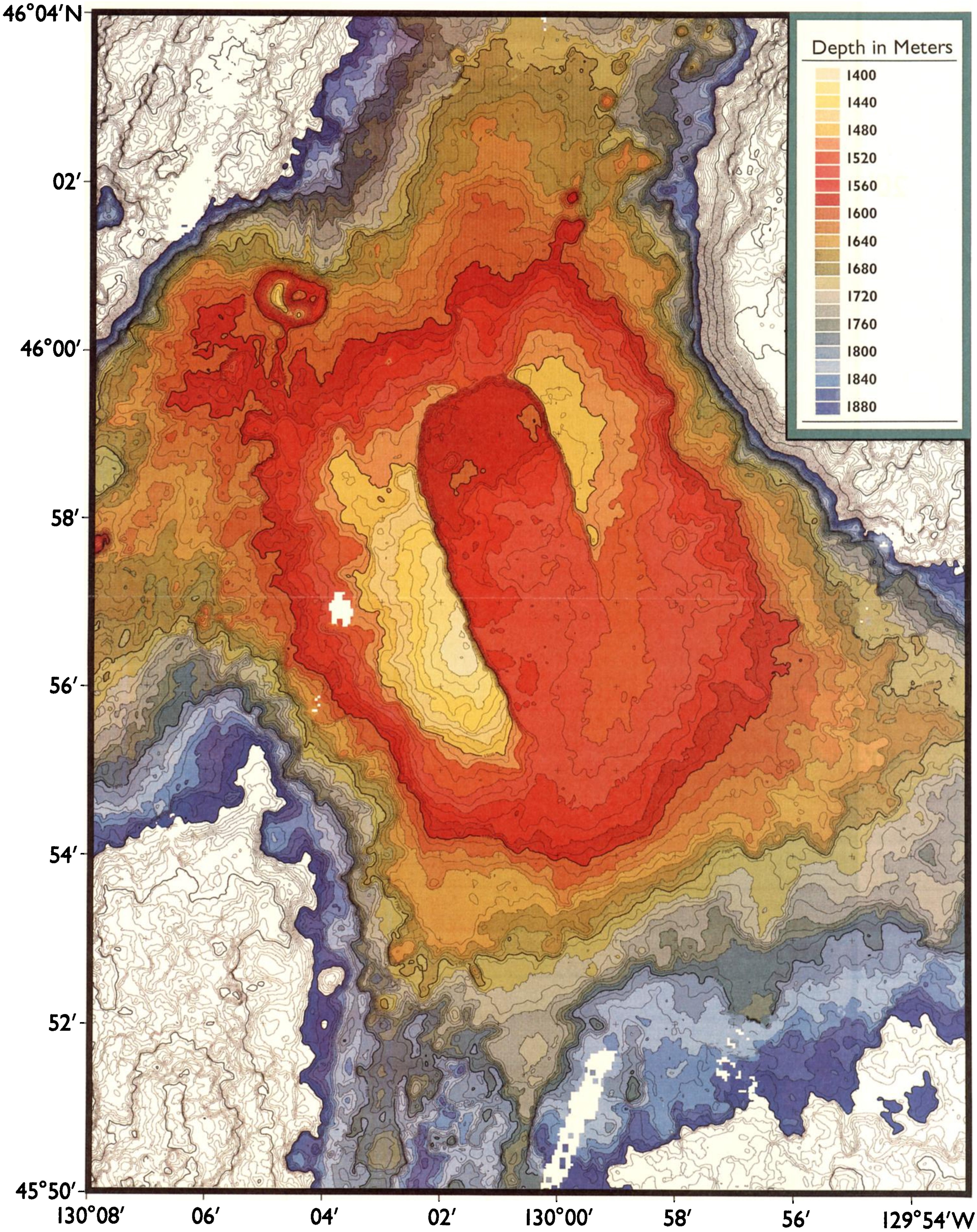
(Received February 10, 1990;
accepted February 10, 1990.)



Axial Seamount Special Section Plate A. Sea Beam bathymetry of central Juan de Fuca Ridge. Contour and color-change interval is 50 m. Soundings are based on a water velocity of 1500 m/s. Sea Beam swaths cover greater than 90% of the seafloor over the mapped area. Navigation for Plates A and B is Loran-C corrected to GPS. See *Embley et al.* [this issue] for details of data collection methods.



Axial Seamount Special Section Plate B. Sea Beam bathymetry of summit of Axial Volcano. Contour interval is 10 m and color change interval is 20 m. Shoalest color interval is 1400–1420 m. Number opposite each color block on legend refers to shallow depth for that color interval. Navigation is based on LORAN-C corrected to GPS. See caption of Plate A for additional information.