Hydrothermal vents on an axis seamount of the Juan de Fuca ridge

Canadian American Seamount Expedition*

The Juan de Fuca Ridge, a 500-km section of the mid-ocean ridge system, is bounded by the Sovanco and Blanco fracture zones[1,2]. Although the ridge spreads at a medium rate (29 mm yr^{-1} half-rate)[3], a significant portion of its crest has a morphology typical of faster spreading ridges; the axial valley is 1–2 km wide within a central horst structure[4]. The ridge crest shoals to 1,500 m at the intersection with the Cobb–Eickelberg Seamount chain forming a broad edifice called 'Axial Seamount' (Fig. 1). Previous studies both north and south of Axial Seamount demonstrated hydrothermal activity associated with the shallowest portions of each of the ridge segments along the Juan de Fuca[5–9], a similar coincidence to that noted for the East Pacific Rise[10]. We report here the results of the first manned submersible expedition to the Juan de Fuca Ridge, which found hydrothermal activity and at least 14 new vent animals in the caldera of Axial Seamount.

During this joint Canada–US expedition, the Canadian submersible Pisces IV completed eight dives with equipment including an externally-mounted stereo camera, a high-temperature probe, titanium water-sampling bottles, devices for sample collection and an observer-held video camera.

The summit of Axial Seamount is a flat-floored caldera, breached at its southern end (Fig. 1). Seamarc I images reveal fissuring and faulting at the intersection of the northern caldera wall and the spreading axis[11], the focus of our study, where a thermal anomaly has been measured[12]. North of the study site, there were fissures towards the south 2-10 m wide and 1-20 m deep, occupying a zone 400 m wide; pelagic sediments were up to 20 cm thick. The exposed and truncated pillow basalt of the caldera wall seemed older than that of the floor. Steep talus slopes along its base were overlapped occasionally by sheet flows of the floor. The northwestern caldera floor was lightly-sedimented glassy basalt with areas of older pillow basalt. Drain-back features with relief to 5 m were common and included collapsed roofs, hollow basalt columns and cavitied and buckled sheet flows.

The fissures on the caldera wall were replaced by one major fissure on the floor (Fig. 2) of ~300-m length, terminated in the north by a talus pile and in the south by a vertical wall beyond which no traces of rifting were found. Only the northern 200 m of the fissure were hydrothermally active with flows greatest at the vents indicated in Fig. 2 where fluids up to 35 °C were discharging through mounds of pogonophoran worms. Lower temperatures (4–7 °C) were measured in cavities of diameter 1 m, where hydrothermal precipitates were essentially absent and the fissure basalts showed no obvious alteration.

East of the fissure (Fig. 2), three chimneys (sulphides and sulphates) rose to 12 m; one pagoda-shaped chimney was still venting water (measured to 19 °C) from lateral flanges and an adjacent spire, 1.7 m high and weighing 160 kg, was collected. The pillars were aligned N–S, but no tectonic features connecting them with an area of diffuse venting 50 m south were found. The onlapping nature of the glassy sheet flows at the chimney bases and the lack of sulphide debris suggest that the lava flows were recent with the major vent fissure being a channel through which the lava may have drained.

Sulphates and sulphides around worm tubes give the chimney samples a spongy texture. The tubes are partially filled by

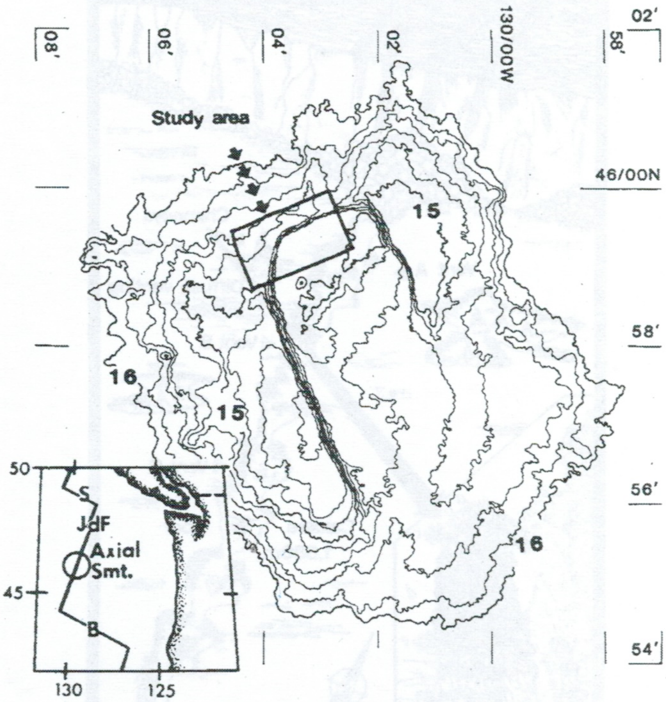

Fig. 1 NOS Seabeam bathymetry of Axial Seamount and Pisces IV study area. Contour interval is 20 m with labels in 100 m. Seamount rises to 1,500 m are compared with flanking ridge axes at 2,200–2,700 m. Caldera measuring about 7 km × 3 km with a flat floor at 1,570 m had a long axis along 340°, oblique to the 020° strike of the Juan de Fuca Ridge. The inset illustrates the setting of Axial Seamount with respect to the Juan de Fuca Ridge and the North American coast. Note the general ridge trend. S = Sovanco fracture zone; JdF = Juan de Fuca ridge; B = Blanco fracture zone.

amorphous silica, with barite constituting 80% of the total and very low anhydrite, suggesting redissolution (Table 1; ref. 13). Zinc sulphide contains galena and intermediate solid solution; textures and galena dendrites indicate rapid crystal growth. This mineralogy must have been produced by temperatures >150 °C[14]. The chemical analyses (Table 1) are similar to others reported from this ridge[9,7] with samples tending to be rich in zinc and silver and poor in copper.

Fluid from vent A has an origin similar to that of the Galapagos springs where deep primary hydrothermal fluid ascends and mixes below the sea floor with local seawater[15] whose proportion may be increased on sampling; assuming only two end members and no magnesium in the primary fluid[15], the magnesium content (Table 2) suggests the sample is 5% primary fluid and 95% seawater. Temperature relationships remain uncertain; extrapolation of the 29 °C vent temperature gives 532 °C for the primary fluid, with quartz thermometry giving a better estimate[15]. The [Si], extrapolated to [Mg] = 0, is 18.6 mmol kg^{-1}, consistent with a temperature of 300-350 °C.

In most respects the chemistry is similar to that of other vents[15–18], but the helium-3 enrichment is markedly different. Global chemical fluxes can be estimated from the element/He systematics of individual vents[17]. Vent A fluid has a $^3He/^4He$ ratio of (8.11 ± 0.15) times atmospheric value, similar to local basaltic-glass values (8.22, 8.36). The absolute ^3He enrichment calculated from the measured $^3He/Ne$ ratio (assuming Ne behaves conservatively) is very high: 580 times the value for air-saturated seawater, in contrast with enrichments of 110 times at Galapagos[17] and 135 times at 21° N (ref. 18) normalized to

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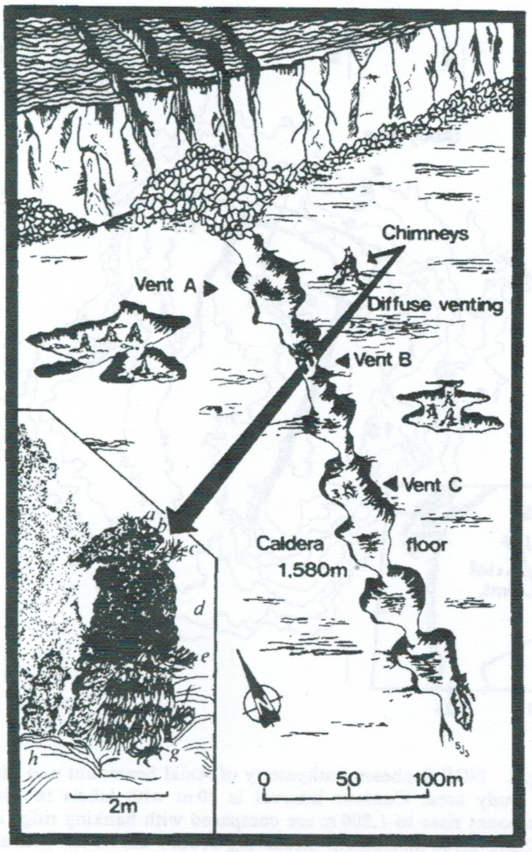

Fig. 2 Drawing of the northern caldera wall and floor on Axial Seamount. Extensive submersible searches revealed fissuring only in a limited zone on the caldera wall. On the floor, the single fissure, trending N–S, comprised a series of depressions 15–25 m wide, 30–50 m long and 5–20 m deep. Concentrated hydrothermal activity was present at three 'vents'. Hydrothermal flows were found east of the fissure on a sulphide chimney and in an area of cracked basalts. Inset: The active sulphide chimney was densely populated in distinct zonation with respect to the warm water flow. *a*, Protozoan colonies (folliculinid ciliate); *b*, polynoid polychaetes; *c*, pogonophorans (white tubes); *d*, limpets stacked one above the other in numbers estimated up to 10^5 on this structure; *e*, pogonophorans and alvinellid polychaetes; *f*, small gold pogonophorans; *g*, majid crabs observed feeding on the pogonophorans. Water flowed from under the ledges at *c* and *e*. The small spire *h* was recovered intact.

the same magnesium concentration. Evidently, ^{3}He–heat ratios may show sufficient variation to make global flux estimates very uncertain.

The Axial Seamount fluid has higher alkalinity than local seawater, its relatively acid *p*H (6.18 versus 6.65 in an equivalent Galapagos fluid), at which iron remains in solution despite the high sulphide concentration, results from its high inorganic carbon content. The CO_2 enrichment (40 mmol kg^{-1}) is similar to that of helium and the source may be magmatic. Alkalinity may have been added during subsurface mixing[19]; in laboratory seawater–basalt experiments at 300 °C, alkalinities of up to 1.3 meq kg^{-1} have been generated.

Dense thickets (4–6 m^2) of pogonophorans overgrew major vents in the fissure, whereas minor vents were surrounded by bacterial mats, small prone pogonophorans and limpets. Colonial protozoans and bacterial mats colonized most surfaces of the active fissure sections and localized bacterial mats delineated areas of diffuse venting south of the sulphide chimneys. The density of vent animals on the one active chimney was high (Fig. 2).

Table 1 Composition of chimney rock samples

Minerals in decreasing order of abundance*

Major	Minor	Trace
Barite	Wurtzite	Galena
Amorphous silica	Pyrite	Cu–Fe ISS‡
Sphalerite†	Anhydrite	Tetrahedrite
Marcasite		

Chemical analysis§

Weight %	Sample 1	Sample 2
Zn	10.1	28.2
Fe	5.8	3.2
Cu	0.1	0.3
Pb	0.6	0.1
Ba	15.0	14.2
Ca	0.2	0.1
SiO_2	41.4	20.4
CO_2	0.3	0.2
p.p.m.		
Ag	342	233
Cd	110	740
Mo	45	32
Co	3	3
Ni	32	11
Mn	470	1,300

In addition to the small spire, three hand specimens were also retrieved.

* Minerals identified by transmitted and reflected light microscopy and X-ray diffraction. († Three electron microprobe analyses measured elemental quantities by weight: Zn, 61.3%; Fe, 4.6%; Cu, 0.7%; S, 33.4%. ‡ Five samples of intermediate solid solution were analysed: Zn, 1.6%; Fe, 29.1%; Cu, 33.5%; S, 35.8%.)

§ Bulk chemical analysis. (Methods of analysis: Zn, Fe, Ba, Ca, SiO_2 by X-ray fluorescence; Cu, Pb, Ag, Cd, Mo, Co, Ni, Mn by direct-coupled plasma; CO_2 by wet chemistry. Sample 1, unoxidized; sample 2, oxidized.)

Table 2 Fluid chemistry

Component	Vent A Axial Seamount	Local seawater (1,600 m)
Mg (mmol kg^{-1})	49.39	52.04
$(^3He/Ne)/(^3He/Ne)_{satd}$	580	1.5
Si (mmol kg^{-1})	1.10	0.16
Cl (mmol kg^{-1})	531.9	538.6
Ca (mmol kg^{-1})	11.06	10.13
SO_4 (mmol kg^{-1})	25.94	27.83
*p*H	6.18	7.7
Alk (meq kg^{-1})	2.66	2.42
ΣC (mmol kg^{-1})	4.32	2.37
Fe (μmol kg^{-1})	2.6	—
H_2S (μmol kg^{-1})	330	—
Mn (μmol kg^{-1})	27.7	—
Li (μmol kg^{-1})	58.0	28
Rb (μmol kg^{-1})	4.4	1.3
Ba (μmol kg^{-1})	1.31	0.15
Sr (μmol kg^{-1})	92±3	88

Fourteen new vent metazoans were recovered in three samples. The pogonophoran (length ≤1.5 m, diameter ≤2 cm) is a new vestimentiferan taxon (M. L. Jones, personal communication). Ultrastructural analyses have confirmed that the bacteria in the trophosomal tissues are definitely intracellular[20]. Two alvinellid polychaetes are new species in the genus *Paralvinella*[21]; the only animal described from tropical vents is an ampharetid polychaete species, *Amphisamytha galapagensis*[22]. Other new species include two polynoid polychaetes (D. Weston, personal communication), three gastropods in new subfamilies under description (J. McLean, personal communication) and a copepod from the pogonophoran tubes[23]; a few tiny bivalves seem to be related to clam and mussel families from other vents (F. Bernard, personal communication); a vent-associated fish was not collected and galatheid and majid crabs, common on the periphery of the vents, are known deep-water species. More extensive descriptions of the Axial Seamount organisms can be found elsewhere[20].

Large quantities of mucus bound the pogonophoran tubes together and provided habitat for many small organisms. The mucus, containing predominantly bacterial filaments but also coccoid bacteria (0.5–1.0 μm in diameter), fragmented alvinellid tubes, diatom frustules and basalt fragments, was intimately associated with alvinellid polychaetes and may be produced by them. The mucus was incubated on board ship in filtered vent water with $NaH^{14}CO_3$ to detect dark-CO_2 fixation. The measured rate of CO_2 incorporation (86.3 mg-C kg-dry wt^{-1} day^{-1}; $n = 6$, s.d. = 23.4) suggests that these bacteria are significant primary producers. The rate of CO_2 fixation by bacteria in the same emitted vent water collected for chemical analyses gave a value of 2.42 mg-C m^{-3} day^{-1}, which is in the range measured in waters of the Galapagos vents[24]. Presence of thiosulphate at 1 mM increased CO_2 incorporation to 3.7 mg-C m^{-3} day^{-1} and, at 10 mM, the rate was 4.4 mg-C m^{-3} day^{-1}. This response indicates that sulphide-oxidizing bacteria were active in the vent water. Bacterial cell numbers, counted by epifluorescent microscopy, were 3.5×10^4 cells cm^{-3}, significantly lower than those reported for Galapagos vent waters[24,25].

The unique features of Juan de Fuca hydrothermal systems will be investigated further with data from the expedition to the ridge in the summer of 1984.

We thank Al Witcombe and the crew of the Pisces IV; Captain S. Gulati and the crew of MV Pandora II; Karen Lamphere of Oceano Systems for help in navigation; Fisheries and Oceans Canada and Energy, Mines and Resources Canada for financial and logistical support; NOAA for providing preliminary versions of Seabeam and Seamarc I coverage. Canadian authors were supported in part by NSERC and American authors by NSF grants OCE 81-17049, OCE 81-11713 and OCE 81-00980. We also thank Tony Fitch, Pat Shaw, Dick Tripp, John Edmond, Roy Hyndman and Harmon Craig.

Received 12 June; accepted 23 October 1984.

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