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Hydrothermal vents near a mantle hot spot: the Lucky Strike vent field at 37°N on the Mid-Atlantic Ridge

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Abstract

The Lucky Strike hydrothermal field occurs in the summit basin of a large seamount that forms the shallow center of a 65 km long ridge segment near 37°N on the Mid-Atlantic Ridge. The depth and chemistry of the ridge segment are influenced by the Azores hot spot, and this hydrothermal field is the first Atlantic site found on crust that is dominated by a hot spot signature. Multiple hydrothermal vents occur over an area of at least 300 m by 700 m. Vent morphologies range from flanges and chimneys with temperatures of 200–212°C, to black smoker chimneys with temperatures up to 333°C. Cooler fluids from northern vents have higher chlorinities and lower gas volumes, while hotter, southern fluids have chlorinities 20% below seawater with higher gas volumes, suggesting phase separation has influenced their compositions. All gas volumes in fluids are higher than those at TAG and Snake Pit hydrothermal fields. Black smokers exhibit their typical mineralogy, except that barite is a major mineral, particularly at lower-temperature sites, which contrasts with previously investigated Atlantic sites. The fluid chemistry, distribution of the relict sulfide deposits on the seamount summit in the areas investigated using DSV *Alvin*, and contact relationships between active vent sites and surrounding basaltic and sulfide substrate suggest that the hydrothermal system has a long history and may have recently been rejuvenated. Fauna at the Lucky Strike vent sites are dominated by a new species of mussel, and include the first reported sea urchins. The Lucky Strike biological community differs considerably from other vent fauna at the species level and appears to be a new biogeographic province.

The Lucky Strike field helps to constrain how variations in the basaltic substrate influence the composition of hydrothermal fluids and solids, because basalt compositions at Lucky Strike are 10–30 times enriched in incompatible elements compared to other Atlantic hydrothermal sites such as TAG, Snake Pit and Broken Spur. The incompatible element

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enrichment appears to influence the compositions of hydrothermal fluids and solid deposits: fluids are enriched in Ba and the light REE, and barite is a common mineral. For hydrothermal sites from around the world, REE ratios in fluids correlate with the REE ratios in basalts, and high Ba in the substrate is associated with barite in the hydrothermal deposits. Therefore the chemistry of the substrate exerts an important control on both fluid trace element and solid chemistry of sea floor hydrothermal systems, even for those constructed on bare rock. The deep mantle processes that give rise to hot spots ultimately are manifested in distinctive compositions of hydrothermal fluids and solids.

Keywords: Mid-Atlantic Ridge; hydrothermal vents; hot spots; geochemistry; communities

1. Introduction

The occurrence, size, mineralogy and geologic setting of hydrothermal fields on mid-ocean ridges (MOR) may be controlled by many variables, including crustal permeability, magma supply, depth to heat source, sea floor depth, crustal thickness, crustal composition, spreading rate, and the spatial and temporal history of volcanic and tectonic activity. To constrain the relative importance of such parameters, which will serve to guide quantitative models, it is necessary to examine hydrothermal systems in many different tectonic and geographic environments.

The MAR in the North Atlantic (Fig. 1) has only small variations in spreading rate but large variations in axial depth, crustal thickness and basalt composition, due to the influence of mantle hot spots on the ridge, most notably those near the Azores and Iceland [1]. It thus provides the potential for investigating effects other than spreading rate on hydrothermal

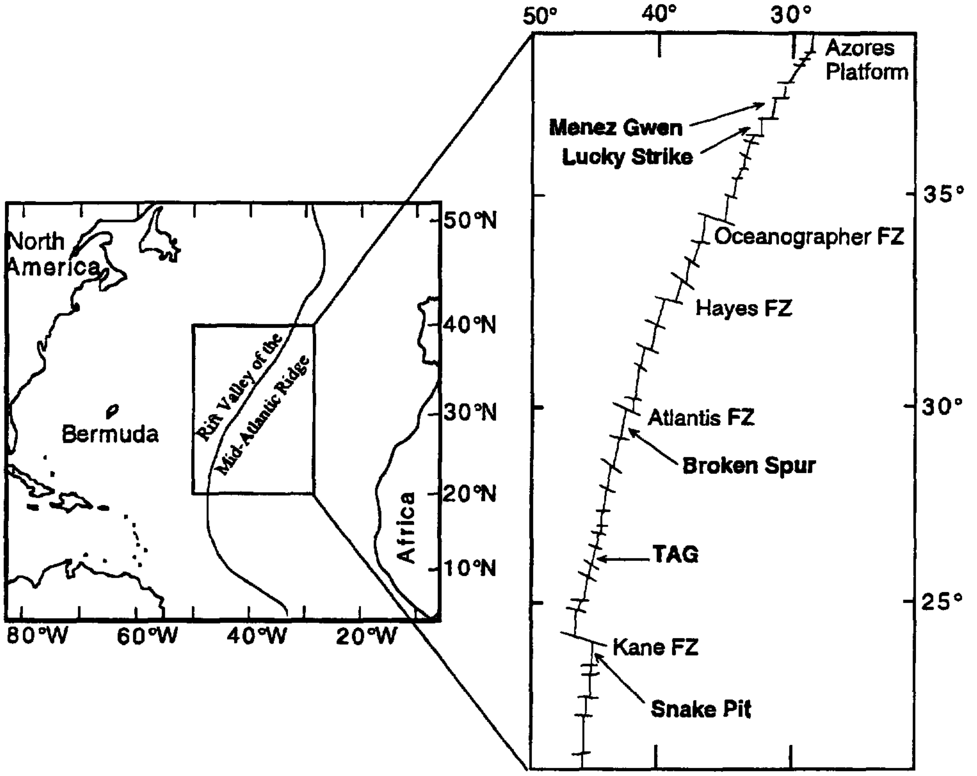


Fig. 1. Location of the Lucky Strike hydrothermal field in the context of the northern mid-Atlantic Ridge. Other known Atlantic hydrothermal sites are indicated. Sites discovered subsequent to Lucky Strike include Broken Spur (at 29°N) [4], Menez Gwen (at 38°N) [5], and the Logatchev hydrothermal field at 14° 45′N [6] There are indications from water column anomalies that several additional sites may also be active [7,8].

systems. The French American Ridge Atlantic (FARA) program was conceived in part to discover new hydrothermal sites on crust with diverse characteristics. Prior to FARA, only two sites of high temperature hydrothermal activity had been discovered: on the MAR–TAG at 26°N (e.g., [2]), and Snake Pit at 23°N (e.g., [3]). TAG and Snake Pit are on slow-spreading ocean crust with normal (i.e., deep) axial depth and crustal thickness [9], and basaltic substrate composed of typical ocean ridge basalt depleted in incompatible elements such as K, Ba and the light rare earth elements (REE) [10]. A clear need, therefore, was to find new sites on thick, shallow crust with a composition enriched in incompatible trace elements.

To discover such a hydrothermal site, a coordinated mapping and sampling strategy was implemented which focused on the anomalous bathymetry and crustal composition caused by the Azores hot spot. A multibeam bathymetric map between 34°N and 41°N [11,12] was used as the basis for the FAZAR expedition, which obtained closely spaced (~ 5 km) rock samples from the neovolcanic zone [13,14], and explored for chemical anomalies in the water column to locate hydrothermal activity [14–17].

Serendipitously, one of the dredges (D-15) sampled an active hydrothermal field, recovering sulfide deposits covered with live organisms characteristic of hydrothermal vent communities, hence the name "Lucky Strike" [14]. During six *Alvin* dives in June 1993, several hydrothermal vents were discovered at the Lucky Strike site. This paper presents the first-order geochemical, volcanic, tectonic and biological characteristics of Lucky Strike, and places the observations in the larger context of other known ridge hydrothermal sites. In particular, the aim is to consider how the anomalous depth and chemical composition of the crust caused by the hot spot may have influenced the diverse manifestations of hydrothermal activity.

2. Observations

The MAR exhibits a gradient in sea floor depth, from less than 1000 m at the center of the Azores platform near 39°N to 3500 m just north of the

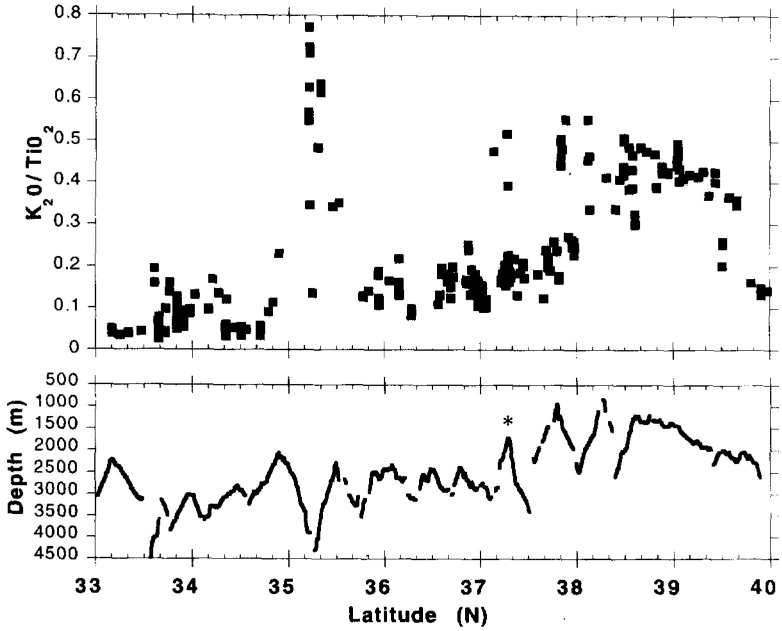
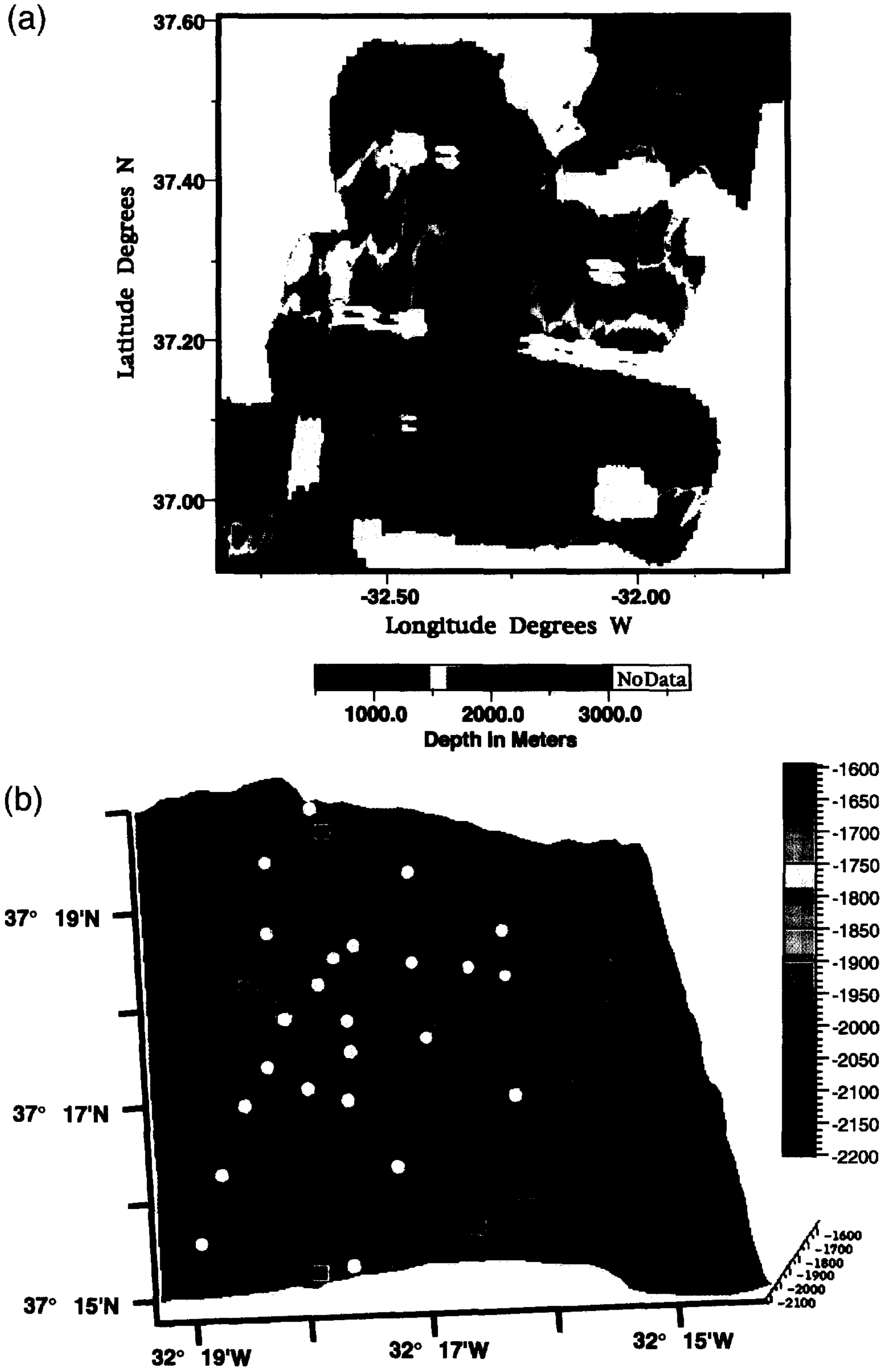


Fig. 2. Depth and chemistry variations across the Azores hot spot and Oceanographer chemical anomaly. Depths are the minimum depths within the rift valley, from [12]. K_2O/TiO_2 data are from samples collected during the FAZAR expedition (Langmuir, unpubl. data). Location of the Lucky Strike segment is indicated by an asterisk on the lower diagram. Note that K_2O/TiO_2 ratios for the TAG, Snakepit and Broken Spur areas are 0.09 ± 0.01, about half the level of even the less-enriched rocks from the Lucky Strike segment.


(a)
37.60
37.40
37.20
37.00
Latitude Degrees N
-32.50
-32.00
Longitude Degrees W
NoData
1000.0
2000.0
3000.0
Depth In Meters
(b)
37° 19'N
37° 17'N
37° 15'N
32° 19'W
32° 17'W
32° 15'W
-1600
-1650
-1700
-1750
-1800
-1850
-1900
-1950
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-2050
-2100
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-1600
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-2100

Hayes transform near 34°N (Fig. 2). In this region, there are thirteen ridge segments that vary in length from < 10 km to ~ 90 km [11,12]. The Lucky Strike segment (Fig. 3) is the third segment south of the Azores platform. It is ~ 65 km long with depth ranging from 1550 m, at the summit of Lucky Strike seamount, to greater than 3000 m at the intersections with the northern and southern offsets that delimit the segment. Rectangular in shape, the rift valley of the Lucky Strike segment has a nearly uniform width of 11 km between the rift valley walls. This is in contrast to other MAR segments, such as the FAMOUS segment, where the axial valley narrows to as little as 3 km at its midpoint [18]. Detrick et al. [12] estimated crustal thickness variations associated with the Lucky Strike segment using mantle Bouguer gravity anomalies, and obtained a model crustal thickness at the center of the segment of ~ 9 km, substantially greater than the 6 km thickness of normal ocean crust, and similar to the 10 km model crustal thickness estimate for the center of the Azores platform. Therefore, axial depth and crustal thickness at Lucky Strike both reflect the influence of the Azores hot spot.

2.1. Geological description of Lucky Strike seamount

A striking feature of the Lucky Strike segment is the prominent seamount in the center of the rift valley that forms a broad platform extending nearly across the rift valley (Fig. 3). The seamount has an area of ~ 50 km^2 and maximum relief above the rift valley floor of ~ 250–300 m. Multibeam bathymetry shows the seamount summit consists of three cones that rise ~ 150 m above a central depression. Dredge 15 from the FAZAR expedition began in the depression between the three cones, and dredged the west flank and top of the eastern cone. The dredge recovered very fresh, aphyric glass nuggets; moderately altered, highly vesicular pillow fragments with no glass; and pieces of active hydrothermal deposits covered with vent organisms.

Observations from *Alvin* indicate that the west-facing flank of the eastern cone of Lucky Strike seamount consists of a series of N–S trending pillow ridges separated by small valleys up to 30 m deep and less than 50 m wide. These topographic features create a rugged terrain but are on a scale that is below the resolution of multibeam bathymetry collected from surface ships. The overall N–S dominated tectonic character of the seamount summit, as imaged by TOBI side-looking sonar ([19], L. Parson, pers. commun., 1995), is confirmed by the bottom observations. All lavas recovered from the eastern cone are older, highly vesicular lavas. During the *Alvin* program, very fresh glassy lava was recovered from a dredge on the southern cone's north slope. That lava is relatively aphyric, consisting primarily of sheet flow fragments, and has a similar chemical composition to the glass nuggets from Dredge 15. A Nautile dive program in 1994 found that the very fresh lava formed a lava lake in the center of the summit depression [20].

2.2. Chemical compositions of basaltic lavas

Chemical compositions of basalt samples from Lucky Strike seamount are all enriched in incompatible elements relative to normal MORB, but fall into two distinct compositional groups (Table 1). Older-appearing lavas present on top of the summit cones are particularly enriched in incompatible elements, with as much as 300 ppm Ba and 300 ppm Sr. Very fresh, younger, less vesicular lavas of the central depression are less enriched (60 ppm Ba, 110 ppm Sr), but still contain significantly higher concentrations of incompatible elements, such as K and Ba, than N-MORB (see Table 1). Enrichment in Lucky Strike samples includes all "incompatible" trace elements that prefer liquid to solid during mantle melting processes, such as K, Rb, Cs, Ba, La and Pb. These results suggest a large contrast in crustal composition between the Lucky Strike segment and the TAG, Snake Pit and Broken Spur segments.

The combination of lava and hydrothermal sample characteristics indicates that Lucky Strike seamount

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Fig. 3. (A) SIMRAD multibeam bathymetry (100 m grid) of the Lucky Strike ridge segment. Simrad bathymetry from the Sigma expedition [11]. Lucky Strike seamount occurs within the black box in the center of the segment, shown in (B). (B) Bathymetric perspective view of Lucky Strike seamount shown as color surface model (80 m gridded data). The hydrothermal sites occur within the depression defined by the three central cones. Black boxes are dredge locations; white circles are rock core locations. Chemical data for many of these locations are given in Table 1.

Table 1
Chemical compositions of basalt samples from the Lucky Strike seamount

Sample	n	Depth [a]	Lat N [b]	Long W [b]	SiO_2	TiO_2	Al_2O_3	Fe_2O_3 [c]	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	Sum	Ba	Sr
Atlantis II 129-6 DCP data																	
2602-3	1	1609	37.294	32.274	48.71	1.18	16.60	7.77	8.43	0.137	14.40	2.27	0.611	0.244	100.35	287	290
2602-5	1	1566	37.299	32.272	48.78	1.19	16.05	8.04	8.72	0.143	14.14	2.24	0.630	0.246	100.18	281	284
2604-3	1	1565	37.296	32.272	48.69	1.18	16.12	8.03	8.72	0.140	14.01	2.34	0.592	0.257	100.08	296	295
2605-1	1	1635	37.293	32.275	50.41	1.24	17.40	5.73	7.04	0.104	15.34	2.24	0.600	0.244	100.34	316	317
D1-3		1660	37.299	32.279	49.80	1.16	16.48	7.82	8.71	0.139	14.17	2.26	0.575	0.225	101.34	270	280
D2	4	1702	37.289	32.280	50.26	1.03	14.62	10.90	8.11	0.181	11.92	2.18	0.184	0.130	99.51	59	109
Atlantis II 127-1 and 127-2 (Fazar Expedition) microprobe and shipboard plasma																	
								FeO [d]									
RC103-2	5	1864	37.253	32.293	51.17	1.10	14.90	10.02	7.84	0.19	11.98	2.30	0.18	0.11	99.79		
D37	8	1959	37.256	32.300	51.40	0.98	15.03	9.07	8.28	0.17	13.02	2.14	0.17	0.13	100.39	51	111
D36.B	8	2274	37.256	32.288	51.89	1.07	14.71	9.93	7.74	0.18	12.09	2.32	0.17	0.15	100.24	55	99
D36.A	10	2274	37.256	32.288	51.85	1.14	14.98	9.91	7.48	0.17	11.85	2.39	0.21	0.15	100.11	61	110
RC104	5	1804	37.267	32.285	50.98	1.07	14.83	10.08	8.24	0.17	11.85	2.29	0.18	0.12	99.81	59	114
RC106-1	5	1707	37.277	32.270	51.06	1.05	14.77	10.17	8.09	0.20	11.70	2.34	0.20	0.14	99.72		
RC116	10	1755	37.278	32.291	49.99	1.22	15.95	7.07	8.82	0.14	13.75	2.26	0.57	0.25	100.01	188	253
RC41	5	1561	37.284	32.281	50.75	1.26	15.46	8.24	8.37	0.17	12.95	2.28	0.49	0.22	100.19		
D15	26	1706	37.291	32.283	51.48	1.07	14.69	9.80	8.14	0.17	12.06	2.17	0.20	0.14	99.93	62	109
RC105	10	1770	37.291	32.300	51.19	1.07	14.81	9.53	8.13	0.18	12.31	2.23	0.20	0.14	99.77	62	117
RC43-1	5	1614	37.297	32.281	51.06	1.05	14.81	9.88	8.10	0.22	12.04	2.23	0.20	0.14	99.71		
RC42	5	1768	37.302	32.292	51.35	1.28	14.64	10.18	7.55	0.18	11.74	2.42	0.21	0.16	99.72		
RC107	5	1808	37.312	32.267	51.53	1.28	14.65	10.29	7.36	0.18	11.62	2.40	0.24	0.17	99.72	65	113
RC108-1	5	1801	37.316	32.279	50.86	0.92	14.91	8.99	8.77	0.17	12.85	2.07	0.15	0.12	99.81	44	98
RC109	5	2125	37.316	32.279	51.95	1.37	13.91	10.57	7.34	0.19	11.40	2.67	0.24	0.18	99.82		
RC109-3	5	2125	37.316	32.279	50.78	0.99	14.97	9.31	8.50	0.17	12.59	2.11	0.22	0.14	99.76		
MARK [e]					49.44	1.62	15.66	10.94	7.71	0.178	10.94	3.02	0.132	0.171	99.83	9.9	131
TAG [e]					50.02	1.41	15.38	10.39	8.66	0.174	11.23	2.76	0.076	0.136	100.20	7.5	112
Broken Spur [e]					49.53	1.45	15.24	10.93	7.95	0.182	11.54	2.77	0.073	0.132	99.74	7.5	100

[a] Dredge locations are "On bottom". [b] Rock core locations are midway between deploy and recovery positions. [c] Plasma Fe is total Fe as Fe_2O_3. [d] Microprobe and shipboard plasma Fe is total Fe as FeO. [e] Average MARK basalt from neovolcanic ridge [64]; TAG and Broken Spur basalts are from Langmuir (unpubl. data).

is a composite feature composed of rocks of variable age, flow morphology and chemical composition. The hydrothermal sites discovered by *Alvin* are located on older, enriched, vesicular lavas, but near a very fresh, young flow within the seamount summit basin.

2.3. Morphology and mineralogy of hydrothermal deposits

Active vents investigated by *Alvin* are dispersed over an area 700 m by 300 m, at depths ranging from 1618 m, in the north, to 1730 m, in the south (Fig. 4). A summary of characteristics of each vent locale is given in Table 2. Northern sites (Statue of Liberty and Sintra) have fluid temperatures ranging from 200°C to 212°C. Statue of Liberty is a chimney and flange structure built directly on basalt. The active flange, composed of barite with lesser amounts of marcasite + pyrite and sphalerite, forms a ~ 2 m wide ledge around the base of a mound of inactive massive sulfide spires and flanges (Fig. 5BFig. 6A) [21]. Pieces of massive sulfide spires are dominated by either chalcopyrite or marcasite. Chalcopyrite-dominated spires contain minor marcasite + sphalerite + barite near the outer edges, while marcasite-dominated spires contain minor chalcopyrite and voids filled with large (up to 3 mm) barite crystals,

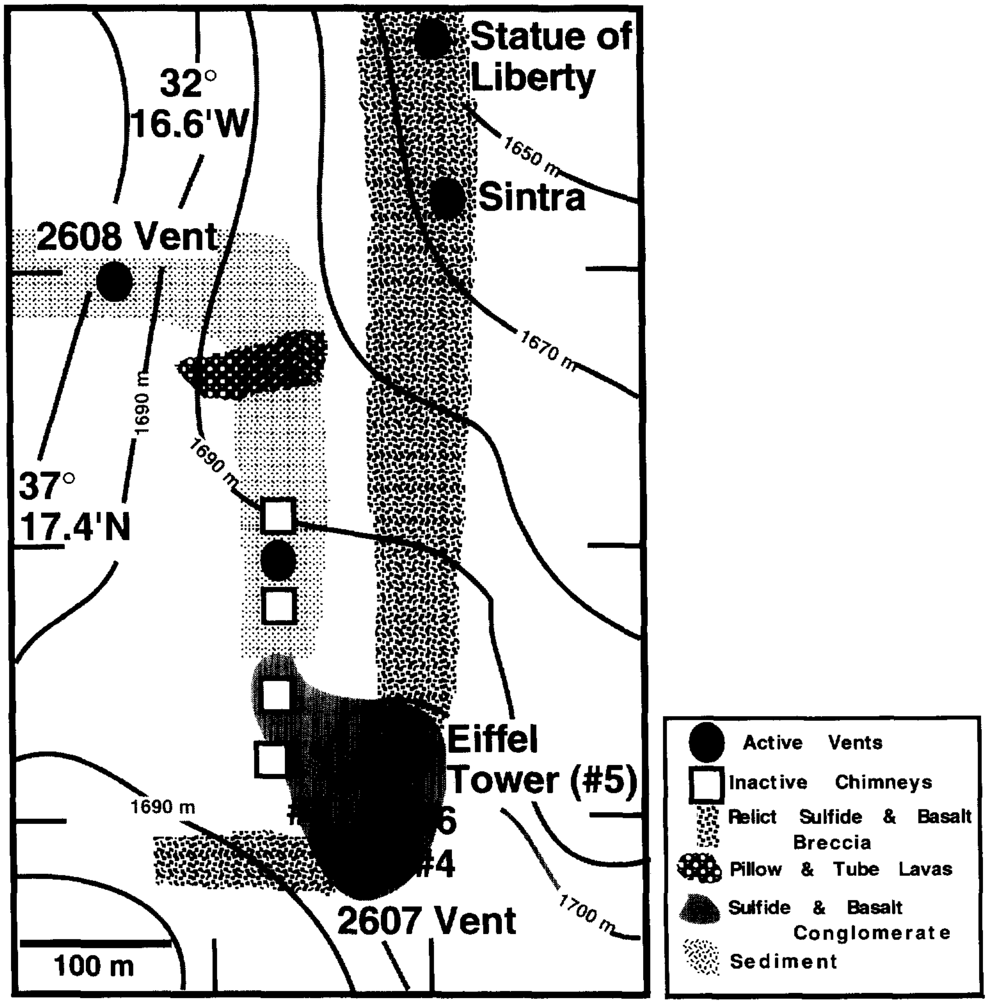


Fig. 4. Close-up map of the Lucky Strike vent sites sampled by *Alvin*.

Table 2
Morphology and mineralogy of active vent sites in the Lucky Strike hydrothermal field

Vent site	Location		Depth (m)	Morphologic characteristics	Fluid temperatures	Mineralogy [a]
Northern region of vent field						
Statue of Liberty (Marker #1)	37°17.59′N	32°16.49′W	1646	2 m wide active flange at base of a mound consisting of inactive chimney spires $\sim$ 2–3 m high	Fluid pooled beneath flange: 156–200°C	Flange: bar with mar ± pyr. and sph Chimney spires: cpyr, mar,sph, bar; some late silica
Sintra (Marker #3)	37°17.53′N	32°16.48′W	1646	Spire $\sim$ 5 m high; active on one side, inactive on the other. Smaller (< 1 m) inactive chimneys around base. Talus apron (30 m in diameter) of massive sulfide blocks	Both low temperature diffuse flow (8–14°C), and 197–212°C focused flow on active side of spire	Inactive side: pyr + cpyr; outer oxidized layer with ata and non; Active side: conduit lined with mar, minor cpyr and sph; outer wall of mar, bar and sph; mid-wall of mar + bar + anhy with minor sph
Southern region of vent field						
2608 Vent	37°17.50′N	32°16.64′W	1715	Single spire $\sim$ 10 m high	Focused flow: 333°C	All locations have interior chimney walls of massive cpyr with variable amounts of pyr.
Eiffel Tower	37°17.33′N	32°16.51′W	1700	Tapered spire $\sim$ 20 m high; active on one side, inactive on the other	Focused flow up to 325°C	Outer chimney walls: pyr and anhy with minor sph and mar.
Mounds (#4)	37°17.27′N	32°16.51′W	1706	All mounds sites are small chimneys (< 1 m high) with outer diameters of < 10 cm on top of small (< 1–3 m diameter) sulfide mounds	Focused flow: 292°C	Trace amounts of bor, cov, dig, late amorphous silica and bar (in some samples)
Mounds (#6)	37°17.30′N	32°16.52′W	1704		Focused flow: 298°C	
Mounds (#7)	37°17.28′N	32°16.54′W	1708		Focused flow: 297°C	
2607 Vent	37°17.27′N	32°16.53′W	1706		Focused flow: 319°C	

[a] pyr = pyrite; mar = marcasite; bar = barite; cpyr = chalcopyrite; sph = sphaerite; dig = digenite; cov = covellite; any = anhydrite; ata = atacamite; non = nontronite.

euhedral (~ 500 μm) sphalerite crystals, and late amorphous silica.

Sintra consists of a 5 m high spire that is active on the southwest side but inactive on the other side (Fig. 5A). Massive sulfide talus from the inactive side has 5 mm thick, brown, oxidized outer layers that include patches of green atacamite and yellow nontronite, and interiors comprised of massive pyrite and chalcopyrite with trace amounts of sphalerite. Both low-temperature diffuse flow (8–14°C), and a zone of more focused high temperature (197–212°C) flow are present on the active side. The region of focused flow is zoned from a central conduit lined with large (2 mm) blades of marcasite, with minor chalcopyrite and sphalerite. This grades outward to a mid-wall mineralogy dominated by marcasite, barite and anhydrite with minor sphalerite, to an outer wall of marcasite, barite and sphalerite. There are several small (< 1 m), inactive chimney structures around the base of the active spire, and the whole complex is surrounded by a talus apron (~ 30 m diameter) of blocks of massive sulfide with outer oxidized layers

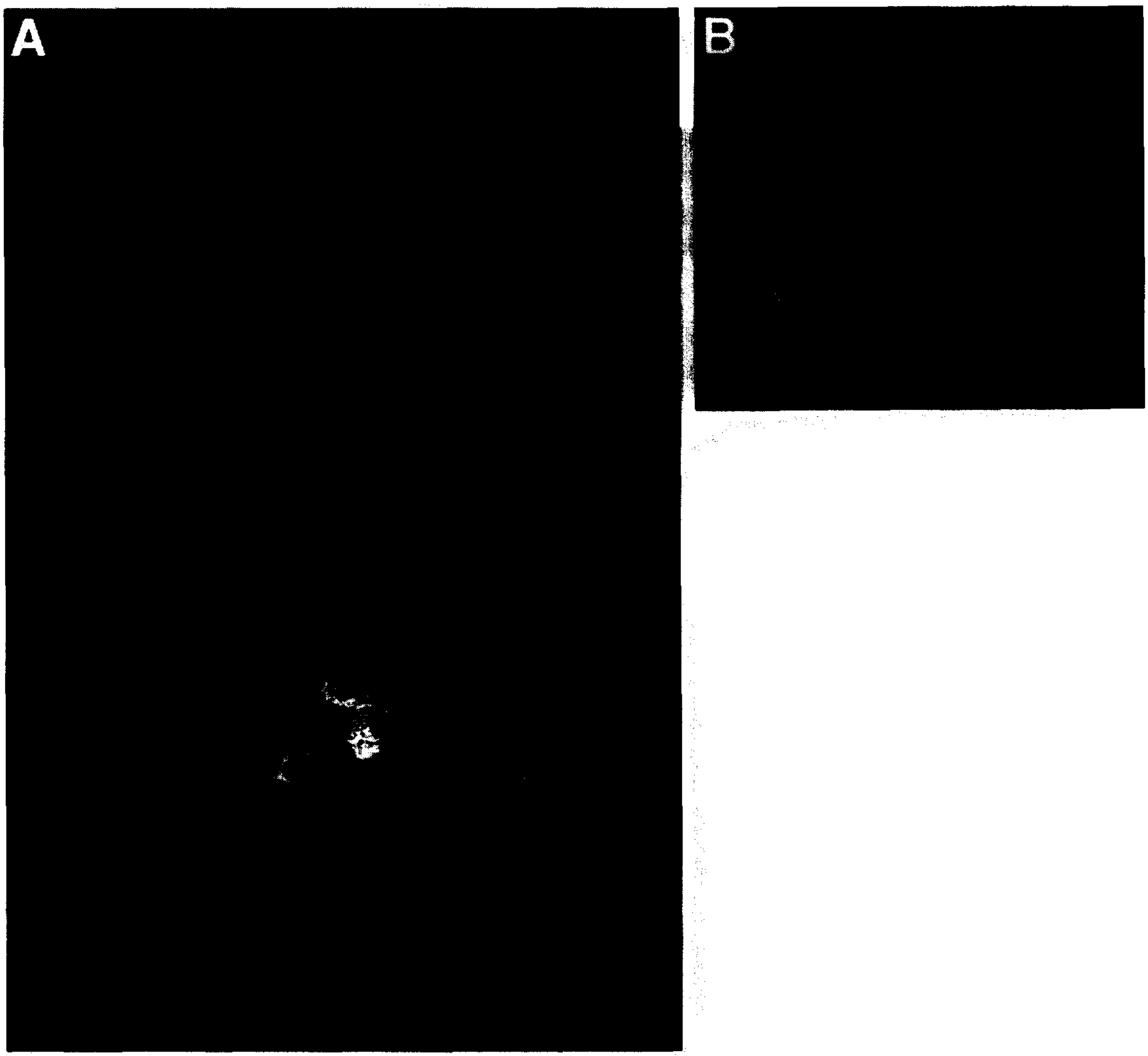
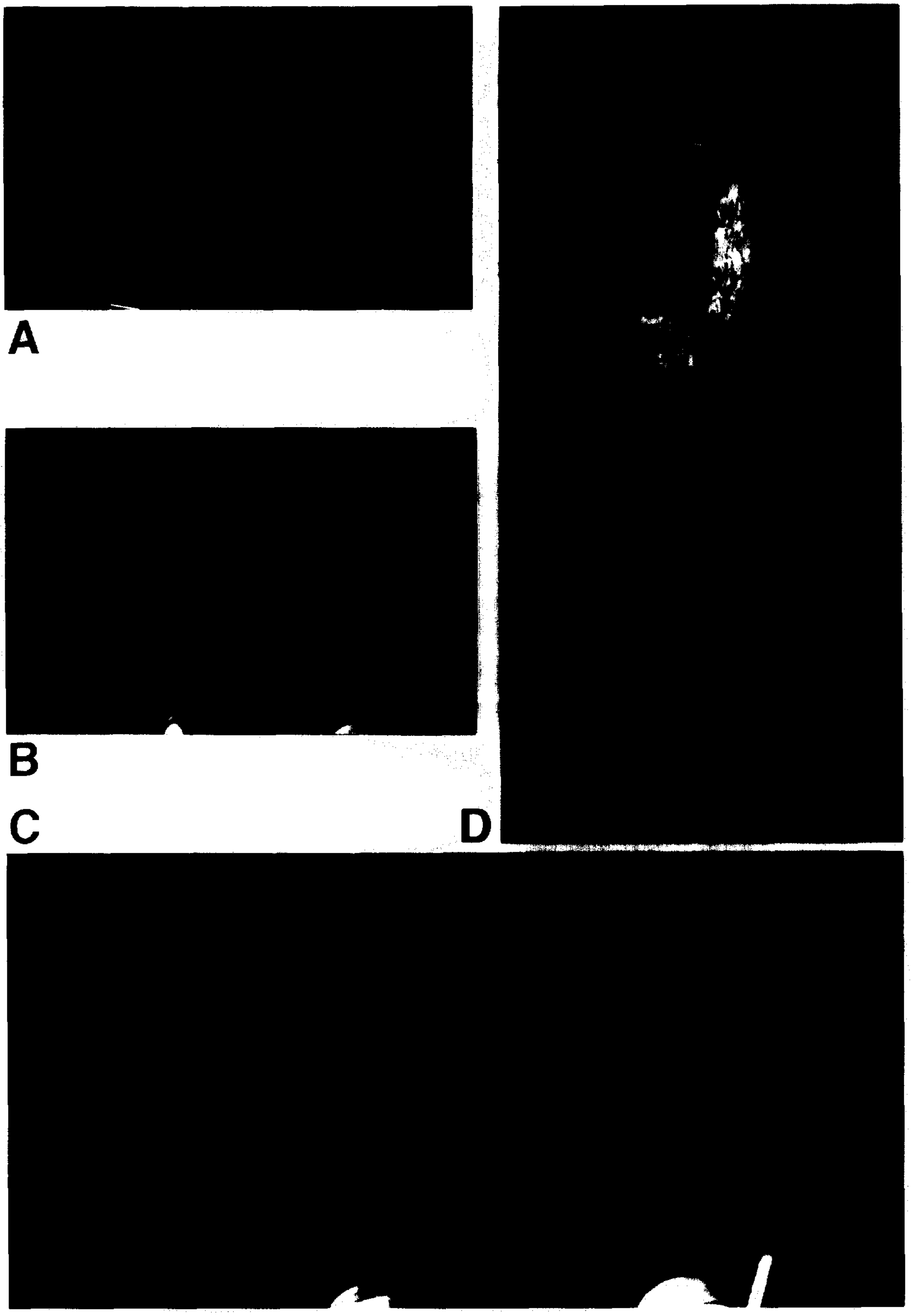


Fig. 5. (A) The chimney Sintra. The line attached to the number 3 is about 1 m in length. (B) Statue of Liberty. The chimney on top is inactive. Fluids at 200°C come from under the flange at the lower left. A temperature probe about 1 m in length can be seen resting on top of the flange.


A
B
C
D

similar to those observed on the inactive side of the spire.

Southern hydrothermal sites at Lucky Strike are located on top of slabs of hydrothermally cemented breccia. This breccia is composed of fragments of basaltic glass and plagioclase crystals (both of which are rimmed with amorphous silica) and sulfide and barite grains, all cemented with silica and barite.

The most common type of vent structures in the southern area are small, active black smoker chimneys (< 0.5 m high with outer diameters < 10 cm) on top of small (< 1–3 m diameter) sulfide mounds, venting fluids with temperatures which range from 303°C to 319°C (the "Mounds Vents"; Fig. 6B,C). There is also lower temperature diffuse flow which emanates from cracks in the conglomerate (Fig. 6C) and supports mussels and white flocculent material. Just north of the small mounds, there is a 20 m high, tapered spire (Eiffel Tower) (Fig. 6D). This spire is similar to Sintra in its morphology and venting is also restricted to one side; however, fluid temperatures at Eiffel Tower are higher, up to 325°C. The highest temperatures in the vent field (333°C) were measured at a 10 m high, narrow chimney structure (2608 Vent) located northwest of the Mounds Vents (see Fig. 4), in an area that is on the periphery of the lava pond in the summit depression [20]. All measured temperatures at the southern vents in the Lucky Strike field are below the boiling point at 1700 m — 355°C [22].

Chimney samples recovered from high temperature vent sites (Eiffel Tower, Marker 7, Marker 4, and the 2607 and 2608 Vent sites, Fig. 4) have typical black smoker mineralogy, except that interior walls of some conduits are composed of massive chalcopyrite with variable amounts of intergrown pyrite instead of monomineralic chalcopyrite. Outer walls of these chimneys are composed of pyrite and anhydrite with minor amounts of sphalerite and marcasite. Trace amounts of bornite, covellite, digenite and late amorphous silica are observed towards the exteriors of some samples. Barite is present in the outer layers of some samples but is less abundant than in chimneys from Sintra and Statue of Liberty.

2.4. Chemistry of the vent fluids

Fluids at Lucky Strike were sampled in pairs using the standard *Alvin* titanium syringe "majors" sampler. Seventeen pairs of sample bottles were collected from seven different vents. One bottle was dedicated to the analysis of gases, the other to the analysis of H_2S and other dissolved species. Total alkalinity, pH, hydrogen sulfide, silica, weight percent NaCl by refractive index, and total gas volumes were determined on board ship by standard methods [16,23,24]. Only shipboard data are reported here in conjunction with magnesium data determined on shore. Rare earth element (REE) data have been reported by Klinkhammer et al. [25]. Further analyses of the fluids are ongoing and will be reported elsewhere (K. Von Damm et al., in prep.). Data in Table 3 are extrapolated to $Mg = 0$ mmol/kg, the standard method of reporting vent fluid compositions, to correct for variable amounts of sea water entrainment during sampling. This assumes that any Mg measured in the fluids is an artifact of mixing with seawater during sampling. This correction may not be valid for Statue of Liberty vent, where four different samples each contain 10.6 ± 0.3 mmol/kg Mg. This is either a remarkable coincidence, or may indicate that fluids venting at this site actually contain this amount of Mg.

Northern and southern sections of the vent field have different fluid compositions and temperatures (Table 3). Northern, cooler vents have chlorinities similar to, or slightly less than, the chlorinity of ambient seawater (Sintra fluids are 3% depleted relative to seawater). Southern vents have chlorinities approximately 20% depleted relative to seawater. Low chlorinity fluids have also been reported recently at Broken Spur [26]. Northern vents are also characterized by lower silica contents (~ 12.5 mmol/kg) in comparison to southern vents (~ 15.6 mmol/kg). These values are lower than those com-

Fig. 6. (A) Close-up of the flange at the base of Statue of Liberty, which is covered by yellow mussels, along with some pink sea urchins. Temperature probes can be seen above and below the flange. The picture is 2 m across. (B) Small black smoker characteristic of the southern sites. Note the lack of a significant chimney and biological activity. The picture is about 3 m across. (C) Black smoke exiting an anhydrite-rich chimney. Cracks in the background are emitting diffuse flow and are populated by mussels. Field of view encompasses about 10 m. (D) A composite from three photographs of the Eiffel Tower. The tower is 20 m tall and is intensively colonized by mussels.

Table 3
Hydrothermal fluid sampling sites and end member compositions

Vent area	n	Temp (°C)	Si (mmol/kg)	H_2S (mmol/kg)	pH [a]	Alk_t [b] (meq/kg)	NaCl (wt%)	Gas volumes (ml NTP/kg)
Northern sites								361–474
Statue of Liberty	8	202	12.8	3.2	4.2	0.2	3.5	
Sintra	6	212	13.2	1.9	4.9	0.1	3.5	
Southern sites								430–680
Eiffel Tower	6	325	15.7	3.3	4.1	−0.02	2.9	
Marker 4	2	297	16.0	2.8	4.1	−0.03	2.9	
Marker 6	4	303	17.1	3.1	4.1	−0.4	2.9	
Marker 7	2	302	16.3	1.4	4.0	−0.06	2.9	
2607 Vent [c]	2	319	16.3	3.1	4.5	0.3	2.9	
2608 Vent	0	333						
Seawater	4	4.5	0.013	0	7.9	2.2	3.5	

[a] Measured at 25°C, 1 atm.
[b] Total alkalinity.
[c] Also one of the mounds vents.

monly found in other MOR hydrothermal fluids [27], but are similar to those at Axial Seamount on the Juan de Fuca Ridge [28], which is at a similar depth to Lucky Strike. All fluids at Lucky Strike have relatively low hydrogen sulfide contents compared to other MOR vent fluids (Table 3).

Gas results also show distinct differences between northern and southern vents. Northern sites, which are at shallower depths, have lower gas volumes (361–474 ml NTP/kg) than the southern vents (430–680 ml NTP/kg). Higher gas contents in lower chlorinity fluids are consistent with a model invoking subcritical phase separation. In all fluids, CO_2 is the major gas (13–26 mmol/kg), and represents 75–80% of the total extracted gas. This is two times higher than TAG. Other gases that contribute to the total volume are H_2S (10–20%), N_2 (6–12%), CH_4 (2–4%), H_2 (0.1–0.2%), Ar (0.1–0.2%), CO and higher hydrocarbons (traces only). CH_4 is relatively homogeneous in all sampled vents, with no apparent difference between low and high temperature sites. However, H_2 appears to be enriched in the southern sites, particularly for the Marker 6 site, where a value of 0.40 mmol/kg was measured.

2.5. Time series temperature variations

Temperature is an important parameter of hydrothermal fluids and serves as an indicator of cycles of vent activity and thermal habitats of invertebrate taxa (e.g [29–31]). Vent fluid temperatures were measured at selected sites using self-logging probes [32] specific for either low ($< 150°C \pm 0.5°C$) or high ($\geq 150°C \pm 1°C$) temperatures. The high temperature probes were used to examine end-member hydrothermal fluid temperatures, while the low temperature probes were used to investigate the thermal habitat of organisms.

Two probes were deployed for 21 h (1 record every 6.4 min): one at the upper lip of the major flange structure at the Statue of Liberty site, the other in high temperature water pooled beneath this flange. The probe at the flange lip was positioned so that "overflow" of flange pool water could be monitored. The resulting 22.5 h temperature record is complex, with intervals of variably warm water (10–30°C) overflow between shorter intervals of ambient (4.2°C) or near ambient (5–10°C) temperatures (Fig. 7A). These short-term fluctuations are characteristic of regions where invertebrate–bacterial symbioses thrive; they reflect the "simultaneous" supply of oxygen-rich sea water and sulfide-rich hydrothermal fluids required by the symbioses (e.g., [33]). While variations in overflow of flange pool water at a single point were detected, the flange pool temperature itself was a constant 200°C ± 1°C.

Two temperature probes were deployed by *Alvin*

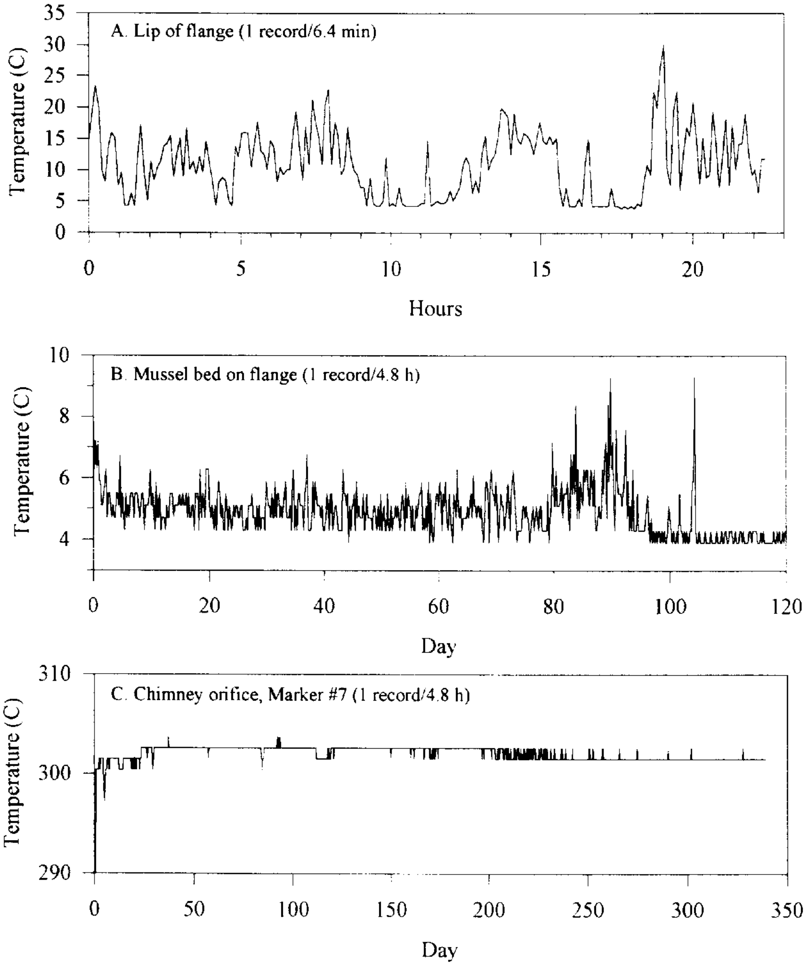


Fig. 7. Temperature records of biological environments and chimney interiors. Note the differences in scale for the three panels. The top panel shows variations on the top of a flange over a 1 day period. The pool beneath the flange remained at 200°C ± 1°C over this same time period. Both temperature probes can be seen in Fig. 6A. The middle and lower panels show temperature variations over months up to a year for the biological environment on top of the flange (probe deployment shown in Fig. 5B) and for a black smoker chimney interior. Note the remarkable constancy of temperatures for the chimney over a period of almost 1 year. See discussion in text.

at the end of the dive series and left to record temperatures for ~ 12 months (1 record every 4.8 h for 340 d). They were recovered in 1994 by the Nautile dive program [20]. The low temperature probe was placed on the same Statue of Liberty flange where the short term measurements were made during the cruise, but positioned to record temperature variations experienced by the mussel bed covering the flange. The temperature immediately overlying the mussel bed (Fig. 7B) varied little from 5.0°C (±0.6°C) until, between 80 and 90 days, the temperature increased to 5.8°C (±1.1°C). After 100 days the probe recorded an ambient temperature of 4.5°C and 5°C, and on recovery was found displaced to the non-hydrothermally active sea floor below and beside the flange. From point measurements it is clear that small deviations in probe position can result in significant differences in the temperature field. Thus the slight increase in temperature at 80 days could be due to a real change in the pattern of fluid flow at a fixed point or to slight displacement of the tip of the probe by a motile organism (including mussels).

A high-temperature probe inserted into the vent at Marker #7 in the Mounds field (Fig. 4) recorded stable temperatures of 301–302°C over 339 days (Fig. 7C). Long-term records of high temperature vents on the East Pacific Rise at 9°46′–51′N have also shown thermal stability or gradual increase (~ 7°C over 4 months) in temperature at some vents. However, large fluctuations (~ 20–100°C) at one vent over periods of several days to weeks have also been observed (Fornari et al., submitted), possibly associated with a recent sea floor eruption [34].

2.6. *Biological observations*

Lucky Strike vents are dominated by a previously undescribed bathymodiolid mussel species that is morphologically and genetically distinct from that found at Snake Pit on the MAR (R. Gustafson, pers. commun., 1994) [35]. Lucky Strike mussels cover surfaces of sulfide edifices at Statue of Liberty and Eiffel Tower (Fig. 6A,D), at times completely obscuring the mineral substrate beneath, except for small patches where higher temperature fluids exit. The mussel beds are visually reminiscent of mussel-dominated, shallow-water intertidal zones. Point measurements of temperature indicate the mussels are in water as warm as 14°C.

Preliminary characterization of mussel size frequencies illustrates the presence of discrete size classes, with the likelihood that the largest class represents multiple recruitment events. This kind of size-class structuring suggests synchronous control over reproduction and episodic recruitment in this species [35]. Microscopy of mussel gill tissue indicates that, as in the mussel from Snake Pit [36], Lucky Strike mussels host both sulfide-oxidizing and methylotrophic endosymbiotic bacteria. There is a high incidence of a commensal polychaete in the mantle chamber of mussels (> 95% in mussels > 1 cm length). This polychaete is morphologically indistinguishable from *Branchipolynoe seepensis*, first described from mussels at the Florida Escarpment seep site [37] and since recorded as a commensal in mussels at Snake Pit [38].

Other invertebrates cohabit Lucky Strike vents. The most unusual element of the vent fauna is an undescribed species of sea urchin in the genus *Echinus* (M. Sibuet, pers. commun., 1994). Echinoderms in general are rare at hydrothermal vents and sea urchins are previously unreported. Lucky Strike urchins occur in low densities (approximately 1–15 per site) at the edge of the mussel beds. At least two species of bresiliid shrimp occur at Lucky Strike. One species appears to be closely related to *Chorocaris chacei*, known from TAG and Snake Pit, while the other, more abundant, shrimp is clearly a new species in the genus *Chorocaris* [39]. A bythograeid crab, tentatively identified as *Segonzacia* sp. (Guinot, pers. commun., 1994) is found in low numbers at Lucky Strike; the genus is known from TAG and Snake Pit. At least 7 gastropod species have been collected from Lucky Strike, only one of which (*Protolira valvatoides*) is reported from other MAR hydrothermal vents (A. Waren, pers. commun., 1994). An undescribed species of ampharetid polychaete is also known from the Lucky Strike material. Several amphipod species have been identified from Lucky Strike [40]. Taxonomic identifications of other small invertebrates (principally polychaetes and small crustaceans — ostracods, copepods, isopods and tanaids) are pending.

Fish species known from bathyal depths were observed at and near the Lucky Strike vents, but no vent-specific fish were recognized [41]. Gut contents of a bythitid fish (*Cataetyx laticeps*) indicate it had fed on shrimp and mollusk shells from the vent community. The most abundant fish observed was the chimaerid *Hydrolagus mirabilis*.

Unlike most other hydrothermal communities, there is no conspicuous peripheral fauna associated with the Lucky Strike vent sites. The transition between dense mussel beds and the surrounding non-vent environment is abrupt. The only biological indication of proximity to warm water is shell chaff derived from mussel beds near individual vents.

3. Discussion

3.1. *History and setting of the Lucky Strike hydrothermal field*

The Lucky Strike hydrothermal field occupies a position within a segment of the MAR rift valley that has long been hypothesized to be conducive to hydrothermal activity [42]: the shallow point of a ridge segment, centered between ridge offsets. However, this may not be the sole hydrothermal site within this segment. Based on evidence from ZAPS water column sampling [15], a deeper site has been hypothesized to be present south of Lucky Strike Seamount. German et al. [7], using water column data, identified another possible hydrothermal site at the southern ridge transform intersection of the Lucky Strike segment. Data from sediments within the rift valley in the Lucky Strike segment show two discrete regions of elevated metal concentrations: one centered on Lucky Strike seamount and the other, larger, anomaly near the southern end of the segment [43].

Location of hydrothermal vents within the summit depression of a seamount raises the question of local structural control on the locations and distribution of vents. Based on the summit morphology, lava geochemistry, and relationships between the three cones, the depression appears to be a consequent feature formed by late-stage constructional volcanism which created the summit cones. Lava composition of young lava in the depression sampled during Dredge 15 (Table 1) is distinct from highly enriched lavas that make up the summit cones of the seamount. While Lucky Strike seamount bears certain gross morphological and genetic similarities to Axial Volcano on the Juan de Fuca Ridge [44,45] (e.g., hot spot dominated, isolated central volcano at a shallow point on a MOR crest), the central depression is not a caldera. Available structural data from TOBI sonar imaging indicate a generally N–S tectonic lineation which cuts the seamount flanks and portions of the cones — there is no indication of circular or circumferential structures on the summit [19] (L. Parson, pers. commun., 1995). The N–S trending faults and lineaments have apparently influenced the volcanic construction at Lucky Strike. Evidence for this includes constructional pillow ridges mapped on the eastern cone that may have nucleated over pre-existing faults in the rift valley. Preliminary data from TOBI side-looking sonar images [19] confirm the extent and plan-view arrangement of faults and constructional lineaments on the eastern part of the Lucky Strike seamount.

There is evidence that the Lucky Strike hydrothermal field has existed for a substantial period of time, and may have undergone a recent rejuvenation in activity. For example, mussel-shell chaff and sediments that appear to be hydrothermal in origin are far more widespread than the areas of active venting, and the Statue of Liberty vent is a largely extinct chimney with only vestiges of remaining activity. Much of the sea floor traversed by *Alvin* on the eastern side of the summit area appears to have been influenced by hydrothermal activity. Hydrothermally cemented breccias, extensive relict sulfides, and small relict chimneys throughout the Lucky Strike hydrothermal field, suggest previous activity at this site.

A long history of hydrothermal activity and recent reactivation would also be consistent with the evidence from the lavas. The eastern cone and much of the edifice of Lucky Strike seamount are made up of older, vesicular lavas with no glass rinds and significant sediment cover. More recent lavas in the summit depression are very fresh and glassy with a much less enriched chemical composition and no phenocrysts. In fact, the visible freshness of this younger lava, with pristine nuggets of glass with no visible alteration, is equal to fresh lavas we have observed from the EPR. It is possible that the recent volcanic activity has influenced the apparent resurgence of hydrothermal venting.

3.2. Contrasts between northern and southern vents

Dive observations and preliminary analyses of fluid and substrate samples suggest that portions of Lucky Strike investigated during the *Alvin* diving can be separated into two distinct areas. Much of the sea floor in the northern area is covered with relict sulfides, indicative of past episodes of hydrothermal activity. Active sites in this area are barite-rich and have morphologies (i.e., chimneys, spires and flanges) that differ from the southern sites. Mussels and other organisms colonize the surfaces of the northern hydrothermal structures.

In contrast, active vents in the southern area are located on top of slabs of hydrothermal breccia. Diffuse flow emanates from cracks in this material, supporting mussels and bacteria. The most common structures are small ($< \sim 1$ m tall) black smoker chimneys located on top of sulfide mounds. Mineralogically, these chimneys are dominated by chalcopyrite and anhydrite, probably reflecting the higher temperatures of the hydrothermal fluids. There is a marked absence of biological activity associated with these vents.

Measured temperatures and chlorinities from vents in the southern part of the vent field differ substantially from those in the north (Table 3). Fluids from Eiffel Tower and the Mounds vents form an indistinguishable group with a chloride depletion of ~ 20% relative to the ambient seawater value. Such a large depletion likely reflects phase separation, which is consistent with the measured total gas contents of Lucky Strike fluids. Phase separation of sea water at 1700 m requires T ≥ 355°C, which is at least 22°C greater than the highest measured temperature of any Lucky Strike vent fluid.

The silica contents of Lucky Strike vent fluids also display two distinct trends: the northern, cooler vents have lower concentrations of dissolved silica than the southern, hotter vents. If it can be assumed that quartz is the phase controlling dissolved silica content, then the Si concentration will be a function of pressure, temperature and salinity. In general, at temperatures below ~ 400°C, the higher the temperature the higher the dissolved silica content. Most hydrothermal vent fluids in which the dissolved silica systematics have been carefully examined are those with temperatures significantly greater than the ~ 200°C observed in the northern vents [46]. Studies on continental geothermal systems have shown that, at temperatures < ~ 180°C, a more soluble silica phase may control the dissolved silica contents [47]. If northern vent fluids are truly 200°C fluids which have not reacted at higher temperatures, then it is possible that a phase other than quartz may play a significant role in the evolution of those fluids. The simplest interpretation is that the lower silica contents of the northern fluids reflect equilibration with quartz at lower temperatures than the southern fluids.

While most large depletions in chloride are attributed to processes involving phase separation (e.g., [28]), the case for small depletions is less clear cut (e.g., [46]). Fluids that have 3% depletion in chloride could be explained by: (1) small input of water, perhaps from mineral dehydration; (2) recharge of the seamount hydrologic system occurring at greater depths as salinity in the Atlantic decreases with depth; or (3) mixing with a low chlorinity vapor phase. Northern Lucky Strike fluid may also be unusual in that it appears to exit the sea floor with Mg concentrations of about 10 mmol/kg, rather than with the ≤ 1–2 mmol/kg common for hydrothermal fluids. Four of the six fluid samples collected from the Statue of Liberty vent had Mg concentrations of 10.6 ± 0.3 mmol/kg. Having four samples cluster within the analytical error of the measurement is unlikely if the fluids are mixtures of a more Mg-poor fluid with seawater. Although it is possible that this may be "true" 200°C fluid (i.e., it has not reacted at higher temperatures), relevant experimental data [48,49] suggest that at all temperatures greater than 150°C, the Mg content should decrease to < 1 mmol/kg. Low sulfide concentrations in these fluids (< 3.3 mmol/kg) most likely also reflect the lower temperature regime. One possible scenario is that the fluid has been cooled by mixing with seawater, and has probably lost both sulfide and metals, owing to precipitation in the subsurface. However, the pH and alkalinity data argue against sulfide precipitation as the mechanism to explain the low sulfide contents — this requires further work.

3.3. Comparison with other hydrothermal fields

Many hydrothermal fields sampled to date along the MAR occur at or near the shallowest point in each ridge segment, even though the specific geologic and tectonic settings vary. Snake Pit and Broken Spur are located on volcanic ridges within the neovolcanic zone, while TAG is located at the base of a broad salient protruding from the eastern median valley wall on 100,000 year old crust. Lucky Strike and Menez Gwen have similar settings, in that both occur on the summit of large seamounts in the center of their respective ridge segments. All these sites have an abundance of hydrothermal material, and hydrothermal activity appears to have been periodically rejuvenated — as interpreted from our dive observations at Lucky Strike, and determined by geochronological studies of TAG and Snakepit [52,53]. These similarities occur despite the differences in depth and crustal thickness. Therefore, these aspects may be robust characteristics of many sites in a slow-spreading environment.

Mineralogically, the barite-rich nature of Lucky Strike hydrothermal deposits distinguishes them from hydrothermal deposits at TAG, Snake Pit and Broken Spur, but makes them similar to those found at Menez Gwen (e.g., [4,5,54,55]). Discharge of hydrothermal fluids with chlorinities less than seawater, and high gas contents, also distinguish Lucky Strike fluids from TAG and Snake Pit vent sites. The total gas extracted from all of the different vents at Lucky Strike is three times higher than at TAG, and methane is seven to ten times higher than at Snake Pit.

In terms of vent structure, morphology, distribution and composition, Lucky Strike bears a stronger resemblance to vent sites on the Endeavour Segment of the Juan de Fuca Ridge; both have flanges and significant amounts of barite [56,57]. Other hydrothermal areas which are present at shallow depths and bear some resemblance to Lucky Strike are the Lau Basin field [50], at a depth of ~ 2000 m in the western Pacific, and Axial Seamount — a large axial volcano on the central part of the Juan de Fuca Ridge where hydrothermal activity occurs at a depth of 1550 m (e.g [28,44,45,51]) and evidence for phase separation has been documented [28].

4. A new biogeographic province?

Two attributes of the ecology of Lucky Strike are unusual: (1) the predominance of mussels on sulfide chimneys, a habitat elsewhere occupied by swarming shrimp (TAG and Snake Pit) or Alvinellid polychaetes (East Pacific Rise) or tube worms/limpets/Alvinellids (northeast Pacific); and (2) the lack of a peripheral fauna. Vent mussels, in general, tend to occupy lower temperature regions of a vent field (e.g., [33,36]). Where mussels occur on sulfides at Lucky Strike, temperatures are elevated above ambient by only a few degrees. In other systems, the vent biota occupy regions of relatively warm water (20–40°C). The lack of a peripheral fauna (typically suspension feeders, including anemones, serpulid polychaetes and barnacles) may be related to efficient clearance of nutrients by the mussels, such that populations of free-living, suspended microorganisms cannot support a peripheral fauna.

The Lucky Strike biological community is sufficiently different from other vent faunas at the species level to be considered one of five biogeographic provinces (the others being northeast Pacific (Gorda, Juan de Fuca and Explorer Ridge), eastern Pacific (East Pacific Rise and Galapagos spreading center), western Pacific (Mariana, Lau, Fiji and Manus back-arc systems) and Mid-Atlantic (TAG, Snake Pit and Broken Spur). The discovery of vents at Menez Gwen with faunas closely allied to Lucky Strike [58] suggest that this new biogeographic province may be referred to on a regional scale as the Azorean province. The distinctiveness of the Azorean vent faunas at and north of 37°N from vent faunas south of 30°N on the Mid-Atlantic Ridge contrasts with the continuum of vent faunas over similar distances on the East Pacific Rise [59]. Van Dover [60] presents a model of contrasting biogeographic patterns on fast- and slow-spreading ridge systems that predicts more differentiation of faunas on slow-spreading systems, due to a variety of isolating mechanisms, including greater distances between active vents and topographic isolation by the basin-like structure of the rift valley and the closer spacing of large ridge offsets. An alternative model is that the Azorean province may reflect simply a depth control on the distribution of vent organisms. Vent faunas known from south of 30°N on the MAR occur at depths greater than 3000 m while the explored vents of the Azorean province are at 1600 m (Lucky Strike) and ~ 800 m (Menez Gwen). Pressure tolerances of species may dictate species distribution, although for at least one enzyme system, the threshold for pressure tolerance occurs at ~ 500 m, suggesting that tolerance to 500 m allows an organism to tolerate far greater pressures [61].

5. Influence of the chemical composition of the crust on hydrothermal fluids and solids

A principal aim behind the search for a hydrothermal site on oceanic crust influenced by a hot spot was to evaluate the possible effects of crustal substrate composition on the compositions of hydrothermal fluids and their associated mineral deposits. Since fluids largely acquire their chemical composition through interaction with the crust, the substantial variations in crustal concentrations of certain elements could be reflected in fluid chemistry. Alternatively, mineral/fluid equilibria could influence fluid chemistry in such a way that the fluid carries little or no signal from the variations in the rock substrate composition. For example, silica solubility will be determined by the minerals present, temperature and pressure, and have very little dependence on the silica content of the host rock. Indeed, discussions of fluid compositions in the literature have interpreted the variability almost exclusively in terms of physical conditions, mineralogy, phase precipitation at the surface, or the alteration state of the host rock (see [62] for a substantive review).

Lucky Strike is a particularly suitable site to investigate the importance of substrate composition, because of the influence of the Azores hot spot and the consequent high concentrations of Ba, Pb, the light rare earth elements (REE), K, Cs, and Rb in the basalts.

The two materials that could be influenced by the chemical composition of the basaltic substrate are the fluid composition and the compositions of the precipitated hydrothermal deposits. For some elements, such as Ba, reliable fluid compositions are particularly difficult to obtain because of the insolubility of the mineral barite, which rapidly precipitates upon interaction with seawater sulfate. In this case the compositions of the mineral deposits are more likely to be indicative of the Ba contents of the fluid. Other elements, such as the REE, are well measured in the fluids (e.g., [63,64]), and have a complex precipitation history during mixing with seawater; hence, the hydrothermal fluid chemistry should carry the more reliable signal.

There is an obvious association between the high Ba of Lucky Strike basalts and the abundance of barite in the hydrothermal deposits. This association is supported by the high concentrations of Ba in the Lucky Strike fluids (up to 80 μmol/kg) [65]. Barite is also abundant at the Menez Gwen site just to the north, where the basaltic substrate is also enriched in Ba. Barite is not reported to be present at TAG and Snakepit [54,55], however, consistent with the very low Ba in the host basalts (Table 1). This difference in mineralogy is also apparent in the bulk compositions of the hydrothermal deposits, as shown in Table 4. Over a wide range of bulk composition, Lucky Strike deposits are enriched by a factor of 50–100 in Ba relative to TAG and Snakepit.

Consideration of data from other sites supports the influence of substrate composition on the mineralogy of hydrothermal deposits. As noted previously by various workers [66–69], enrichments of Ba in basement rocks are often associated with greater abundance of barite in vent deposits. Compilation of data from these sites suggests that, whenever the substrate has less than 20 ppm Ba, no or only minor barite is present while, when the volcanic substrate has more than 50 ppm Ba, barite is a common mineral. It is important to note, however, that Pb apparently does not show as simple a dependence on the substrate, since Lucky Strike is not particularly

Table 4
Comparison of bulk sulfide compositions from Atlantic hydrothermal sites

	Lucky Strike			Tag [a]			Snakepit [b]
	Flange	Chimney	Chimney	Mound	Black smoker	White smoker	
n				8	6	5	16
Cu (wt%)	0.31	1.14	1.95	4.6	9.4	0.5	2.6
Fe	11.44	24.1	29.1	15.3	14.2	2.2	38.1
Zn	5.63	12.95	1.71	34.8	0.08	58.4	8.3
S	24.9	36.5	38.8	33.9	16.3	29.2	35.4
SiO_2	< 1	1.2	< 1	2.8	0.5	6.6	2.6
Ca	0.11	< 0.1	5.3	0.13	15	0.06	0.66
Ba	39.7	14.9	9.1	0.02	0.011	< 0.012	
Pb (ppm)	1700	505	290	323	< 24	772	684
Sr	8600	1900	2593		1297		75
Ag	148	117	42	628	4	738	74
As	310	790	620	70	13	91	251

[a] Data from Tivey et al. [30] tables 1 and 2.
[b] Data from Fouquet et al. [54] table 2.

enriched in Pb compared to other sea floor vent fluids.

Interpretation of the fluid data is more contentious. REE concentrations in Lucky Strike fluids have been reported by Klinkhammer et al. [25], and their interpretation is that there is no signature from the characteristics of the underlying basaltic substrate, based on the low total REE contents relative to Sr/Ca ratios. Indeed, some EPR fluids have total REE three times higher than the Lucky Strike fluids with the most elevated concentrations. An alternative approach, derived from well-established methods applied to igneous rocks, makes use of REE ratios. REE *abundances* in hydrothermal fluids change by orders of magnitude for reasons that are not well understood but probably relate to mineral precipitation and reaction. *Ratios* are much more difficult to change, and should be a more robust indicator of the parental fluid characteristics. In addition, REE ratios differ substantially in the substrate between normal MORB far from hot spots and enriched MORB near hot spots.

A comparison of rock and fluid REE ratios for bare rock hydrothermal deposits is shown in Fig. 8. Fig. 8A,B shows that REE ratios behave coherently in both basalts and hydrothermal fluids. Fig. 8C,D shows that the La/Nd and La/Er ratios of fluids and basalts correlate well. The Lucky Strike fluids have higher La/Nd and La/Er ratios than fluids from TAG and Snake Pit, just as the basalts, through which the fluids circulate, do. While the controls on total REE abundances remain an open question, these

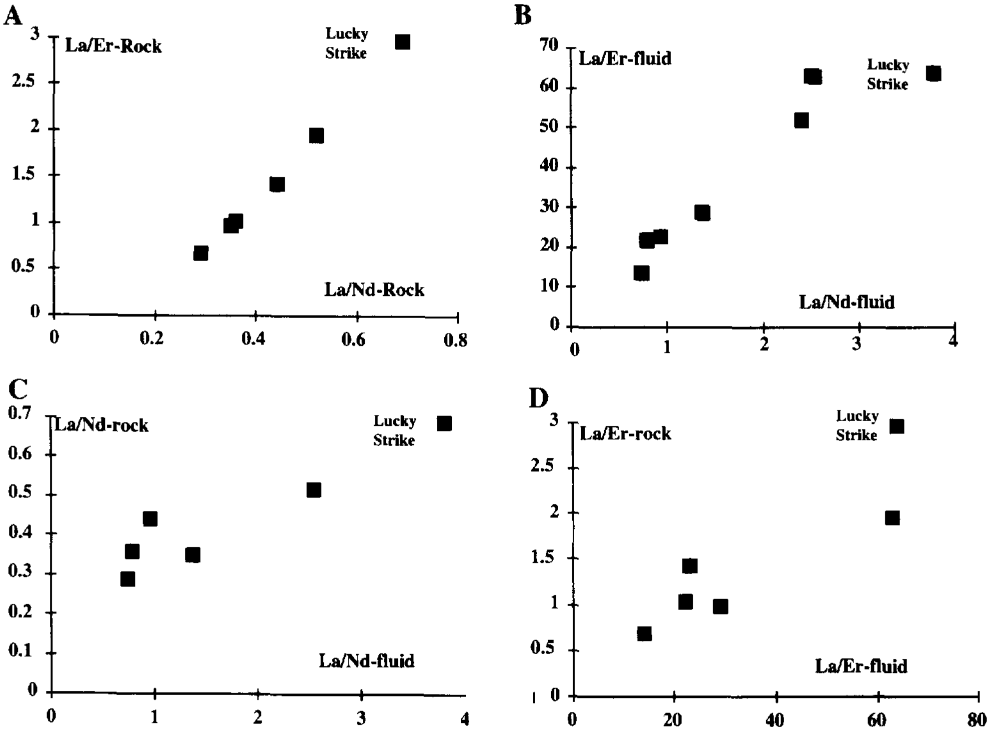


Fig. 8. Comparison of rock and fluid chemistry for REE from bare rock hydrothermal sites in the Atlantic and Pacific, including Lucky Strike. Average REE for fluids are calculated as the ratio of the means of the two elements (i.e., $\Sigma La/\Sigma Nd$) in order to avoid overweighing of low concentration samples, which do not contribute significantly to the total REE budget. This procedure gives a reasonable average, but does not allow calculation of standard deviations. The two top panels show that REE ratios correlate well in both host rocks and hydrothermal fluids. The bottom panels show the correlations between mean ratios for rocks and fluids, suggesting that La enrichment in the rocks influences the composition of the fluid. Fluid and rock data are Lucky Strike ([25], Langmuir unpubl. data), Broken Spur ([26], Langmuir unpubl. data), TAG ([71], Langmuir unpubl. data), MARK [64,72], 21N ([64], Walker, unpubl. data), 11–13N ([64], JOI Synthesis), and Marianas [64,73]. Fluid data for Endeavour are from [64]. No REE data are available for the Endeavour basalts.

data suggest that the substrate imparts a distinct REE signature to the fluid, and may exert a fundamental influence on important aspects of the fluid chemistry.

This preliminary discussion is far from a quantitative model, but it supports a relationship between basaltic substrate, fluid chemistry and the mineralogy of hydrothermal deposits. This is hardly surprising, since the highly incompatible element abundances vary by almost two orders of magnitude in the host basalts. It would be even more remarkable if the water/rock reactions completely disguised such differences, especially for trace species.

6. Conclusions

The Lucky Strike hydrothermal field exhibits a number of characteristics that contribute to our expanding knowledge of the characteristics of and controls on sea floor hydrothermal systems. The site appears to have had an extensive history; hydrothermal deposits and volcanic eruptions appear from geological relationships to have a substantial range in age. The variations in fluid composition are organized geographically, and are not simply related to cooling or mixing processes. There is evidence for phase separation in the subsurface, and possibly for a fluid exiting the sea floor with Mg contents as high as 10 mmol/kg. The temperature of fluids from one chimney was very constant throughout 1 year. The hydrothermal biological community is sufficiently different from other sites in the Atlantic and elsewhere to define a new biogeographic province.

The hydrothermal deposits are distinctive for the Atlantic due to the abundance of barite. The enrichment of the basalt substrate in incompatible elements, caused by the influence of the Azores hot spot, has led to a light-REE enrichment in the fluid composition, and the barite-rich nature of the mineral deposits. In combination with data from other regions, the Lucky Strike data suggest an important substrate contribution to the chemical compositions of hydrothermal fluids and their associated mineral deposits.

In general, many of the characteristics of Lucky Strike seem to result from a combination of slow spreading rate and substrate control. Like other MAR sites [70], Lucky Strike appears to have been active over a substantial time interval, and to be localized on the scale of a ridge segment. There is one large site in the center of the segment rather than chimneys distributed along much of the length of the segment, such as occurs along the EPR [34]. These characteristics probably reflect the slow-spreading environment, which conceivably could have a deeper heat source, stable fault patterns, and a longer wavelength of hydrothermal circulation cells. The substrate, on the other hand, influences the trace element compositions of the fluid and the specific mineralogy, and possibly physical properties, of the solid deposits.

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