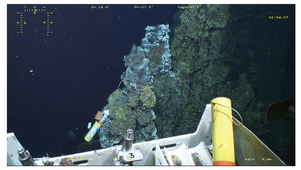

Formation of the seafloor massive sulfides at the Lucky Strike segment, Mid-Atlantic Ridge

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Introduction

Metal-rich hydrothermal deposits or seafloor massive sulfides (SMS) have been identified and mapped at the Lucky Strike segment in the Mid-Atlantic Ridge. This study aims to determine the age of the SMS deposits from the Lucky Strike hydrothermal field using the ^{226}Ra/Ba method on hydrothermal barite. Furthermore, using high resolution (~1m) bathymetry will aid to extract two sets of information: 1) volumes (and tonnages) and 2) fault information (strike and dip).

Main objectives:

-Understand the evolution of the Lucky Strike hydrothermal site by determining ages of the deposits, accumulation rates, and the timing and spatial relationships to faulting and volcanism.

-Evaluate the influence of the Azores hot spot on the chemistry of the hydrothermal deposits at Lucky Strike.

❶ Geological setting

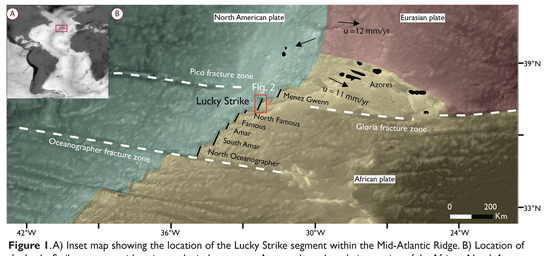

Figure 1. A) Inset map showing the location of the Lucky Strike segment within the Mid-Atlantic Ridge. B) Location of the Lucky Strike segment with major geological structures. Arrows show the relative motion of the African, North America, and Eurasian plates with half spreading rates (u) from George and Sankar (2010).

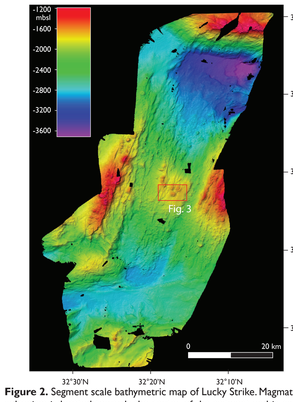

Figure 2. Segment scale bathymetric map of Lucky Strike. Magmatism and volcanism is located towards the center of the segment and is expressed as a bathymetric high.

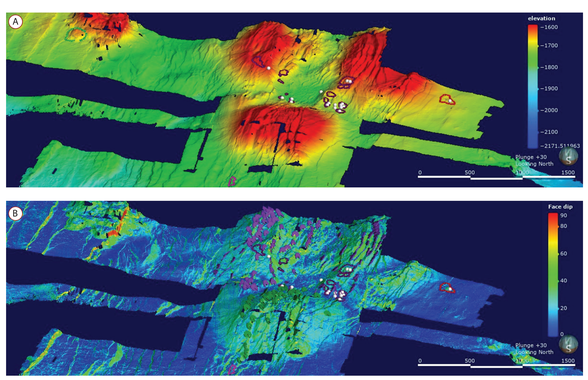

Figure 3. A) Oblique view (30°) of bathymetric map from the central area of Lucky Strike, resolution is ~1m, hydrothermal sites are in polygons, white points are sampled sites. B) Dip face map used to determine structural measurements and individual measurements are in circular features, purple for the northern part of the rift and green in the southern part of the rift.

❷ Seafloor massive sulfide (SMS) deposits

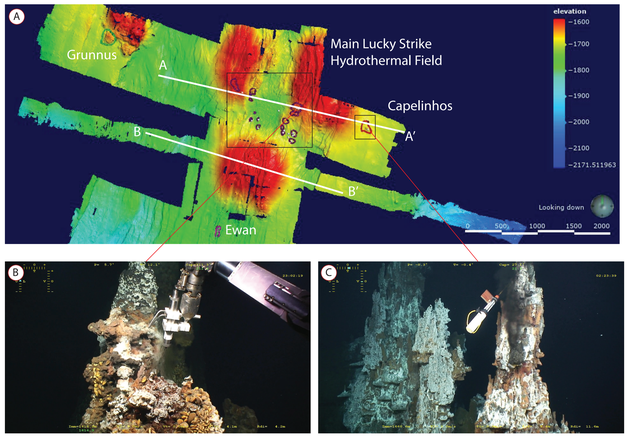

Figure 4. A) Hydrothermal sites from the Lucky Strike segment. Cross section location A-A', B-B' (see Structure section) B) High temperature venting at a sulfide chimney at the Sintra field within the Main Lucky Strike hydrothermal field (on axis). C) Chimney structures and high temperature venting at the Capelinhos field (off-axis)

❸ Structure

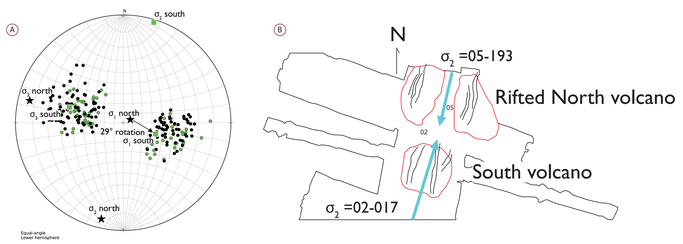

Figure 5. A) Stereonet of poles to fault planes in the northern rift (black circles) and in the southern rift (green circles). Arrow shows a clockwise rotation of 29° from the northern rift to the southern rift. Stress orientations in black stars (northern rift) and green squares (southern rift). B) Sketch of study area highlighting slight variations in σ_1 trend as well as plunge, both plunge towards the bathymetric low between the volcanic edifices.

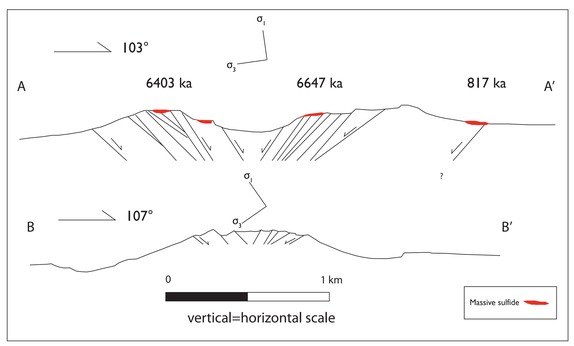

Figure 6. Cross section from the center of Lucky Strike. Location of cross section are in Fig. 4A. Sections are perpendicular to σ_2. Section A-A' shows the dissected northern volcano with the oldest SMS ages in the MLSHF and Capelinhos to the east. Section B-B' shows the faulted southern volcano with no SMS deposits.

❹ ^{226}Ra/Ba geochronology of hydrothermal deposits

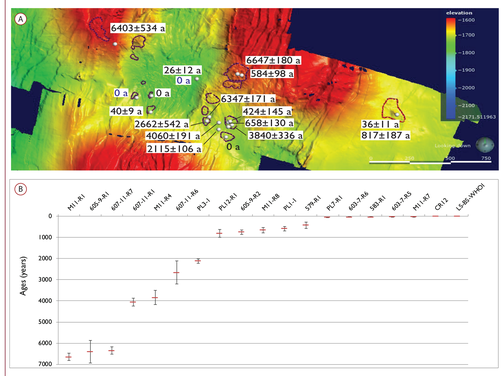

Figure 7. A) Map of hydrothermal sites (polygons) and sulfide/sulfate samples (white) that were dated using the 226Ra/Ba method. 0 ka in blue ages are precipitates from temperature probes (used as zero ages). B) Diagram showing ages of sulfide/sulfate with uncertainties.

The ^{226}Ra/Ba method (U-series radiometric dating) was used to date sulfide/sulfate samples from Lucky Strike. Using the equation below:

$$t = \frac{\ln(N_0/N) \times 1600\,\text{years}}{\ln 2}$$

N_0=Initial ^{226}Ra/Ba ratio
N=Samples ^{226}Ra/Ba
1600 years=^{226}Ra half-life

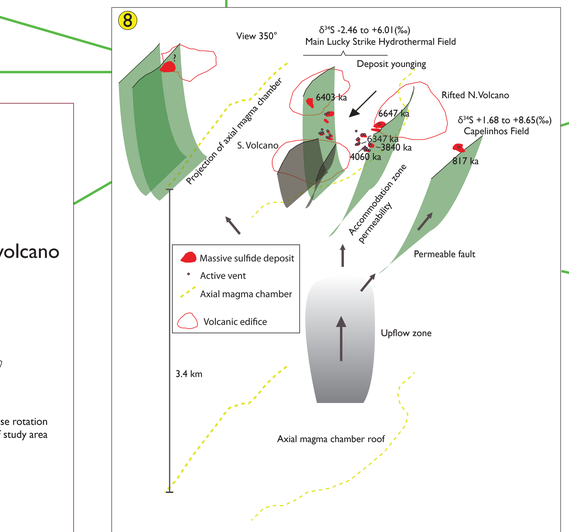

Figure 12. Summary sketch from the Lucky Strike hydrothermal field. Axial magma chamber outline from Combier et al. (2015).

❻ Sulfur isotope systematics

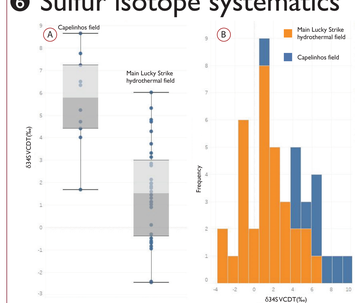

Figure 11. A) Box plot of in-situ sulfur isotopes from marcasite and chalcopyrite from the Lucky Strike hydrothermal field. B) Frequency diagram showing sulfur isotope compositions of the Lucky Strike hydorthermal field, divided between the on axis (MLSHF) and the off-axis site (Capelinhos).

❺ Volumes and tonnages

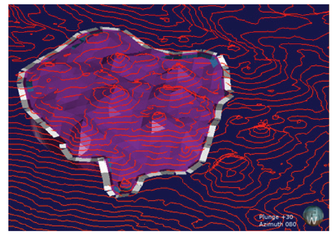

Figure 8. A) Example of volume estimation for the massive sulfide deposits at the site Sintra. Contours every 2 meters (red) and outline of the deposit (gray). B) Location of the site in A).

Table 1. Volumes and calculated tonnage of sulfide deposits from Lucky Strike. Tonnage calculated with a density of 3.1 t/m3 (Tivey et al. 1999).

Site name	Volume (m^3)	Tonnage (kt)	% of total tonnage
Capelinhos	94,801	294	12.9
Sintra	293,380	909	44.8
Sintra	35,454	110	
Tour Eiffel	28,277	88	3.9
Isabel	24,075	75	7.0
Isabel	8,115	25	
Isabel	19,257	60	
Montsegur	19,164	59	2.6
White Castle	16,952	53	2.3
Cypress	3,020	9	0.4
Crystal	3,228	10	0.4
Other	285	1	0.0
Other	57,246	177	7.8
Other	9,569	30	1.3
Other	121,210	376	16.5
Total	**734032**	**2275**	

❻ Mineralogy and composition of SMS

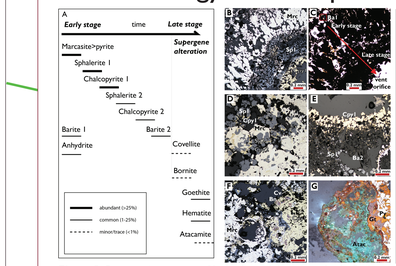

Figure 9. Paragenetic sequence of hydrothermal deposits at Lucky Strike.

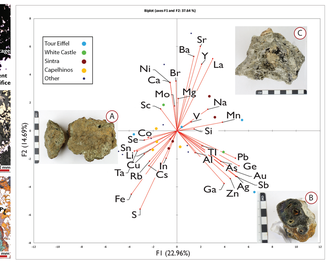

Figure 10. Principal component analysis (PCA) of bulk rock geochemistry from the MLSHF and Capelinhos hydrothermal sites. Images of hand massive sulfide samples illustrate groupings. A) Chalcopyrite dominated. B) Sphalerite dominated. C) Barite dominated.

Discussion and conclusions

-SMS deposits at Lucky Strike have a minimum **age of 6647±180 a.** The oldest deposit being within the MLSHF (on axis) and based on current available samples, the oldest age of Capelinhos (off-axis) is 817±187 a.

-Deposit age youngs towards the south. This is consistent with the volcanic evolution that is evident from the bathymetric map i.e. the most recent volcanism is the southern volcano.

-Deposit location is controlled by the intersection of fault **enhanced permeability** at the MLSHF where an accommodation zone (shift in principal stress fields between the N and S volcanoes) focuses most of the fluid flow and the **axial magma chamber (heat source)** is located (3.4 km below). Another control is by deeper penetrating faults that can tap into the heat source at a greater depth (e.g. Capelinhos).

-Fluid recharge and discharge at Lucky Strike occurs along the ridge axis.

-A total of **2.3 Mt of massive sulfide** has been estimated at Lucky Strike, with the largest individual site being Sintra (in the MLSHF) that accounts for 45% of the total estimate. Other methods of volume estimation are being tested in order to further validate this number.

-Based on the oldest age determined and the tonnage estimate an accummulation rate of **342 tons/year** has been determined for the Lucky Strike hydrothermal field.

-Mineralogy is consistent with groupings determined with the PCA where the inner walls of chimneys that are composed of high temperature minerals such as chalcopyrite (Cu) and lower temperature assemblages such as sphalerite (possibly contains most Zn, Ga) and marcasite (probably contain most of the Ge, As, Au and Ag). The other grouping reflects mineralogy from barite and anhydrite rich samples i.e. Ba, Ca, and Sr (that commonly replace Ba in barite).

-Average Cu=7.6 wt%, Zn=5.2 wt%, Ba=2.0 wt%, Au=0.5 g/t. (n=23).

-Geochemical composition of the SMS at Lucky Strike are likely influenced by the Azores hot spot based on the content of Ba, which is reflected in the abundance of barite in these deposits.

-Sulfur isotope data shows more positive δ^{34}S values at the Capelinhos site compared to the MLSHF. This suggests that fluid at **Capelinhos has undergone more mixing with seawater** because fluid is controlled by a deeper penetrating fault. The **MLSHF has δ^{34}S values closer to the magmatic values** (~0) but also has slightly negative values that might be associated with SO_2 disproportionation associated with magma degassing.