

115 and 0.2 wt% H₂O, the latter consistent with the experimentally measured solubility of water in melt under 1 atm water vapour pressure²⁸.

Thus far, δD is the only compositional parameter which we have found to vary significantly with water content within obsidian suites from a single eruptive sequence. Crystal content, which might be expected to increase with decreasing water content, remains low and in some sample suites crystals are virtually absent. In view of the isotopic evidence for degassing, uniformly low crystal contents throughout eruptive sequences have two important implications: (1) low water (and low δD) melts are metastable (that is supercooled due to loss of water) when erupted, and (2) second boiling phenomena do not contribute to bubble growth during eruption. Vapour exsolution and subsequent explosive eruption of these magmas are apparently solely due to decompression during upward intrusion.

The hydrogen isotope systematics described here should also apply to subvolcanic regimes. The exsolution and loss of a free vapour phase would thus explain the hydrogen isotope data of O'Neil *et al.*¹⁹ on porphyritic rocks in Australia, and corroborate the interpretation of Nabelek *et al.*²⁰ of hydrogen isotope variations in a high level granitic pluton in Nevada. The hydrogen isotope composition of magmatic water retained by the magma is dependent on the magma's degassing history.

Conclusions

Hydrogen isotope and water analyses of obsidian from several rhyolitic eruption sequences indicate that progressive, *in situ*

degassing of magma occurs at depth beneath the volcanoes during the eruptive sequence. This degassing appears to be a necessary prelude to non-explosive eruption of magma as flows or domes. Initial (pre-eruption) magmatic conditions consistent with the data are 3 wt% H₂O and $\delta D = -60$ to -65% .

Fractional distillation of the magma column can produce rhyolites with δD values as low as -130% (wt% H₂O = 0.2) without any detectable interaction with meteoric water. Water exsolved from a melt in a volcanic conduit may also show a large depletion in deuterium, with δD becoming more negative with time. Hydrogen isotope ratios of H₂O in fumarolic gases on active volcanoes may thus serve as a measure of magma evolution. Water vapour with δD values more negative than the -40 to -80% range accepted for magmatic water¹⁸ may be released from the melt and these δD values do not necessarily indicate incorporation of meteoric water.

Water contents were determined at Sandia National Laboratories with support from the Office of Basic Energy Sciences, US Department of Energy, under contract DE-A04-76DP00789. Oxygen isotope analyses were performed in the Department of Geology, University of California Davis. The laboratory and mass spectrometer at this department were constructed with partial support through NSF grants EAR 79-13238 and EAR 79-11144, and funds from the University of California. N. Ingraham assisted in the hydrogen isotope preparations, and Dr J. R. O'Neil permitted use of the hydrogen isotope mass spectrometer. We thank H. W. Stockman and C. R. Carrigan for helpful comments.

Received 6 July; accepted 14 September 1983.

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Formation of fossil hydrothermal chimneys and mounds from Silvermines, Ireland

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Sulphur isotope analyses reveal that the fossil hydrothermal pyrite mound and tubes at Silvermines were produced by the reaction of hydrothermal Fe(II) with bacteriogenically-reduced sulphur species ($\delta^{34}S$ range: -18.4 to -42.5%). This took place in a brine pool dominated by hypersaline Carboniferous seawater. This is in contrast to their modern, but considerably larger, morphological counterparts forming by direct precipitation of hydrothermal sulphides on the East Pacific Rise at $21^\circ N$.

THE Silvermines orebodies in Central Ireland consist of three contiguous sedimentary zones, two of which (the Mogul 'B' and Upper 'G' zones) are pyritic zinc + lead deposits, while the third

(the Magcobar deposit at Ballynoe) is composed of baryte. They occupy one horizon in a Lower Carboniferous succession of unmetamorphosed and only slightly deformed carbonates¹⁻³. That they were laid down as chemical sediments is beyond doubt¹⁻⁴, the most telling evidence being the occurrence of plastically deformed sedimentary sulphide (S. Taylor, personal

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Fig. 1 Example of a 360-Myr old hydrothermal chimney from the Silvermines Zn+Pb+Ba deposit (8 mm chimney diameter).

communication) and jasper intraclasts as components in the ubiquitous submarine debris flow deposits found within, and just above the orebodies. Their age, deduced from their setting, is late Tournaisian, 360 Myr (ref. 5).

Cross-cutting veins of galena(PbS)+sphalerite(ZnS)+baryte(BaSO₄)+quartz are clearly spatially and genetically related to the sedimentary ores: they mark the conduits that channelled the solutions from depth to the early Carboniferous sea floor^{3,4,6}.

We know from recent discoveries at 21° N on the East Pacific Rise (EPR) that as hot (~350 °C)⁷, metal-bearing aqueous solutions exhale from oceanic crust into near freezing seawater, immediate precipitation of sulphides by quenching leads to the formation of chimney spires (originally anhydrite⁸) and mounds composed, now, essentially of pyrrhotite (Fe_{1-n}S), pyrite (FeS₂), chalcopyrite (CuFeS₂) and sphalerite (ZnS) or wurtzite (a sphalerite polymorph)^{9,10}. The δ³⁴S of the pyrite is relatively uniform, ranging from +1.4‰ to +3.0‰ (ref 11). (Figure 4a shows the full range of S-isotope results from EPR chimney sulphide.) It has been demonstrated that ~90% of the sulphur was released from basaltic crust during hydrothermal metamorphism by the circulating seawater-hydrothermal fluids¹¹.

The submarine hot springs that fed the Silvermines exhalative sulphide and baryte orebodies should have produced similar structures, an expectation satisfied by Larter *et al.*⁴ who discovered a pyrite mound and small chimneys in the Ballynoe baryte deposit (Fig. 1). The Silvermines chimneys, although morphologically comparable to those at 21° N on the EPR, have their own distinct character. The individual chimney spires have a smaller diameter (EPR ranging from 0.5 to 400 mm^{7,10} whereas Silvermines are generally ≤20 mm⁴) and are composed almost entirely of pyrite. These differences presumably relate to the marked contrasts in their marine and tectonic settings. The wider chimneys of the EPR are constructed at a seawater depth of 2.5 km as products of the exhalation of a vigorous hydrothermal convective system. The circulating fluid is dominantly seawater¹¹, modified by reaction with, and driven by heat from solidifying magma intruded at a constructive plate margin¹². Iron, copper and zinc sulphides are appreciably soluble in these conditions¹³. At Silvermines the hydrothermal system was probably driven by heat within the continental crust¹⁴ and was consequently of lower vigour and the discharge rate proportionally lower. Moreover fluid inclusions indicate that the temperature of the effluent was certainly <150 °C, having been cooled from ~250 °C by shallow crustal mixing with a solution of higher salinity (20% NaCl equiv. wt% compared with primary solution around 12% NaCl equiv. wt%). The most likely candidate for the dense brine is highly saline seawater¹⁵, produced by evaporation on the margin of the fault-controlled basin¹⁶ which occupied the area of Silvermines during the Lower Carboniferous.

We report here the results of a sulphur isotope study on this first discovery of fossil hydrothermal mound and chimneys. Although we expected further contrasts with the EPR chimneys to be revealed, we were not prepared for the remarkably light values of δ³⁴S‰ in some of the tubes, a factor that requires extreme bacteriogenic fractionation of sulphate (Table 1). These unusual values may help us to identify the feeder zones in other sediment-hosted exhalative zinc+lead deposits.

New finds and descriptions

In the EPR hot spring areas, the vents are invariably found in mounds, which comprise accumulations of mineral debris and chimney clusters. Each EPR mound covers an area of 15 × 30 m with a height of 2–10 m^{9,17}. The remnants of a comparable mound have now been recognized in the south-east corner of the Ballynoe open-pit baryte deposit, where the surface is essentially a silicified footwall pavement (Fig. 2). Although this area has been damaged by heavy plant excavators, distinctive features can still be recognized. The most convincing relic is a massive lenticular body, 3 × 8.5 m in plan and up to 2 m high (10 m E of 10500 N, 10900 E, Fig. 2). It consists exclusively of pyrite at its base with an increasing baryte content towards the top. Although most of the pyrite is massive or colloform there is one outcrop near a discontinuity on the east edge of the open pit where large (≤40 mm) pyrite cubes and tabular baryte crystals (≤30 mm across) have been developed, presumably as a result of continued chemical reworking of the mound by hydrothermal fluids (black ornament, Fig. 2). Around this mound is a mappable development of pyrite, with minor baryte, exhibiting textures akin to those in the mound and chimneys, varying from 0.01 to 1.5 m thick (fine stipple, Fig. 2).

Well developed chimneys were described by Larter *et al.*⁴ as being tubular (0.1–20 mm in diameter), and comprising concentric pyrite layers (0.05–1 mm thick), suggestive of Liesegang rings; and an outer coating of crystalline, tabular baryte laths, termed peripheral baryte (≤10 mm in length). The matrix between these vents is dominantly barytic. These we term type I chimneys and rods.

Type II chimneys are similar to type I in that they exhibit a tubular form, are composed mainly of concentrically zoned pyrite, and are about the same size: they differ in several aspects. Instead of the central canals comprising framboidal pyrite⁴, the type IIa vents either have a central infilling rod composed of white/grey translucent sphalerite (cleiophane), coated with microcrystalline pyrite, or are empty. Framboidal pyrite is generally less abundant in the outer zones where radiating acicular pyrite crystal dominates. Baryte is a minor associate of type II vents: peripheral baryte has not been found. Instead, where chimneys do not abut, they terminate with an outer layer of euhedral to subhedral pyrite and sphalerite. These textures are reminiscent of a crystal garden. The structures appear to have begun life as thin colloform developments or tubular films, grown from colloidal FeS₂, with diffusive and osmotic processes increasing their thickness and length. As with type I vents, type IIa tubes come from the Ballynoe baryte deposit; type IIb tubes come from the Mogul zinc+lead deposit, but are essentially similar to type IIa (see also ref. 18). Only type IIa tubes have been found *in situ*.

Isotopic results

All isotopic analyses were obtained using standard techniques^{19–21}, and are reported as δ³⁴S‰ differences relative to the Cañon Diablo Troilite (CDT) standard. Analytical uncertainty is about 0.3‰—the difference between duplicate complete analyses.

Baryte results are bimodal around +14.2‰ and +20‰ (Table 1). All pyrite ratios are isotopically very light, particularly the outermost zones of the type I vents. The lightest value from these zones, -42.5‰ (sample Bal-10), is the most fractionated sulphide result reported from any Irish ore deposit. Type I pyrite results show a notable variation of ~10‰ from outer through

Table 1 S-isotope results of the hydrothermal chimneys and rods from the Silvermines Zn+Pb+Ba deposit

Chimney type	Laboratory no.	Sample no.	Mineral	Sample site	$1\delta^{34}\text{S}_{\text{CDT}}(\text{‰})$
I	S 3493	AB -5	Pyrite	Central zone	-31.3
I	S 3960	BAL -1	Pyrite	Central zone	-33.5
I	S 3492	AB -4	Pyrite	Central and inner zones	-38.8
I	S 3494	AB -1	Pyrite	Central and inner zones	-38.2
I	S 3958	BAL -9	Pyrite	Central and inner zones	-38.1
I	S 3959	BAL-10	Pyrite	Outer zones	-42.5
I	S 3977	BAL -7	Pyrite	Outer zones	-40.4
I	S 3495	AB -2	Baryte	Peripheral	+19.2
I	S 3496	AB -3	Baryte	Peripheral	+20.4
I	S 3962	BAL -3	Baryte	Peripheral	+14.2
I	S 3964	BAL-11	Baryte	Peripheral	+14.2
I	S 3982	AB -6	Sphalerite	Matrix to chimneys	-18.9
I	S 3938	BAL -4	Sphalerite	Matrix to chimneys	-20.6
IIa	S 3954	BPU-10	Pyrite	Innermost zone	-21.2
IIa	S 3955	BPU -5	Pyrite	Innermost zone	-19.0
IIa	S 3957	BAL -8	Pyrite	Innermost zone	-21.4
IIa	S 3960	BPU -2	Pyrite	Innermost zone	-20.2
IIa	S 3999	BPR -1	Pyrite	Innermost zone	-18.4
IIa	S 4000	BPR -4	Pyrite	Mid zones	-20.2
IIa	S 4001	BPR -6	Pyrite	Mid zones	-19.4
IIa	S 3961	BPR -3	Pyrite	Outer zones	-18.7
IIa	S 4002	BPR -3	Pyrite	Outer zones	-19.9
IIa	S 3978	BAL1-1	Pyrite	Outer zones	-23.7
IIa	S 4318	BPI-01	Pyrite	Botryoidal cap to chimney	-21.1
IIb	S 3990	Mogul Pipe	Pyrite	Inner zones	-17.2
IIb	S 3991	Mogul Pipe	Pyrite	Outer zones	-11.6

to inner zones (Fig. 3). The $\delta^{34}\text{S}$ in sphalerite associated with these vents is considerably heavier.

All analyses on type IIa vents were of pyrite since this was the only mineral available in sufficient quantity for this technique. Unlike type I, these results show no significant variation across the zones: they give an average value of -20% . Type IIb vents give results of -17.2% (inner) and -11.6% (outer). The significance of these type IIb results will not be discussed until more substantial data can be collated.

Previous S-isotope studies

Two S-isotope studies have been carried out on these deposits. Concentrating on the Lower 'G' discordant and Upper 'G' stratiform orebodies, Greig *et al.*²² interpreted the inter-mineral variations of $\delta^{34}\text{S}$ in terms of changes in isotopic equilibria between S-isotopic species in the exhaling fluids. These changes were held to be the result of variations in f_{O_2} (fugacity), pH and temperature, fashioned by host rock-hydrothermal solution reactions, as the mineralizing fluids passed through the rock pile via the Silvermines fault system.

The validity of much of this interpretation is now in doubt. The hypothesis was grounded in the epigenetic, replacement model for the genesis of the Upper 'G' and the baryte zones. Myriad sedimentary features in and associated with the ore have shown this model to be untenable^{1-4,23-25}. Thus an alternative interpretation of the data is required. For example, instead of the $\delta^{34}\text{S}_{\text{baryte}}$ from the Ballynoe deposit being the product of equilibrium isotopic exchange in a fluid (that is, oxidation of reduced sulphur), it is now considered to have formed by reaction of exhaled Ba(II) with contemporaneous Lower Carboniferous seawater sulphate^{1,4,6}. Hence, the S-isotope ratio of the baryte is indistinguishable from the range of values proposed for Lower Carboniferous seawater sulphate, that is $\delta^{34}\text{S} = +14$ to $+22\%$ (ref. 26). (Note the Lower Carboniferous seawater sulphate analyses show a greater inter-basinal spread of $\delta^{34}\text{S}$ than most other geological periods²⁷.) As more data have become available on the conditions of mineral deposition at Silvermines, it is clear that disequilibria between all phases were pervasive in the upper, sedimentary ores; and that sulphate was out of equilibrium with sulphide in the lower, epigenetic ores.

Nonetheless, we agree with the conclusions of Greig *et al.*²², that fractionations between sulphide species in the Lower 'G' replacement orebody approach equilibrium, and concur that the sulphur was derived from depth, with a $\Sigma^{34}\text{S}$ of around $+3\%$.

In the second study, Coomer and Robinson⁶ reinterpreted the S-isotope data based on a hydrothermal exhalative model, in which ore precipitation occurred both in epigenetic-type veins, and in sedimentary lenses on the sea floor. This basis is satisfactory in the light of the discovery of the hydrothermal chimneys described above. They suggest that a mixed source for the sulphur in the sulphide was available. The first is a deep-seated source similar to that suggested by Greig *et al.*²², which precipitated minerals, particularly galena and sphalerite, at or near equilibrium in changing physicochemical conditions. Such a source of sulphur accords with the isotopic characteristics of the vein as well as the replacement epigenetic deposits, like the Lower 'G' zone. The second sulphide-sulphur source was derived from the low temperature bacteriogenic reduction of seawater sulphate, an explanation consistent with the bulk of S-isotope ratios of the Upper 'G' and 'B' orebodies.

Combining results from both studies and comparing them with the chimney isotope data (Fig. 4b) shows that type IIa tubes are broadly comparable with the average pyrite values for the Silvermines sedimentary deposits, whereas the type I vents have notably lighter ratios. Baryte results span approximately the same range, but sulphate in the orebodies does not exhibit a discernible bimodal distribution.

Genetic model

The isotopic results of type I chimneys are particularly unusual: the lightest value, -42.5% , being extraordinary in most comparable geological environments.

We discuss a genetic model for both types of tube based on the sulphur isotope results, the fluid inclusion data¹⁵, and the geological environment as determined from the tectonics and sedimentology of the area¹⁶. Fluid inclusion studies indicate temperatures of exhalation below 150°C . This is, of course, in marked contrast to the issuing temperatures of 350°C indicated for the EPR black smokers. Fluid inclusion salinity analyses¹⁵ on peripheral baryte, and a sample of baryte from the Ballynoe

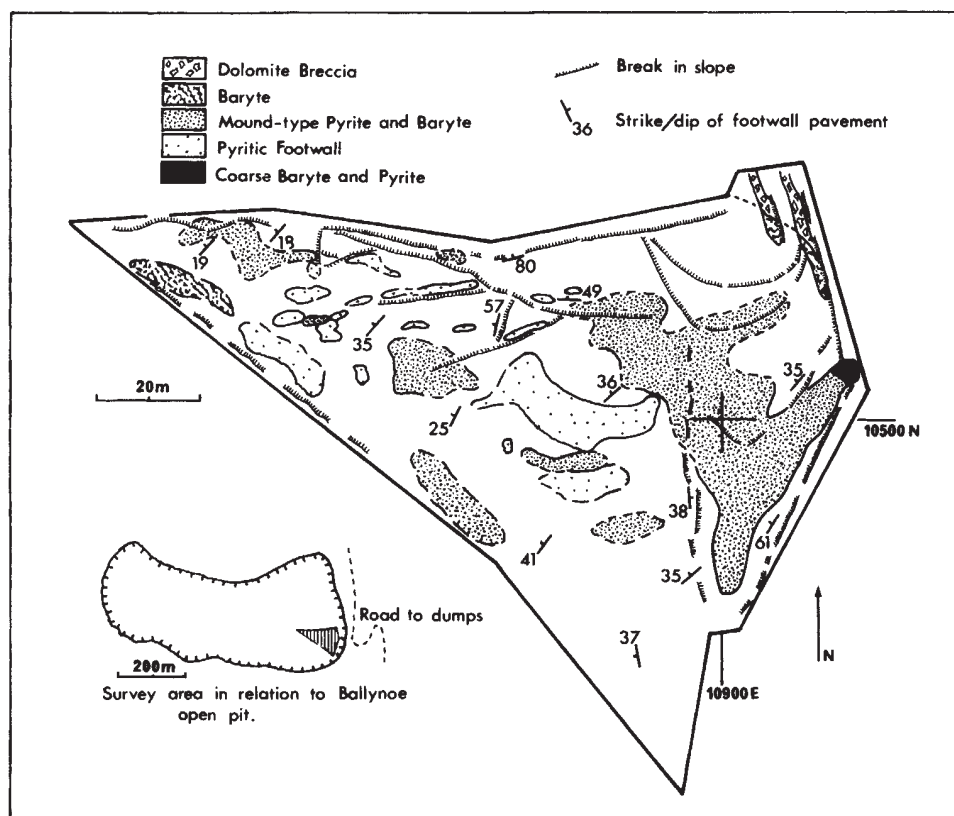


Fig. 2 Detailed map of the remains of a hydrothermal mound site in the Ballynoe open pit baryte deposit. The area is on generally northward dipping silicified footwall (no ornament).

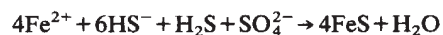
deposit, which showed early diagenetic recrystallization of baryte causing cusping of still-soft pyritic mud (fig. 4 of ref. 16), indicated that the fluid at, and just beneath the sediment-seawater interface had an 18–22% NaCl equiv. wt% salinity. This compares with an ~12% NaCl equiv. wt% salinity in the primary mineralizing solutions. We suggest the former fluids reflect the presence of a brine pool in the Silvermines depression at the time of the mineralizing event (Fig. 5).

We are dealing with extreme disequilibrium fractionations of $\Delta^{34}\text{S}_{\text{SO}_4-\text{H}_2\text{S}}$ between 37 and 60‰ so we can say that the bacterial reduction of sulphate provided the major source of sulphur for the tubes. Although sulphate-reducing bacterial remains have not been isolated from the deposit, indirect evidence for their probable presence may be indicated by the notably high total organic carbon content of type I pyrite, which gave a value of 8.6% (total organic carbon analysis by LECO Carbon Analyser). The bacterial reduction of sulphate has been discussed at considerable length, both experimentally (see refs 28–30) and theoretically (see ref. 31), elsewhere. Despite the thorough nature of such research, detailed interpretation of bacterially produced sulphur isotope results has not been possible for ancient environments, where precise details of the physical, chemical and particularly bacterial (/organic) environments have been obliterated by time.

In our model (Fig. 5) we envisage the most significant bacterial reduction of sulphate taking place in the halocline (the gradational salinity interface between 'normal' seawater and the brine pool). The salinity in this region could be low enough not to inhibit bacterial activity; and suspended carbonaceous material, accumulated in a density trap, would provide an adequate reservoir of organic material necessary for the reduction process. Normal seawater would not host these bacteria since they are obligate anaerobes. Present-day stratified basins indicate organic and bacterial concentration in the halocline^{32,33}, thus corroborating our model.

Chimneys and rods have only been found in the higher parts of the Silvermines basin, specifically adjacent to the main east-west fault. We suggest that this was in the region at which the halocline intersected the sea floor.

This region may also provide the more oxidizing conditions required for pyrite precipitation, for example, by way of the notional reaction (at $p\text{H} \sim 7.5$):



We suspect also that the type II structures formed nearer the base of the halocline than type I. This is suggested from the fact that type I chimneys were completely absent from the Upper 'G' deposit which is structurally lower than the Ballynoe deposit, where both types are found.

To explain the differences in fractionation between type I and type II tubes we invoke variations in their formation site and/or their formation time (with respect to the mineralizing event).

For example, it has been noted that the larger the sulphate pool, the greater the expected degree of fractionation³². Thus, because of the more elevated sites of type I vents with respect to the brine pool, it is likely that sulphate availability would be greater there than at type II sites, where sulphate depletion through baryte precipitation would have occurred. Additionally, the sulphate reservoir available for reduction in the centre of type I pipes is likely to have been less than at the periphery, and this may account for the isotopic zonation exhibited by these vents (see Fig. 3).

An attractive interpretation of the sulphur isotope results hinges on the time factor. If we consider that the extent of fractionation resulting from the bacterial reduction was $\Delta^{34}\text{S}_{\text{SO}_4-\text{H}_2\text{S}} = 40\%$ throughout economic deposition at Silvermines, then approximately -20‰ (a value corresponding to the deposit average) would be the $\delta^{34}\text{S}$ expected from reduction of Lower Carboniferous seawater sulphate^{26,34}. This relates directly to type II vent results. Type I vents, however, would need a considerably lighter sulphate ($\delta^{34}\text{S} \approx 0\%$) for reduction to produce fractionation up to -40‰. Such a light sulphate would accrue if bacterially produced 'normal' sulphides ($\delta^{34}\text{S} \approx -20\%$) were oxidized to sulphate in the brine pool (a process involving insignificant fractionation, hence resultant sulphate $\delta^{34}\text{S} \approx -20\%$) and subsequently homogenized with seawater sulphate. The mixing ratio of these two reservoirs was unlikely

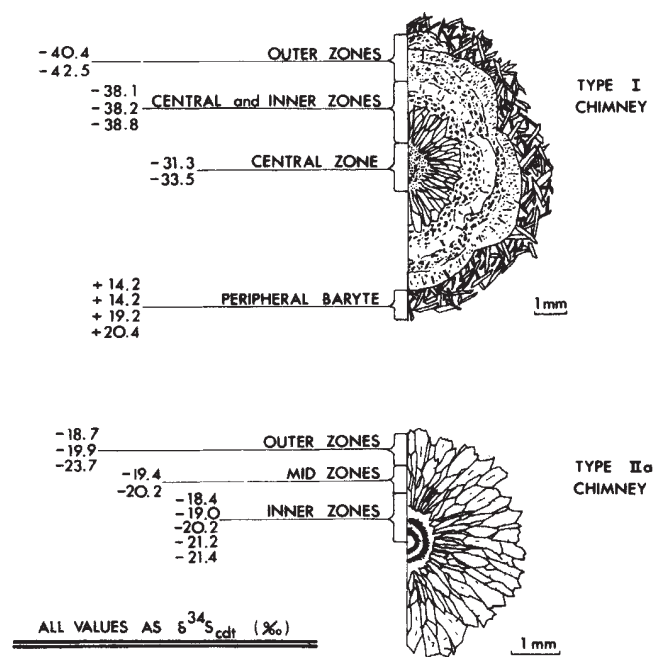


Fig. 3 Zonal representation of S-isotope results (as $\delta^{34}\text{S}_{\text{CDT}}(\%)$) from types I and IIa hydrothermal chimneys from Silvermines. All results are from analyses of pyrite unless otherwise indicated.

to have been constant, hence the 10% spread in $\delta^{34}\text{S}$ ratios exhibited by the type I chimneys and rods.

Temporally the latter circumstance would relate to the waning of a mineralizing pulse or to periods of quiescence. Subsequent introduction of metals would precipitate the unusually light sulphide. This then, may have been the period of precipitation for type I vents, whereas type II vents precipitated during active mineralization, when most sulphide would have been precipitated and thus have been unavailable for oxidation. Perhaps then, considering this model, it is no coincidence that the lightest reported sulphide $\delta^{34}\text{S}$ from any Lower Carboniferous, Irish orebody occurs adjacent to the lightest reported sulphate $\delta^{34}\text{S}$ from these deposits. However, because of the probable localized and transient nature of these circumstances, we would not expect a significant light sulphate reservoir to have existed at Silvermines.

A third alternative is that type II vents are a hybrid of epigenetic sulphide ($\delta^{34}\text{S} \approx +3\%$) and bacterially produced sulphide ($\delta^{34}\text{S} \approx -30\%$ to -40%). Such an assumption is consistent with the probable greater hydrostatic pressure implied by the structurally deeper position of most type II tubes with respect to palaeo-sea level which we may expect to have hindered volatilization of primary H_2S .

The peripheral baryte of the chimneys exhibits a range of 6.2% (from +14.2 to +20.4%) and the limited data presented have a bimodal distribution. Given an average Lower Carboniferous seawater value of around +19.5% (refs 6, 26, 34) it is evident that $\delta^{34}\text{S}$ was depleted in some of this baryte. We consider an isotopic contribution from minor oxidation of sulphide to be responsible for this ^{34}S depletion. Such an explanation was previously suggested for a similar variation in the S-isotope ratios of sulphate in the Red Sea brine, which spanned 5.9% (from +16.0% to +21.9%)³⁵. We suspect, however, that the tendency of peripheral baryte ratios to exhibit bimodality is probably a facet of the small number of analyses.

A vadose origin for the tubular pyritic structures is ruled out by the discovery of these extreme fractionations of the sulphur

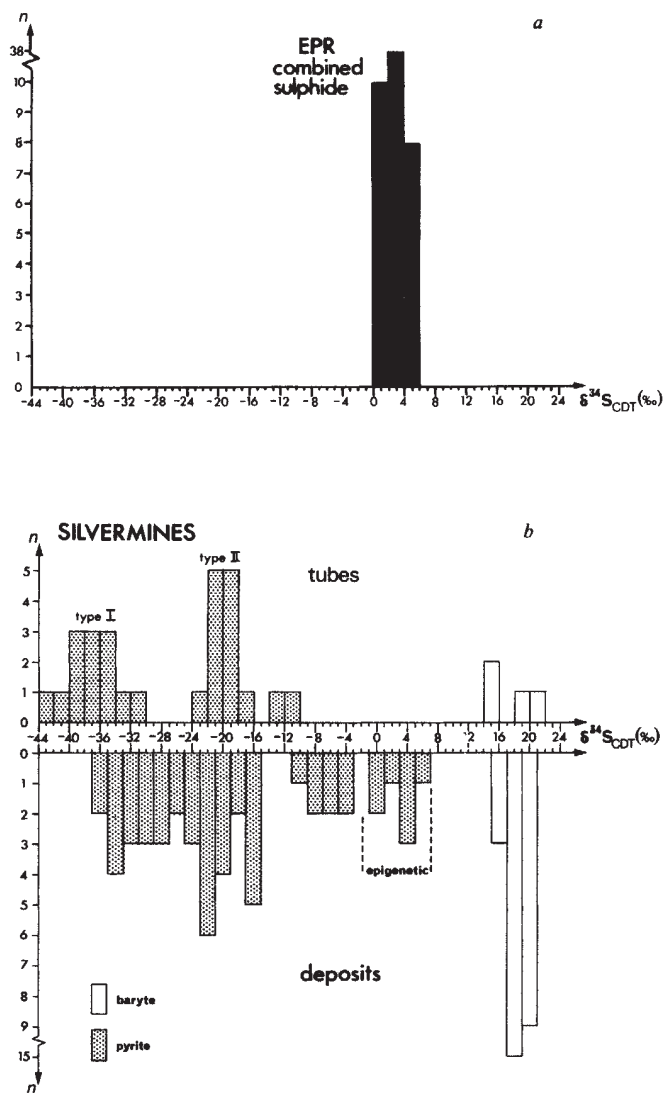


Fig. 4 a, Histogram of all published S-isotope data from the sulphides of the East Pacific Rise hydrothermal sites^{10,11,38}. b, Histogram comparing the S-isotope results of the Silvermines tubes with the published results of the same minerals from the associated deposits^{6,22}.

isotopes in the sulphides. Where true sulphide stalactites do occur, at Pine Point in Canada, their $\delta^{34}\text{S}$ values are indistinguishable from those in the hypogene ores which have a tightly defined average of +20.1% ($\sigma = 2.6\%$) (refs 36, 37, and J. R. Kyle and D. F. Sangster, personal communication).

Relevance for mineral exploration

Our study shows that S-isotope analyses could be a valuable tool in intra-prospect exploration, even where the interpretation of the results is quite subjective. The mounds and chimneys mark the main areas where upwelling mineralizing solutions approach towards, and discharge into, the sea. Larter *et al.*⁴ pointed out that epigenetic sulphide and sulphate developments may be sited below these zones, hence their utilization as pointers to mineralization is potentially valuable (particularly considering that the type IIb vents were found above the Pb+Ag-rich Lower 'G' zone on the same segment of the Silvermines fault). Even where chimney structures are destroyed by

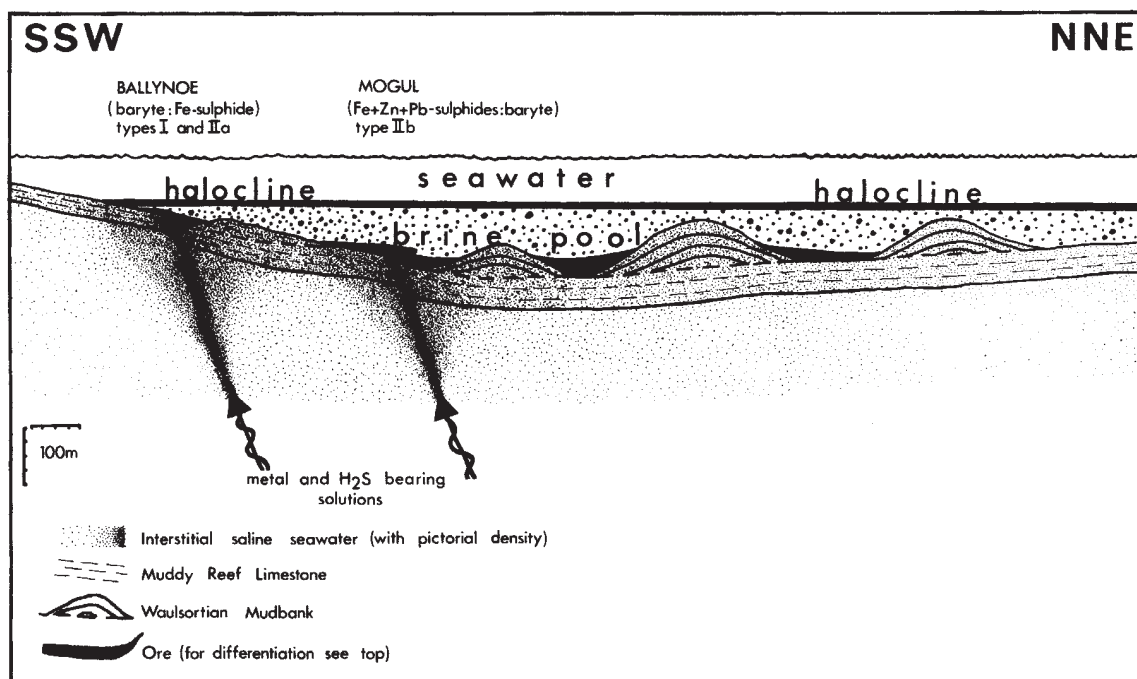


Fig. 5 Model depicting the environment of mineral precipitation at Silvermines. Metal-rich exhalant carries $\Sigma^{34}\text{S}$ sulphide at +3‰ (primary) in fluid of ~12 wt% NaCl equiv. Interstitial seawater and brine pool have salinity ~20 wt% NaCl equiv. The halocline hosts SO_4 reducing bacteria, and organic material which has been caught in a saline density trap. Bacterial fractionation produces sulphide $\delta^{34}\text{S}$ values between -18.4‰ and -42.5‰ in the tubes.

metamorphism, or remain undiscovered, a sulphur isotope study on this type of sediment-hosted exhalative deposit (formed within a brine pool), may be of practical value in revealing feeder mound sites, since unusually light $\delta^{34}\text{S}$ results seem to be diagnostic of such material.

We expect similar isotopic variations, particularly the very light sulphide sulphur values around the fossil hydrothermal vents, and the primary (heavy) sulphide sulphur of the lower feeder zones, to be revealed by comprehensive studies on orebodies like Navan in Ireland, and H. Y. C. McArthur River and Lady Loretta in Australia. Moreover, present day chimneys may yet be discovered exhibiting similar fractionations where

hydrothermal fluids issue in a halocline above a brine pool developing in a constricted ocean such as the Red Sea.

We thank the staff and workers of Magobar and Mogul Mines for patient and willing assistance, particularly Graham Smith and Stewart Taylor. We thank with Dic Larter, Iain Samson, Allan Hall, Paul Duller, Andrew Russell, John Sherwood and Rob Willan for valuable discussions. The invaluable help of Marg Cox and John Rouse during S-isotope analyses is gratefully acknowledged. Chris Cornford (Britoil) kindly ran the T.O.C. analyses. A.J.B. is supported by a NERC award. M.L.C. publishes with the approval of the Director, Institute of Geological Sciences (NERC).

Received 14 March; accepted 2 September 1983.

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