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## The role of dense brines in the formation of vent-distal sedimentary-exhalative (SEDEX) lead–zinc deposits: field and laboratory evidence

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**Abstract** A majority of the world's sediment-hosted exhalative (SEDEX) lead–zinc deposits are vent-distal. They are not underlain by a discordant alteration zone or stockwork vent complex that would indicate the path by which ore fluids reached the seafloor. The absence of a vent complex, together with sulfide mineral replacement of host rock mineral assemblages has led several investigators to suggest that, in spite of the well-layered nature of these deposits, mineralization was formed by sub-seafloor lateral migration of ore fluids along permeable strata. Field observations, supported by simple laboratory experiments, however, suggest an alternative process for characterizing the genesis of vent-distal SEDEX deposits. Cool, saline brines (e.g., ~120 °C and > 15 wt% NaCl equiv.) are denser than seawater and, upon discharging into the sea, would flow away from the discharge vent as bottom-hugging fluids, similar to the behavior of turbidity currents. Their high densities and velocities prevent them from mixing with overlying seawater, thereby precluding significant cooling and dilution of the ore fluid. Upon coming to rest in a seafloor depression, the addition of H<sub>2</sub>S and/or dilution of the ore fluids to lower salinities result in the eventual precipitation of a vent-distal SEDEX deposit. Furthermore, the dense ore-forming fluid can sink into permeable sediments beneath the brine pool by displacing less dense pore water. The ore fluids are thus capable of effectively overprinting and/or replacing pre-existing minerals in the consolidating sediment pile.

**Keywords** Brine(s) · Lead · Zinc · Sedex · Vent-distal · Exhalative · Sedimentary

### Introduction

Sedimentary exhalative (SEDEX) deposits are considered to have formed by the precipitation of sulfide minerals from warm fluids discharged into the sea through fractures in the seafloor (Goodfellow et al. 1993; Lydon 1995). The resultant deposits are large and commonly internally layered, with sulfide-rich beds interlayered with sulfide-poor beds. A significant feature of some SEDEX deposits is the so-called feeder pipe, the "...zone of reaction between up-flowing hydrothermal fluids and footwall sediments" (Goodfellow et al. 1993, p. 205). The stratiform deposits that are directly underlain by a discordant feeder pipe and alteration complex are termed vent-proximal in reference to their position relative to the exhalative vent. Those SEDEX deposits that are not underlain by such a feeder and alteration complex are referred to as vent-distal, being spatially disconnected from hydrothermal vent zones (Lydon 1995). In spite of the absence of feeder zones, however, vent-distal deposits are stratiform, concordant with enclosing strata, and display well-developed internal layering. Indeed, many such distal deposits (e.g., Mt. Isa, HYC, Howards Pass) are regarded as typical SEDEX deposits.

Although most descriptions and genetic models of SEDEX deposits emphasize the footwall feeder pipe and the attendant alteration, not all deposits share this distinctive feature. A compilation of world SEDEX data indicated more than 80% of SEDEX deposits are vent-distal (Sangster and Hillary 2000). Lydon (1995, p. 144) suggested that many proximal zones have gone unrecognized because "...the most common hydrothermal minerals [are] similar to the rock-forming mineralogy of terrigenous sedimentary rocks that have been metamorphosed to greenschist facies...". The fact remains, however, that many economically important SEDEX deposits occur in essentially pristine host rocks without visible discordant alteration zones or vent complexes. Several are not even hosted in clastic rocks, but in

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marine carbonate rocks (see Table 1 in Goodfellow et al. 1993) where footwall alteration should be readily identified. Thus, although one might quibble about the exact proportion of distal versus proximal SEDEX deposits, a majority of SEDEX deposits are vent-distal and therefore genetic models must take this into account. However, for example, neither Goodfellow et al. (1993) nor Lydon (1995) devote more than a paragraph or two to the concept of vent-distal SEDEX deposits.

To further complicate matters, it has been proposed that some SEDEX deposits are not the result of exhalative processes but represent diagenetic replacement of sedimentary host rocks by sulfide minerals (Neudert 1983), and that ore fluids moved laterally through the host rocks (Eldridge et al. 1993). This genetic model has been referred to as the "permeation model" by Williams (1990).

The high proportion of vent-distal SEDEX deposits contrasts with volcanogenic massive sulfide (VMS) deposits of which at least ~95% are vent-proximal (M. Hannington, J.M. Franklin, A. Galley, personal communication, 2000). This marked difference between the two major classes of exhalative deposit-types precludes a simple extension of a VMS buoyant-plume process to a majority of SEDEX deposits.

Against the backdrop of these uncertainties, this paper explores two main questions relating to the origin of vent-distal SEDEX deposits:

1. What type of fluid is most likely to have been responsible for deposition of vent-distal deposits?
2. If all vent-distal SEDEX deposits are, in fact, the products of exhalative activity, can the observations of Neudert (1983), Williams (1990), and Eldridge et al. (1993) regarding diagenetic replacement be accommodated by an exhalative model?

### Fluids that form vent-distal SEDEX deposits

As Lydon (1995) suggested, vent-distal deposits could result from bottom-hugging fluids (i.e., fluid that move laterally along the seafloor) collecting in seafloor depressions distant from their discharge zone. It is this concept that is the subject of this paper. The fluid dispersion processes were first detailed by Sato (1972) who pointed out that, upon discharge, the density of the brine, relative to the density of ambient seawater (1.02 g/cm<sup>3</sup> at 20 °C), determines its behavior. The initial density of the brine is controlled by its temperature and salinity and this density changes during mixing with seawater.

Sato (1972) demonstrated that two main types of ore fluids, differing in density, are involved in the formation of exhalative deposits. Dense fluids (i.e., low temperature, high salinity) are heavier than ambient seawater when they are discharged and, regardless of the degree of mixing, would invariably remain on the seafloor. In

contrast, less dense (i.e., high temperature, low salinity) fluids would be lighter than seawater and would produce buoyant plumes upon entering the sea. Sato also recognized an intermediate density fluid (high temperature, high salinity), with a starting density only slightly less than that of seawater. Upon mixing with seawater, these fluids would initially form buoyant plumes, but, with further mixing, their densities would increase to a point at which the plume would collapse and they would occur as bottom-hugging brines. Sato's calculations regarding collapsing plumes (or buoyancy reversal) assumed discharging fluids of no greater than ~180 °C. Turner and Campbell (1987) later showed that, at higher temperatures, the field of buoyancy reversal is significantly increased over that shown in Sato's (1972) diagrams. Sato's theories on the behavior of metalliferous fluids in seawater have since been confirmed experimentally (Turner and Gustafson 1978; Solomon and Walshe 1979; McDougall 1984a, 1984b) and by observations of buoyant plumes in the "black smokers" of modern seafloor hydrothermal systems (e.g., Barrett and Jambor 1988). Low-temperature, high-salinity fluids, however, have not yet been observed in natural systems.

Although Sato (1972) and Turner and Campbell (1987) illustrated their arguments through the use of temperature vs. density plots, here these diagrams are reconstructed using a temperature vs. salinity plot (Fig. 1). Using data from Haas (1976) and Turner and Campbell (1987), a direct comparison of fluid inclusion data with seawater densities is possible without the need

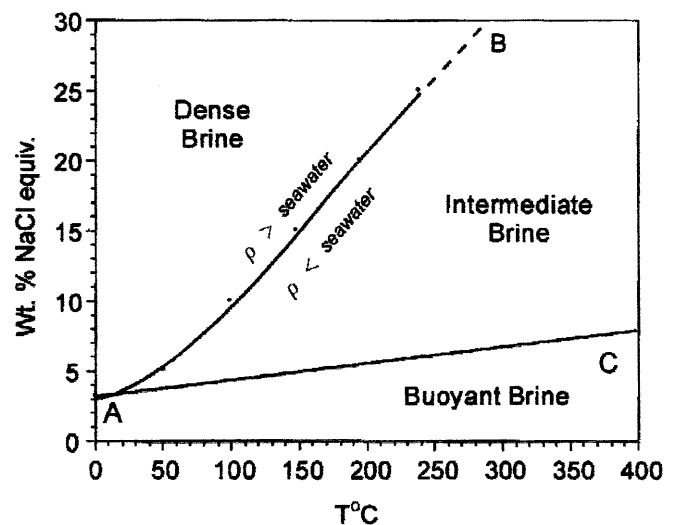


Fig. 1 Temperature versus salinity plot. Point "A" is the position of seawater at 2 °C. Line AB is the seawater isodensity line; points on this line have the same density as seawater at 2 °C ( $\rho = 1.028 \text{ g/cm}^3$ ). Ore fluids that plot below this line are less dense than seawater; fluids plotting above the line are denser than seawater. Data from Haas (1976). Line AC defines the lower limit of the field of buoyancy reversal (data from Turner and Campbell 1987). The field between AB and AC is one in which a discharging fluid is initially less dense than seawater and rises as a buoyant plume. After mixing with seawater, the fluid becomes heavy, the plume then collapses, and the fluid collects on the seafloor as a dense brine

to consult tables relating temperature and salinity to density. Instead of using Sato's seawater values (i.e., 20 °C,  $\rho = 1.02 \text{ g/cm}^3$ ), those of Turner and Campbell (1987; i.e., 2 °C, 3.2 wt% NaCl,  $\rho = 1.028 \text{ g/cm}^3$ ) are taken here as more representative of conditions on the seafloor. Based on these parameters, a seawater isodensity curve can be constructed (line AB in Fig. 1) such that any fluid possessing a combination of temperature and salinity falling on this line will have a density equal to that of seawater at 2 °C.

Thus, by plotting fluid inclusion temperature and salinity measurements on Fig. 1, one can readily compare the density of the fluid with that of seawater. Mixing of the discharged fluid with seawater will move the composition along a straight line joining the initial discharge point with that of seawater (point A in Fig. 1). Ore fluids possessing salinities less than that of seawater are uncommon.

Fluids plotting above line AB would be denser than seawater and would remain so regardless of how much mixing took place. The dense mixture could not form a plume, but, rather, would always migrate as a bottom-hugging brine. Aside from a small degree of turbulence produced by artesian pressures of the venting fluids or at the "toe" of a moving density current, mixing would not take place. The fluid would retain its original physical and chemical parameters (e.g., temperature and salinity) and, therefore, density. A vent-proximal deposit would form only if discharge took place in a seafloor depression; if not, the dense fluid would move downslope to collect, from single or multiple venting events, in a distant depression.

Line AC in Fig. 1 defines the lower limit of the field of buoyancy reversal (Turner and Campbell 1987); any fluid plotting below line AC in Fig. 1 would always be less dense than seawater, regardless of the degree of mixing, and would always form a buoyant plume upon discharge. In general, these buoyant fluids form vent-proximal deposits because most of the base metals are precipitated beneath the seafloor, or in the immediate vicinity of the vent because of rapid quenching of the hot fluid as it comes into contact with seawater-saturated rocks. The process by which this type of fluid would form sulfide deposits has been described by Lydon (1988) and is not discussed further.

Intermediate fluids (plotting between lines AB and AC on Fig. 1) would initially form a buoyant plume and follow a mixing line toward seawater. As mixing continues, however, the mixing line will cross the seawater isodensity line AB at which point the fluid density would exceed that of seawater and the plume would collapse to form a dense fluid on the seafloor. The degree of mixing required to produce such a collapsing plume from an initially high-temperature fluid would be high, however, and it is doubtful whether the base-metal content of the resultant heavy fluid would be significant.

In summary, it is clear that relatively cool, highly saline fluids (i.e., above line AB on Fig. 1) are those most likely to form vent-distal deposits because of their

capacity to migrate away from the vent site as bottom-hugging brines. They will form vent-proximal deposits only in those special cases where they discharge into a pre-existing depression. Fluids of intermediate densities, although potentially capable of producing similar bottom-hugging brines, are unlikely to result in vent-distal SEDEX deposits.

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### Fluid inclusions in SEDEX deposits

Whereas fluid inclusion studies of the vent-proximal volcanogenic massive sulfide (VMS) deposits (e.g., Pisutha-Arnold and Ohmoto 1983) and modern seafloor mineralization (e.g., Rona 1988) have shown that most, if not all, of these deposits are formed from high-temperature, low-salinity fluids, remarkably few fluid inclusion studies have been carried out on SEDEX deposits. Ansdell et al. (1989) and Gardner and Hutcheon (1985) examined fluid inclusion systematics on the Tom and Jason deposits, respectively, in Yukon Territory, Canada. Leitch (1992) published data from the Sullivan deposit, British Columbia, Canada, but admitted there was a question as to whether the measured homogenization temperatures reflected the effects of post-ore metamorphism. The Silvermines deposit, Ireland, regarded as a SEDEX deposit by Samson and Russell (1987), was the subject of a detailed fluid inclusion study by these workers. If results from these four examples are accepted as valid estimates of the temperatures and salinities of the ore fluids, then the data indicate buoyancy-reversal fluids were involved in all cases. All four deposits, however, are vent-proximal, suggesting rapid, in-situ sulfide mineral deposition.

The fact remains that no fluid inclusion data are available for vent-distal SEDEX deposits, probably because ore-related minerals in vent-distal SEDEX deposits are characteristically extremely fine-grained and therefore unsuitable for microthermometry. Even for vent-proximal deposits, such studies are normally carried out on vent-related minerals rather than on minerals from the fine-grained, stratiform, distal parts of the deposits.

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### Comparison with MVT fluids

Because of the absence of fluid inclusion data on the world's vent-distal SEDEX deposits, it is necessary to look elsewhere for possible clues as to the nature of fluids that formed these deposits. Mississippi Valley-type (MVT) deposits (Leach and Sangster 1993) share many features in common with SEDEX lead-zinc deposits including metal ratios, lead and sulfur isotopic compositions, and a genetic relationship to sedimentary basins (Sangster 1990). Furthermore, several MVT districts contain dozens or even hundreds of small deposits that collectively contain as much lead and zinc as individual SEDEX deposits. The many similarities between these two major lead-zinc deposit-types have prompted

suggestions that they might be genetically related (Sangster 1990, 1993), or at least be the products of fluids with similar physical and chemical properties. Thus, MVT-like fluids could be the “missing fluid” responsible for vent-distal SEDEX deposits.

MVT fluids, as revealed by thousands of fluid inclusion measurements, are typically low temperature and highly saline. Approximately 90% of the MVT fluid inclusion data fall in the range 80 to 120 °C and 12 to 28% NaCl wt. equiv. (see Fig. 15 in Sangster et al. 1998), representing a range in density from 1.028 to 1.145 g/cm<sup>3</sup>. The field representing this range falls well above line AB in Fig. 1 and would, therefore, possess the attributes of a bottom-hugging dense brine in a SEDEX environment.

### Movement of the seafloor brine

Overpressured aquifers, tapped by a synsedimentary fault, could provide the force necessary to drive dense brines up to the seafloor (Lydon 1983). Unless the fluids were ejected directly into a seafloor depression, they would move downslope as a gravity current in a manner analogous to that of a turbidity current. In fact, laboratory studies have used brine solutions to simulate turbidity currents and, in these cases, density differences between the gravity currents and ambient tank fluid ranged from 0.027 to 0.059 g/cm<sup>3</sup> (Middleton 1966); the density differences between MVT-like fluids and seawater are somewhat greater, ranging up to 0.117 g/cm<sup>3</sup>.

Undersea turbidity currents, once set in motion, continue to move downslope as long as a density contrast exists relative to seawater and a topographic gradient is maintained. Experiments in flume tanks (e.g., Middleton 1966) confirm that, except for minor turbulence at the flow head, mixing with seawater does not occur and the original density contrast is maintained. Middleton (1966) determined that the velocity of turbidity current heads, on slopes  $\leq 4\%$ , is expressed by the formula

$$v = 0.75 \sqrt{\{(\Delta\rho/\rho)gd_2\}} \quad (1)$$

where  $v$  = velocity of the head,  $\Delta\rho$  is the difference between the density of the current ( $\rho$ ) and that of the overlying water,  $g$  is the acceleration caused by gravity, and  $d_2$  is the thickness of the head. Measured velocities of turbidity currents flowing along shallow topographic gradients typical of continental slopes range from 0.25 to 6.8 km/h (Inman et al. 1976; Lambert et al. 1976; Normark and Dickson 1976; Shepard et al. 1977;). On slopes with much steeper initial gradients, velocities of up to 68 km/h have been either measured or calculated (Genessaux et al. 1980; Piper et al. 1988).

Because the densities of MVT-like ore fluids are similar to those of turbidity currents, it can be assumed that the fluids would be capable of moving distances and at speeds comparable with those of turbidity currents. By analogy, it can be inferred that dense ore fluids can

rapidly move a considerable distance from the discharging vent and form a vent-distal SEDEX deposit.

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### The brine pool

The bottom-hugging brine will move as long as the topographic gradient exists and will come to rest only when the fluid enters a seafloor depression. The speed at which the fluid moves, and the lack of mixing with seawater because of the density contrast, would ensure that the original temperature and salinity of the hydrothermal fluid, which is now distant from the discharging vent, have remained essentially unchanged. Minor seawater mixing because of turbulence at the flow head and along the upper surface of the flow (Middleton 1966) would result in a small amount of sulfide minerals being precipitated en route, but, according to Campbell et al. (1984), these precipitates would be transported into the depression by the rapidly moving brine.

Once accumulated in a topographic depression, the resting immobile brine would also be subjected to the double diffusion process described by Turner (1974), Turner and Gustafson (1978), and McDougall (1984b). Heat diffuses outward, cooling the fluid, and tends to increase fluid density. In contrast, and at the same time, salts in the fluid also diffuse outward, the salinity decreases, and the density of the remaining fluid would tend to decrease. As described by Turner (1974) and Turner and Gustafson (1978), the rate of heat loss greatly exceeds that of salt loss so the net effect of double diffusion is an increase in the density of the fluid in the seafloor depression. For example, assume a fluid at 90 °C and with 20% wt. NaCl equivalent ( $\rho = 1.11$  g/cm<sup>3</sup>) undergoes double diffusion processes in a brine pool. Because heat diffusion out of the fluid is  $\sim 100$  times faster than diffusion of dissolved salts (Stern 1980), the brine rapidly cools to that of ambient seawater temperature (2 °C) with little or no loss of salt such that its density rises to 1.18 g/cm<sup>3</sup>. Therefore, once the brine was localized in a seafloor depression, double diffusion would result in a further increase in its density.

As with all freshly-deposited sedimentary material, the porosity and permeability of the sediment beneath the pool is high, allowing the overlying brine to sink by displacing the less dense pore water. This “sinking brine” process was mentioned by Williams (1978, p. 1033) with reference to the origin of the HYC deposit in Australia. He noted that “The localization of the bulk of the concordant mineralization in the lower part of the HYC Pyritic Shales is probably due to the settling of the saline, and therefore dense, mineralizing solutions to the base of the fine-grained sediment pile”.

To illustrate the sinking brine process for this study, a series of simple experiments were conducted using a fish aquarium, quartz sand, modeling clay, and a saline solution colored with red vegetable dye. A layer of highly permeable quartz sand was placed in the aquarium and a small hollow was made in the sand to represent a

seafloor depression or pool site (Fig. 2a). To emulate a relatively impermeable layer of sediment (e.g., a mudstone layer within carbonate micrite or siliciclastic sandstone), the bottom of the depression was lined with modeling clay and tightly stuck to the viewer's side of the aquarium. A layer of sand was then placed on top of the modeling clay (Fig. 2a) and the aquarium was filled with ordinary tap water ( $\rho = 1 \text{ g/cm}^3$ ) to emulate seawater. The pool was filled with the saline solution ( $\rho = 1.14 \text{ g/cm}^3$ ) to emulate a dense ore-forming fluid (Fig. 2b) thereby creating a density difference between "seawater" and "ore fluid" of  $0.14 \text{ g/cm}^3$ . Although this value is greater than that estimated between seawater and ore fluid, the principles of relative buoyancy remain the same and the higher density contrast simply decreased the experimental time. As anticipated, and within minutes, the dense "ore fluid" began sinking into the sand beneath the depression by displacing the ambient "seawater" pore fluid (Fig. 2c). Eventually all the "ore fluid" accumulated on top of the clay layer

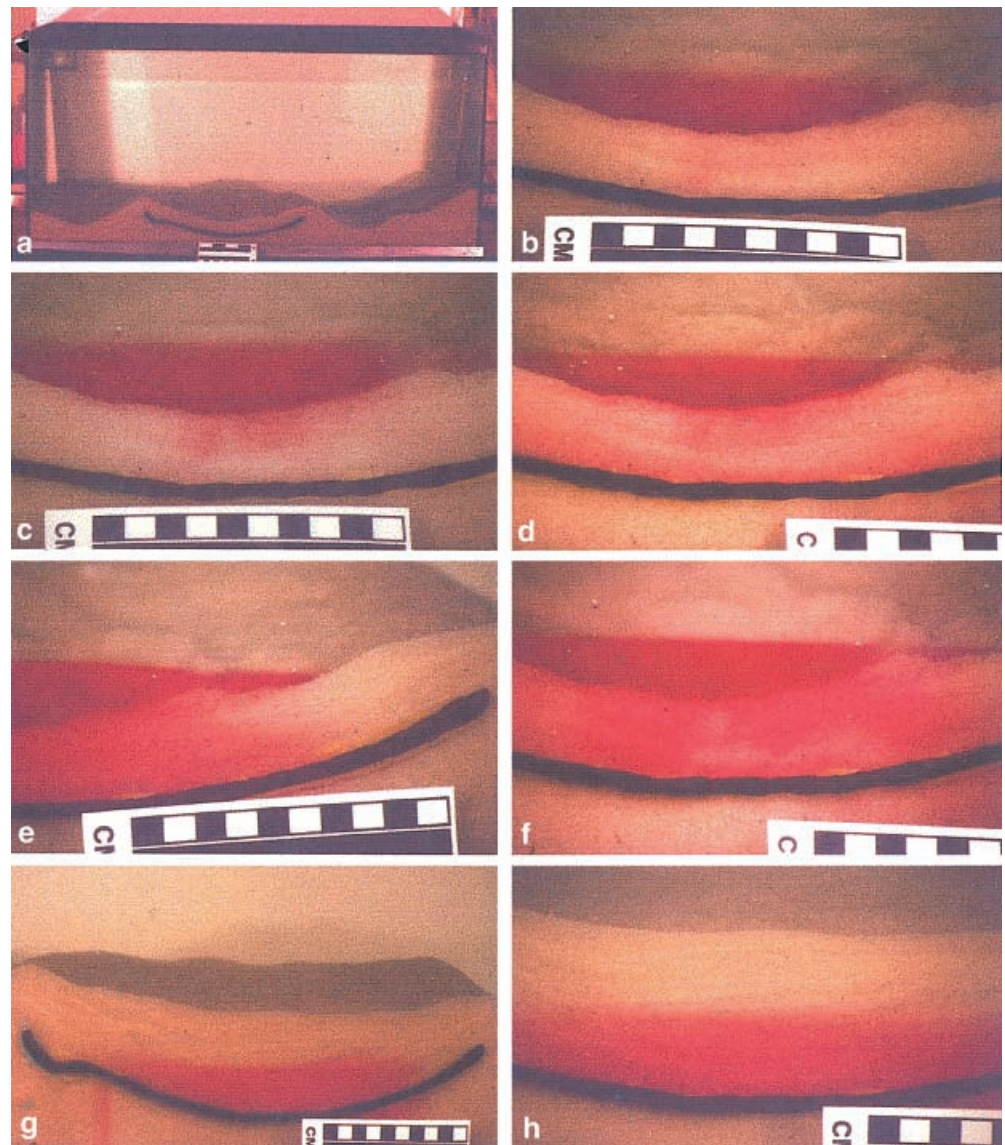
(Fig. 2d) and ambient "seawater" had again filled the pore space in the overlying sand. Replenishment of the depression with more "ore fluid" simply repeated the process (Fig. 2e). After several "refills" (Fig. 2f), the brine pool was allowed to deplete itself and all the "ore fluid" collected on the clay layer. A layer of quartz sand was added to the depleted brine pool to emulate continued sedimentation and, at this point (Fig. 2g, h), the assemblage took on the appearance of a layered SEDEX deposit in which sulfide layers are intercalated with layers of barren sediment.

## Discussion

Physical and chemical properties  
of a dense, metalliferous brine

Although several authors, since Sato's (1972) pioneering effort, have examined the seafloor hydrologic dynamics

**Fig. 2** Laboratory experiment to illustrate the role of a "sinking brine". **a** Water-filled aquarium with a small hollow in quartz sand floored with a ~1-cm-thick layer of modeling clay (*black layer*) tightly attached to the viewer's side of the aquarium and overlain with more sand. **b** Dye-colored saline solution ("ore fluid") placed in hollow immediately begins to sink into the underlying sand. **c** Irregular, downward-projecting "ore fluid" extensions below the brine pool. **d** The first increment of "ore fluid" has ponded against the clay, ambient "seawater" has again filled the sand pores, and a second increment of fluid has been added to the pool. **e, f** As more fluid is added to the brine pool, it continues to sink and eventually to accumulate above the impermeable clay layer. **g, h** The brine pool has been allowed to deplete itself, the "ore fluid" has collected on the clay layer and a layer of quartz sand has been added above the "ore layer". The *small vertical stripe* below the clay in 2G is caused by a small leak between the clay and aquarium glass



of dense brines relative to formation of SEDEX deposits (e.g., Solomon and Walshe 1979; McDougall 1984b), none has described the specific temperature and salinity conditions likely characterizing a bottom-hugging brine. The wide range of possible temperatures and salinities of dense brines (Fig. 1) is an important factor in explaining why most SEDEX deposits are, in fact, vent-distal. It is clear, again from Fig. 1, that a SEDEX ore-forming fluid can exist at temperatures approaching, or equivalent to, those which result in MVT deposits. Sedimentary basins, in which thermal gradients can be expected to be less than those along spreading ridges and in island arcs (where VMS deposits form), normally generate relatively low-temperature hydrothermal fluids. The high salinities that are also required to produce bottom-hugging brines may be produced by dissolution of evaporites within the same sedimentary basin.

Cooke et al. (2000) have stressed that low-temperature, high-salinity brines can carry significant amounts of lead and zinc if the fluids are highly oxidizing (i.e.,  $\text{SO}_4^{2-} > \text{H}_2\text{S}$ ). They proposed the term "McArthur-type" to refer to cool, dense, oxidizing brines, with an average temperature of 150 °C and salinity of 25 equiv. wt% NaCl, and suggested these fluids would be comparable with those that formed MVT deposits. McArthur-type brines would plot above line AB in Fig. 1 and hence be bottom-hugging. Cooke et al. (2000) also noted that deposits formed from McArthur-type fluids generally do not contain footwall stringer zones or vent complexes; that is, they are vent-distal deposits.

En route from its original discharge site to a seafloor depression, the moving brine is subjected to the same double diffusion process described earlier for an immobile fluid. Thus, the moving fluid cools slightly but is not substantially diluted. If, in fact, dense, bottom-hugging brines are of the oxidizing McArthur-type, simple cooling will not result in precipitation of galena and sphalerite (Cooke et al. 2000). The fluid thus reaches its final destination without significant loss of its ore constituents.

#### Water depth and composition

The properties of a bottom-hugging brine also result in a wide range of permissive water depths for the formation of vent-distal SEDEX deposits. In order to reach the seafloor, a potential ore-forming fluid must be prevented from boiling lest the resultant cooling prematurely precipitate sulfide minerals in the sub-seafloor environment. A high hydrostatic pressure of seawater can prevent boiling of the fluids and thus deep water is required to prevent boiling of fluids responsible for VMS deposits, modern black smokers, and vent-proximal SEDEX deposits. For example, water depths of modern seafloor mineral occurrences formed in the vicinity of spreading centers (i.e., from fluids plotting below the line AC in Fig. 1) are in excess of 1,500 m (Rona 1988; Sangster 1990, Fig. 19). In contrast, minimum water depth to

prevent boiling of fluids with compositions above line AB in Fig. 1 can be as little as 5 m (Haas 1971) although they can also form in much deeper water. This indicates that, given the proper temperature–salinity composition of the source fluid, vent-distal SEDEX deposits can form in a variety of seafloor environments and host-rock lithologies, reflecting various ocean depths.

The lack of mixing between a dense brine and the overlying seawater also removes the requirement that an anoxic water column be present in order to form a vent-distal SEDEX deposit as suggested by Goodfellow (1987) and Turner (1992). The ore fluid, not moving as a buoyant plume, would come into only minimal contact with the overlying water column and, therefore, few, if any, sulfide minerals would be precipitated. Galena and sphalerite would, however, be precipitated from McArthur-type fluids in the brine pool by an increase in  $\text{H}_2\text{S}$  (through local reduction of sulfate and/or reaction with pre-existing sedimentary sulfide) or by reduction in salinity through double diffusion (Cooke et al. 2000). The presence of sulfide clasts in some deposits (e.g., Large et al. 1998) could be because of precipitation of sulfides settling out of the brine pool. In summary, an anoxic ocean is not a necessary requirement for the deposition of a vent-distal SEDEX deposit.

#### Processes operating in the brine pool

Many investigators have assumed that the dense fluids would simply collect to form a brine pool. McDougall (1984b), for example, examined the variety of processes that operate when hot dense saline fluids flow into a submarine depression. Although not stated explicitly, the assumption in the "brine pool" model is that the depression is floored with an impermeable sedimentary layer, thereby allowing the heavy ore fluids to accumulate directly on the pool floor. It is unlikely that any freshly-deposited sediment is absolutely impermeable, just that some are less permeable than others. If the pool floor is relatively impermeable, then sulfide minerals will eventually collect directly on the bottom. If, however, the depression is floored with even slightly permeable sediments, the fluid will sink into the unconsolidated sediments. The density contrast between the cooled brine and that of pore-filling seawater results in rapid sinking of the former as demonstrated in the experiments described earlier.

The concept of a seafloor brine sinking into sediments, instead of simply resting on them, may provide a reconciliation of the genetic model controversy concerning the significance of exhalative versus replacement processes for vent-distal SEDEX deposits. Investigators have consistently reported textures indicating widespread replacement of host rock minerals by sulfides and/or one sulfide mineral by another. This phenomenon is particularly evident in SEDEX deposits in carbonate or carbonate-rich rocks such as those in the Middle Proterozoic of Australia where workers have

suggested that these deposits are predominantly replacement in origin (e.g., Neudert 1983; Eldridge et al. 1993; Hinman 1995). A dense ore fluid sinking beneath a seafloor depression might explain how replacement textures can be found in an exhalative deposit. The large surface area of the fine-grained host sedimentary material provides the sinking brine maximum opportunity to react with, and therefore replace, not only the predominant carbonate minerals but also the accompanying clastic silicate and diagenetic components (e.g., pyrite) of the underlying unconsolidated sediment. For example, Large et al. (1998) appealed to a heavy sinking brine to account for some of the overprinting and replacement textures in the HYC deposit. The high initial permeability of the sedimentary material would also allow the sinking brine to precipitate sulfide minerals directly within open pore space, again resulting in what could be interpreted as a later, epigenetic texture.

The sinking brine process might also produce the widespread concordant halos associated with vent-distal SEDEX deposits. For example, the carbonaceous cherty mudstone in the immediate footwall of the XY (Howards Pass) deposit is characterized by "...extremely high contents of  $K_2O$  below the thicker and higher grade sections of the deposit" (Goodfellow 1984, p. 98). Lambert and Scott (1973) and Croxford (1964) also recorded high  $K_2O$  in shales surrounding the McArthur River and Mt. Isa deposits, respectively. Thin, tuffaceous beds at McArthur River, Mt. Isa, and Hilton have reported  $K_2O$  contents exceeding 10%, which are attributed to diagenetic alteration of volcanic glass shards by saline pore waters (Croxford 1964; Lambert and Scott 1973). Large et al. (2000) have described a concordant manganese-rich carbonate halo immediately below the McArthur River deposit. Footwall rocks at Howards Pass contain high "corrected boron" contents which Goodfellow and Jonasson (1986) attributed to abnormally high salinities of metalliferous brines. All these observations would be consistent with the concept of a brine collecting in seafloor depressions and sinking into, and thereby altering, the footwall sediments. In fact, Large et al. (1998) have suggested that sinking brines played a major role in the accumulation of the McArthur River ore lenses and the alteration halos might provide evidence of this process.

It is important to note here that the sinking of a brine could be sufficiently rapid such that a brine pool does not accumulate. Depending on the relative rates of sedimentation and fluid flow into the depression, the ore-forming fluid could sink well below the bottom of the pool, with seawater re-filling the pores behind it, before the next influx of fluid (as in the replenishment of the "ore fluid" in the experiments described above). If little or no sedimentation occurs before the next fluid enters, the second fluid would encounter seawater-filled pores and the fluid sinking process would be repeated. Alternatively, if sedimentation resumes before the next brine influx, subsequent sinking can take place in the newly-deposited sediment when the new fluid arrives.

## Layering in SEDEX deposits

In a homogeneously-permeable sedimentary medium, the sinking brine might be expected to precipitate disseminated sulfide minerals during changes in physical-chemical conditions. This would, however, contrast with the characteristic alternate layering of sulfide minerals and host rock evident in vent-distal SEDEX deposits. Such layering might be effected by permeability inhomogeneities in the sedimentary column beneath the brine-collecting seafloor depression. The experiment described above, in which an impervious layer of modeling clay was placed within the sand beneath the depression (Fig. 2), attempted to examine the effect of such inhomogeneities on the sinking process. With repeated increments of "ore fluid", the porosity of the sand immediately above the clay layer was eventually completely filled with dense fluid resulting in an "ore layer" between the underlying clay and the overlying sand. Sulfide minerals precipitated earlier might further decrease the downward permeability. A later descending ore fluid could collect above this impermeable sulfide-sediment layer and produce a second sulfide layer.

Alternatively, deposition of a relatively impermeable sediment (e.g., mudstone) above a sulfide layer, would, with the next increment of ore fluid, result in precipitation of a sulfide layer directly on the mudstone. Repetition of this sequence could produce the characteristic alternate layering of sulfide-rich and sulfide-poor beds in distal SEDEX deposits.

## Implications for SEDEX exploration

The recognition that most SEDEX-forming fluids probably migrated as a bottom-hugging brine has several implications relative to exploration for SEDEX deposits. For example, such an ore fluid effectively decouples an orebody from an essential associated feeder zone complex with its attendant wall-rock alteration. A vent-distal deposit also need not be situated adjacent to a syn-sedimentary fault, although it is generally acknowledged that such structures appear to be necessary to conduct ore fluids to the seafloor (Large 1983). Removal of the spatial synsedimentary fault association requirement effectively widens the potential favorability area for SEDEX deposits within a sedimentary basin.

Furthermore, it is clear that, under proper conditions, a dense ore fluid can rapidly migrate many kilometers from its discharge site. For example, the Aguilar deposit of Argentina is a vent-proximal deposit hosted in coarse-grained arkosic and calcareous sandstones underlain by a distinctive feeder zone complex (Gemmell et al. 1992). The Esperanza deposit, 15 km along strike in a basinward shale, is a vent-distal deposit. This raises the intriguing possibility that an ore fluid, decanted from the paleo-depression in which Aguilar collected, flowed along the paleo-seafloor to form the Esperanza deposit

in another depression in the manner suggested by McDougall (1984b).

Cooke et al. (2000) noted the tendency for McArthur-type deposits to be larger than those deposited from reduced, high-temperature, low-salinity brines ("Selwyn-type"). Similarly, Campbell et al. (1984) and Converse et al. (1984) suggested that the efficiency of metal extraction from dense brines may approach 100% because the lack of mixing with seawater en route to the final seafloor depression results in nearly complete retention of most metal until the brine comes to rest. Repeated discharge and movement of dense brines into the same seafloor depression could also explain the large size of deposits formed from these fluids. Multiple, superimposed, ore lenses are a characteristic feature of many SEDEX deposits, clearly suggesting repeated pulses of ore fluid travelling to the same seafloor depression. Large et al. (1998) estimated that, on average, more than 10,000 pulses of dense fluid were necessary to produce each of the several ore lenses in the HYC deposit.

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## Summary

1. A large majority of the world's SEDEX deposits are vent-distal.
2. The vent-distal setting precludes a simple application of a VMS mineralization process (vent-proximal) to a majority of SEDEX deposits;
3. A denser-than-seawater hydrothermal fluid would be a bottom-hugging brine that could move rapidly away from the discharge vent at speeds and over distances comparable with those of turbidity currents.
4. Although no fluid inclusion data are available for vent-distal SEDEX deposits, MVT-like fluids, also the products of tectonic processes in evolving sedimentary basins and capable of transporting and depositing economic amounts of lead and zinc, possess the physical-chemical attributes of a dense seafloor brine.
5. The speed at which the fluid moves, and the lack of mixing with seawater because of the density contrast, maintains a relatively constant fluid temperature and salinity until arrival at the site of metal deposition, where close to 100% efficiency in terms of metal transport and deposition may account for the large size and high grade of many SEDEX deposits.
6. The lack of mixing between a dense brine and the overlying seawater also removes the requirement that an anoxic water column be present in order to form a vent-distal SEDEX deposit;
7. The low boiling temperatures of these metalliferous places minimal restrictions on water depths in which discharge can occur, resulting in the formation of vent-distal deposits in a wide variety of depositional environments and host-rock lithologies.
8. Once the ore fluid comes to rest in a seafloor depression, it would be subject to the double-diffusion process, the net effect of which would be to increase further the density of the ore fluid.
9. The high permeability of newly deposited sediments would allow the dense ore fluid to readily sink into the sediments by displacing less dense pore water.
10. In sediments of high permeability, sinking may be sufficiently rapid as to preclude formation of a permanent brine pool.
11. The large surface area of the fine-grained host sedimentary material would provide the brine maximum opportunity to replace and/or alter the sedimentary components of the unconsolidated sediment through which the sinking fluid passes.
12. The high initial permeability of the sedimentary material would also allow the sinking brine to precipitate sulfide minerals directly in open pore spaces.
13. Layering might be effected by permeability inhomogeneities in the sedimentary column beneath the brine-collecting seafloor depression.

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