Salt as a fluid driver, and basement as a metal source, for stratiform sediment-hosted copper deposits

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ABSTRACT

The source of copper for stratiform sediment-hosted copper deposits is considered to be redbed clastics situated stratigraphically below the deposits. However, for one of the principal copper provinces in the world, the Zambian Copperbelt, there is insufficient thickness of redbeds to constitute a viable source. Numerical modeling demonstrates that high-salinity sedimentary brines, generated beneath a halite seal, will develop convective hydrothermal plumes that penetrate through the redbeds, deep into the crystalline basement, despite its low permeability and regardless of the availability of cross-stratal conduits. This greatly expands the volume of the potential metal source for this style of ore deposit.

INTRODUCTION

Sediment-hosted stratiform copper (SSC) deposits are of global economic significance and have been studied for more than a century. There is broad agreement on many elements relating to their formation (e.g., Hitzman et al., 2005; Kirkham, 1989). In terms of stratal architecture, the majority are hosted by laterally extensive, reduced lacustrine or marine sediments that overlie a basal continental redbed succession. A spatial association with evaporitic strata is common, and metal transport is facilitated by chloride complexes in sulfate-dominant brine. Precipitation of copper as sulfide occurs during diagenesis from reduction-oxidation (redox) reactions along the lithochemical interface between the redbed aquifer and the overlying reduced organic-rich shale.

The source of metals for SSC deposits is generally thought to be mafic-silicate minerals or iron oxides in the basal redbed strata. This is supported for most SSC districts by mass-balance calculations (Hitzman, 2000), which show that the amount of metal in the ores is generally proportional to the volume of their redbed metal reservoirs, and the amount of Cu that needs to be leached to account for the ores is ~35 ppm. However, this relationship does not hold in the Neoproterozoic Zambian Copperbelt, where the basal redbeds average only 250 m in thickness. Assuming an areal extent of 100 × 50 km, and 612×10^6 t Cu in the district, this requires leaching of 291 ppm Cu. In an attempt to account for this disparity, Hitzman (2000) argued that mineralized strata are tectonically displaced from a larger metal reservoir. However, the widespread preservation of structurally conformable contacts, both within the lower, ore-bearing portion of the basin fill and between basinal and basement strata (e.g., Selley et al., 2005), invalidates this interpretation.

Previous numerical hydrological modeling of SSC-endowed basins has considered three main drivers for fluid flow. The seminal work of (Jowett, 1986) on the Polish part of the Permian black shale–hosted Kupferschiefer system proposed that mineralization resulted from convective circulation of basinal brines within a sub-ore redbed metal reservoir, beneath a top seal of Zechstein evaporites. In contrast, a subsequent model (Blundell et al., 2003) proposed that the ore fluids originated in the area of a high heat flow anomaly in the basement, and were driven out and updip by seismic pumping associated with episodic activity on normal faults. A third model was proposed in a study of the Mesoproterozoic Midcontinent Rift System in the United States (Swenson et al., 2004): this suggested that marginward-directed sediment compaction–driven flow within the basal redbeds was sufficient to form SSC such as the White Pine deposit.

The association of evaporites with most SSC-endowed basins raises the potential of another, powerful, fluid-driving mechanism not considered in previous hydrological models, i.e., salinity-related density contrast. We use numerical modeling to examine the hydrodynamic effects of the development of high-density brine. The models are based upon a two-dimensional (2-D) profile of the Zambian Copperbelt, and specific issues addressed are (1) whether convective cells will form within the basin profile; (2) whether increased pore fluid density caused by the presence of dissolved solutes affects fluid flow patterns and velocities; and (3) whether the passage of basinal brines is restricted to the basal redbed element, or, and under what conditions, fluid flow pathways expand to incorporate the basement.

HYDROSTRATIGRAPHIC MODEL

The numerous ore deposits that define the Zambian Copperbelt are hosted by the Neoproterozoic Katangan Supergroup. A threefold stratigraphic subdivision comprises the Roan, Nguba, and Kundelungu Groups, that together encompass initial rift to passive margin environments (e.g., Cailteux et al., 2005). This metasedimentary succession unconformably overlies an Archean–Mesoproterozoic basement assemblage of calc-akaline metaigneous rocks and volumetrically subordinate quartzites. Both basement and Katangan Supergroup were deformed and metamorphosed during the latest Neoproterozoic–early Paleozoic Lufilian orogeny.

The timing of ore formation in the Zambian Copperbelt is controversial, and this study is based on the Selley et al. (2005) model, which through the integration of textural, chemical, and chronological constraints proposed a late diagenetic, preorogenic timing for the principal phase of metal introduction. Accordingly, the template for our hydrological models is a schematic geological profile of the Katangan Supergroup stratigraphy with the effects of Lufilian orogenesis removed (Fig. 1). The upper 4 km represent the Katangan Supergroup, whereas the lower part, down to the base of the section at 17 km, represents basement.

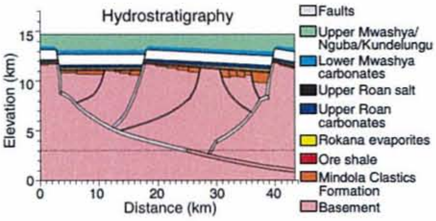

Figure 1. Schematic cross section of Zambian Copperbelt distinguishing hydrostratigraphic elements.

Above ~12 km basement permeability was parametrized by a logarithmic permeability-depth function (which yields values ranging from $10^{-15.8}$ to $10^{-17.5}$ m^2 for depths from 3.7 to 12 km; Ingebritsen and Manning, 1999); below this level it was assumed constant ($10^{-18.3}$ m^2). Basement porosity was specified as 0.57% (Schild et al., 2001).

Katangan Supergroup strata are parametrized according to their dominant lithology and depth of burial. Each hydrostratigraphic element is described briefly below, along with its assigned porosity (n), and the maximum component of the permeability tensor (k_x). A horizontal/vertical permeability anisotropy ratio of 100 was assumed for all Katangan Supergroup strata, consistent with the bedded nature of the succession (Lee and Farmer, 1993), and a ratio of 10 was assumed for the basement (Ingebritsen and Manning, 1999). The full range of physical properties assigned to each hydrostratigraphic element is presented in Table DR1 in the GSA Data Repository.[1]

The Lower Roan is represented by three hydrostratigraphic units. The basal Mindola Clastics ($n = 10.9\%$, $k_x = 2.5 \times 10^{-16}$ m^2) consists of subarkosic sandstones and conglomerates that represent the redbed element of the generalized SSC lithostratigraphy. The Ore Shale, which is the principal host to copper mineralization, consists of fine-grained, reducing, sub-wave-base marine sediments. The overlying Rokana Evaporites comprise a mixed package of sandstones, shales, and evaporitic carbonates. These units are ascribed a relatively low permeability ($n = 7.6\%$, $k_x = 3.0 \times 10^{-18}$ m^2).

The Upper Roan is characterized by microbial carbonate strata, and widespread breccias that have been interpreted to record the former presence of halite (Jackson et al., 2003; Selley et al., 2005). Although the precise depositional geometry of the halite-bearing package is unclear, the ubiquitous and dominantly stratabound character of breccias, which generally reflect the geometry of the precursor evaporitic stata (Warren, 1997), indicates that it was originally laterally continuous at the scale of the Zambian Copperbelt. In our model, the Upper Roan therefore has a layer-cake hydrostratigraphy comprising a basal carbonate unit ($n = 13.1\%$, $k_x = 1.2 \times 10^{-16}$ m^2) and an overlying halite sheet ($n = 0.1\%$, $k_x = 10^{-21}$ m^2). The ~1 km thickness of halite shown in Figure 1 matches that postulated for the Congolese Copperbelt to the north (Jackson et al., 2003), and is considered an upper limit. The lower unit of the overlying Mwashya subgroup is similar to the underlying carbonate strata, but as it occurs shallower in the section it is assigned higher porosity and permeability values (21.4% and 4.3×10^{-16} m^2, respectively). The upper part and all of the overlying Nguba and Kundelungu Groups are modeled as fine-grained clastic rocks ($n = 20.1\%$ and $k_x = 1.5 \times 10^{-16}$ m^2).

Fault propagation during early stages of rifting involved progressive linkage of initially numerous discontinuous fault segments to form throughgoing master fault arrays (Selley et al., 2005). Formation of the latter marks rift climax, and is recorded by the abrupt change from compartmentalized, subaerial Mindola Clastics depocenters to laterally extensive, marine Ore Shale depocenters (Fig. 1). To reflect this structural architecture, a schematic extensional fault network is incorporated in our section. However, questions arise as to assigning appropriate hydrological properties, as brittle fault zones are not only texturally heterogeneous, but may change their hydrological properties cyclically over time (Bense and Person, 2006; Caine et al., 1996). They can act as fluid conduits during and after pulses of deformation, but subsequently become aquicludes when pore space is occluded by mineral precipitation during periods of tectonic quiescence. Therefore, we have modeled both scenarios. For the permeable fault network scenario, fault zone porosity was assigned 1.7%; permeability was calculated as 3 times higher than of the adjacent basement rock at a given depth.

NUMERICAL MODEL

A two-dimensional, transient finite element model has been developed to simulate free thermohaline convection in a heterogeneous, anisotropic, compressible porous medium that is completely saturated by a compressible fluid bearing dissolved sodium chloride (Koziy, 2007). Fluid properties (density, viscosity, heat capacity, thermal conductivity) are functions of temperature, salinity, and pressure (Batzle and Wang, 1992; Holzbecher, 1998; Horne, 1969). The model was applied to the template described above (Fig. 1) which was discretized by a mesh of quadrilateral finite elements.

At the upper boundary, representing the sediment-water interface, hydraulic head is specified to be equal to the boundary elevation, temperature is 10 °C, and salinity is set at 3.57 wt%. The side boundaries are impermeable to fluid, heat, and solute mass transport. The lower boundary can be considered a contact with deep crustal crystalline rocks with extremely low in situ permeability (Morrow and Lockner, 1997) and is considered to be impermeable to fluid and solute fluxes. Assuming a geothermal gradient of 25 °C/km, this boundary is maintained at a temperature of 377.5 °C and a linear initial temperature distribution was set based on this value. Fluid pressure was assigned to be hydrostatic (considering a lithostatic initial condition below the level of the Roan evaporites does not significantly modify model outcomes). To simulate generation of hypersaline brine by dissolution of halite, we follow Sarkar et al. (1995) in assuming that interstitial fluid with an initial seawater salinity (3.57 wt%) becomes saturated (30 wt%) when it comes into contact with the halite.

RESULTS

A series of numerical experiments were run for a simulated period of 2.5 m.y. to test various geological scenarios. The initial simulation was designed to test flow patterns following a period of synsedimentary tectonism. Fault segments <12 km from the top of the section were modeled with 3 times higher permeability relative to wall rocks. Where fault segments offset the Upper Roan halite a low-permeability equivalent to that of halite was maintained to simulate the annealing affects of salt migration into fault zones (Mikkelsen and Floodpage, 1997). Fluid flow was strongly influenced by the Upper Roan halite, which acts as an extensive barrier to fluid flow, separating the model into two isolated hydrological compartments. The sub-halite compartment shows vigorous hydrodynamics, with moderate to high fluid velocities along fault arrays, and stratabound flow in the Mindola Clastics (Fig. 2A). The overall circulation pattern is fundamentally controlled by the descent of brine plumes that, as described by Sarkar et al. (1995), initially nucleate at

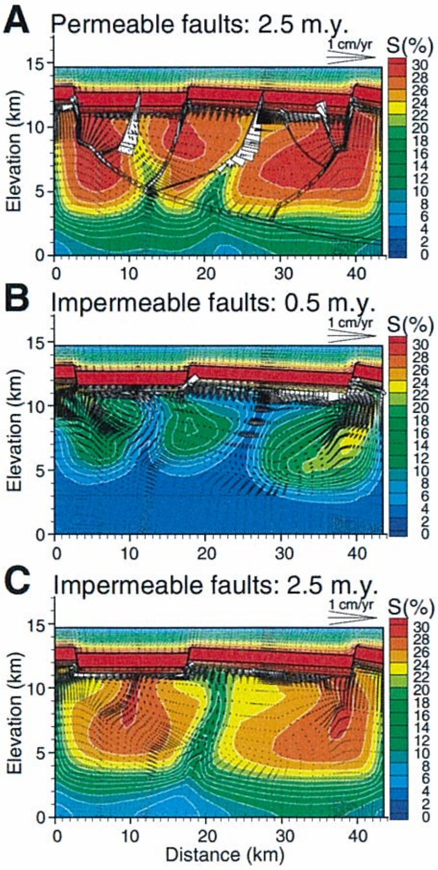

Figure 2. Simulated salinity (S) distribution and specific discharge vectors. A: Permeable fault network scenario, end of the simulation, 2.5 m.y. B: Impermeable fault network scenario at 0.5 m.y. C: Impermeable fault network scenario, end of the simulation, 2.5 m.y.

[1]GSA Data Repository item 2009274, Table DR1 (properties of stratigraphic components), Figure DR1 (supplementary model—effect of the salt layer thickness), Video DR1 (permeable fault network scenario), and Video DR2 (impermeable fault network scenario), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

structural perturbations in the halite layer. In our model, the largest brine plume developed adjacent to the right-hand master fault as a result of dense brines moving downdip beneath the tilted halite sheet (Video DR1 in the Data Repository). This pattern is enhanced to a lesser extent by a thicker portion of the Mindola Clastics adjacent to this fault that facilitates brine descent.

The connectivity of permeable faults and Mindola Clastics horizons provides the template for large convective cells driven by effects of both salinity and temperature (i.e., buoyancy). Descending brine plumes follow the traces of master faults, while heated, less saline fluid ascends along second-order faults, and is then redirected horizontally through the Mindola Clastics aquifer (Fig. 2A). Calculated time-integrated fluid fluxes, proxies for water-rock interaction (Fig. 3A), indicate that the Ore Shale forms a second-order stratal aquiclude, concentrating fluid flow along its basal interface with the Mindola Clastics. The same figure also

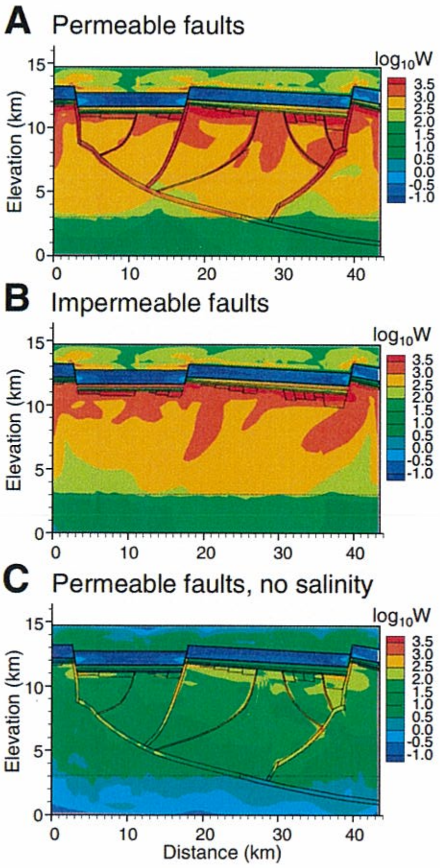

Figure 3. Maps of time-integrated fluid flux divided by volume of solid matrix (water/rock ratio), W, calculated for 1 m³ of rock matrix within finite element. Results are plotted on logarithmic scale for 2.5 m.y. A: Permeable fault network scenario. B: Impermeable fault network scenario. C: Pure water scenario with permeable faults and no salinity.

indicates extensive infiltration of basinal brine beyond the fault network into the low-permeability basement. In the hydrological compartment above the halite unit, dissolved salt rapidly diffuses upward for the initial 740 k.y., after which salinity remains stably stratified (Fig. 2A). Due to the uncertainties pertaining to the original thickness of halite in the Zambian Copperbelt, we have examined the effects of reducing it to ~100 m, but the fundamental fluid flow patterns remain the same (Fig. DR1).

Removing the Fault Network

This scenario was run to test whether buoyancy forces would be sufficient to establish basement-involved fluid-migration cells in the absence of the fault network. In evolving rift systems, this would be the likely situation during periods of tectonic quiescence, when the fault core and surrounding damage zone were occluded by mineral precipitates (Caine et al., 1996). To simulate this situation, the permeability of the faults was assigned the same value as that of the wall rock.

The results clearly show that even where the fault network is sealed, dense brine plumes can still cross the interface between the basinal succession and the low-permeability basement. For the initial 1 m.y. (Fig. 2B), the salinity field retains essentially the same pattern as the permeable fault network scenario, with brine plumes nucleated on perturbations in the halite horizon. However, with no permeable pathways present to channel the descending brines, convection patterns subsequently become disorganized, with highest fluid velocities partitioned into sub-halite stratal aquifers. By the end of the simulation at 2.5 m.y. (Fig. 2C), only the right-hand plume, which is fed by brine moving laterally below the tilted salt sheet, remains deeply penetrative (Video DR2). However, once again, the calculated time-integrated fluid flux (Fig. 3B) shows there has been extensive interaction between the basinal brines and the basement.

Salt as a Driver

The outcomes of the first two models show that dense brines generated in the basin succession will descend into less permeable basement regardless of the state of the cross-stratal fault zones. Outside of the fault network, the calculated flow rates are of the same order of magnitude, and a pronounced footprint of fluid interaction with the low-permeability basement is developed (Figs. 3A, 3B). The obvious question is, what would occur if the pore fluids did not acquire high salinities? To address this, the initial permeable fault model was re-run with a pure water pore fluid composition. The porosity and permeability characteristics of the halite horizon were maintained, but the "salinity" effect was removed. The results show an order of magnitude decrease in flow rates throughout the section relative to the saline pore fluid scenario. In addition, despite the presence of cross-cutting permeable fault zones, the calculated time-integrated fluid flux (Fig. 3C) shows a one to two orders of magnitude decrease in water-rock interaction in the basement succession.

SUMMARY AND CONCLUSIONS

Our numerical experiments effectively simulate the focusing of saline fluids along redbed aquifers below a relatively impermeable stratal aquiclude. If this hydrologic boundary also corresponds with a redox boundary, in this case the interface between the Mindola Clastics and the reduced Ore Shale, extensive stratabound sulfide mineralization could be expected. The models differ from others developed for other SSC districts that incorporate convective flow, in that buoyancy-driven cells extend from the redbed succession across the basin-basement interface. The incorporation of igneous basement rocks into the fluid pathways accords with Blundell et al. (2003), and in the case of the Zambian Copperbelt may explain the copper source problem identified by Hitzman (2000). In our model, the cross-sectional area of the basement where the water/rock ratio is <100 (i.e., the time-integrated fluid flux exceeds the volume of rock by two orders of magnitude; Fig. 3A) is 26.7 times the area of the Mindola Clastics. Assuming that the basement consists of 20% mafics and 80% felsics that have Cu values of 90 and 12 ppm, respectively (Reimann and De Caritat, 1998), it would average 27.6 ppm. As a result, less than half of the available Cu (11 ppm) needs to be leached to account for the Zambian Copperbelt ores.

The results of our modeling also have implications for other SSC districts. The ubiquitous association with evaporitic strata has previously been considered important in ore genesis, because salinity facilitates transport of copper in solution via chloride complexing (Hitzman et al., 2005), and the evaporitic strata act as a top seal to the hydrological system (Jowett, 1986). Our study reveals that evaporites may also be important because of their influence on the density of pore fluids and implied buoyancy effects. Although it deals only with a mechanism of increasing salinity through halite dissolution, it is probable that generation of dense residual brine formed during evaporite deposition would have a similar influence. In our model scenarios the generation of saline pore fluids has the effect of increasing fluid velocities by an order of magnitude relative to pure water. Our model scenarios also indicate that, regardless of metal source issues, the negative buoyancy imparted by the salinity of the fluids will result in basement involvement in fluid circulation being the rule rather than the exception.

In terms of crustal-scale fluid flow, Ingebritsen and Manning (1999) proposed that in the absence of a permeability discontinuity between brittle upper and lower ductile crust, deep metamorphic fluids can be transmitted to the upper crust and mix with meteoric fluids, which are common above 10–15 km. Our numerical models support this contention, and suggest that connate basinal brines are even more likely to penetrate to mid-crustal levels. This has profound implications for many ore deposit genetic models, which are based, at least in part, on the level of the crust at which particular deposit types are thought to have formed; this in turn has implication for the type and the temperature of the ore fluid. Our work, in combination with that of Ingebritsen and Manning (1999), raises the possibility that ore deposit types currently considered unrelated (e.g., porphyry copper, iron oxide copper gold, and SSC deposits) could be genetically linked by sharing elements of the same fluids that have migrated to different crustal levels.

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