Forum

Is the Mount Isa copper deposit the product of forced brine convection in the footwall of a major reverse fault?

COMMENT

A.R. Wilde
School of Geosciences, Monash University, Clayton, Victoria 3800, Australia
K. Gessner
Commonwealth Scientific and Industrial Research Organisation, Exploration & Mining, Perth, Western Australia 6102, Australia

We welcome the contribution of Matthäi et al. (2004), which emphasizes fluid convection as an important process for heat and mass transport in hydrothermal ore deposition and demonstrates the capacity of numerical modeling as a tool for understanding geological processes. Matthäi et al. (2004) investigate whether advection of hot material in the hanging wall of the steeply dipping Mount Isa fault drove hydrothermal convection to create the giant copper deposits. While we agree that hydrothermal convection may be a key process in the formation of the Mount Isa copper deposits, we find it difficult to accept the conclusion of Matthäi et al. (2004) that uplift is the driving mechanism. This is because significant components of the model are at odds with the current understanding of Mount Isa geology, particularly the architecture represented in the model, the magnitude and distribution of permeability, and the interaction of heat transport mechanisms.

There is ample evidence in the Mount Isa area for substantial fluid flow along faults, in particular along the Mount Isa and Paroo faults, which dilated in several tectonic events. While Matthäi et al. (2004) consider the permeability change due to deformation within the wall rock and the mineralized breccia, the faults are not considered as potential pathways. Ignoring faults as fluid pathways is problematic, particularly in view of evidence for large-scale free convection in faults (e.g., Bächler et al., 2003).

There are other aspects of the published cross section that differ from the actual geology. The Lena quartzite is a stratigraphic unit in the middle of the Eastern Creek Volcanics, not, as shown by Matthäi et al. (2004), a separate unit on top of it. Matthäi et al. (2004) have included a hitherto unknown stratigraphic unit, the "Ridewick" on top of the Lena quartzite and beneath the Myally Group. The depiction of a block of "uplifted metasedimentary rocks" west of the fault ignores the presence of metabasalt equivalent to the Eastern Creek Volcanics. Furthermore, it is unclear why the same stratigraphic unit on one side of the fault would be three orders of magnitude more permeable than on the other side, especially since these domains would have had identical metamorphic grade at the onset of faulting.

The hydraulic architecture of the Matthäi et al. (2004) model is characterized by an enormous range of permeability values for which no constraints are given. According to calculations in Turcotte and Schubert (2002, p. 395) the thick breccia zone (copper orebodies) with a permeability of 10^{-12} m^2 should allow free convection at the inferred geotherm of 40 ºC/km regardless of whether heat is advected due to movement on nearby faults or not. In this context it is not clear on what grounds a distinction is made between "self-organization of flow" and "forced convection" (Matthäi et al., 2004; their Fig. 2). The term "forced convection" is commonly used to describe pressure-driven, or pressure-head constrained hydraulic systems. No reference to this is given, leaving the impression that the process modeled by Matthäi et al. (2004) is temperature controlled and should correctly be referred to as "free convection."

The modeling presented by Matthäi et al. (2004) is based on the assumption that 8 km of vertical movement on the Mount Isa fault occurred contemporaneously with copper ore formation. A widely accepted view however, is that copper formed after the main, peak-metamorphic E-W contraction during a minor NE-SW shortening event (e.g., Swager, 1985). In any case, a slip rate of 1 cm/yr (the only case for which flow patterns and temperatures are shown) is very high for a steeply dipping reverse fault like the Mount Isa fault and needs to be justified in terms of the geological record. The model also does not take into account any topography generated by such a rapidly slipping fault and its potential as a driving force for fluid flow.

Fault slip velocities can impact heat transport mechanisms, and Matthäi et al. (2004) claim that the uplift of the hanging wall of the Mount Isa fault, with rates between 1 cm/yr and 1 mm/yr (resulting in a 1.15 cm/yr and 1.15 mm/yr fault slip rate at 60º fault dip), drives the convection responsible for the Mount Isa copper deposit. The difference of one order of magnitude between slip rates can make the difference between a conduction-dominated versus an advection-dominated temperature structure, and therefore will also have significance as to whether a wave-like advective heat anomaly develops across the fault or not. Thermal transport across a moving fault is an "advection vs. diffusion problem" (e.g., McKenzie and Bickle, 1990), and can therefore be expressed by the dimensionless Peclet number:

$$Pe = \frac{lv}{\kappa},$$

where l is the diffusion length of the system (in this case the height of the section affected by faulting), v is the velocity (here the fault slip velocity), and κ is the thermal diffusivity. This means that advection will only govern the thermal structure for $Pe \geq 1$. Assuming a thermal diffusivity of 10^{-6} m^{2}s^{-1}, and taking the length of the system as 16 km (the vertical extent of the Matthäi et al. model), Pe has a value of ~5.8 for a fault slip velocity of 1.15 cm/yr, but only 0.58 for a velocity of 1.15 mm/yr. A velocity of ~1.7 mm/yr would therefore represent a threshold value ($Pe = 1$) for which both heat transport processes would be equally effective. It is therefore difficult to understand how these different velocities can produce a qualitatively similar pattern, as claimed by Matthäi et al. (2004).

Thermally driven flow patterns in hydrothermal systems are highly sensitive to the complex hydraulic architecture of the system, which requires that the architecture used in numerical simulations needs to be as accurate as possible with regard to the observed geology. The conclusions presented by Matthäi et al. (2004) must therefore be regarded as questionable, since the geological-hydraulic architecture of their model is not very well constrained, and the simulation of heat transport appears to be at odds with analytical heat transport calculations.

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REPLY

Stephan Matthäi

Department of Earth Sciences & Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

C.A. Heinrich

T. Driesner

Department of Earth Sciences, Eidgenössische Technische Hochschule (ETH) Zentrum, Sonneggstrasse 5, Zürich CH-8092, Switzerland

We welcome that Wilde and Gessner's comment gives us the opportunity to elaborate further on several aspects of our simulation study (Matthäi et al., 2004). However, we object to all but one of their criticisms.

We accept their point about the stratigraphy in our Figure 1 and apologize to the *Geology* readers for our mislabeling: "Ridewick" should be the Pickwick Formation, which is the upper part of the Eastern Creek Volcanics above the Lena quartzite. It should have been shaded with the corresponding darker gray.

Wilde and Gessner state that flow patterns are sensitive to the "hydraulic architecture"of a system, a statement, which in this general form is correct but trivial. Our choice of stratigraphically controlled permeability variation is not arbitrary but based on actual field observations. This variation has a stronger influence on the flow patterns than the assignment of absolute values to individual beds. Regarding the permeability of the main fault and the western block, Wilde and Gessner should note that the core of transcrustal faults in a compressive setting is often the least permeable (Evans et al., 1997). Therefore, the results by Bächler et al. (2003) on a highly permeable fault in an extensional setting do not pertain to the Mount Isa reverse fault.

Nevertheless, if the western block is kept "impermeable" and the fault permeability is set "high," there is no major change in the flow pattern. Simulations not reported in our paper show a moderate distortion of the westernmost upflow zone toward the fault zone. We did not carry out simulations with a permeable western block for lack of information about its upper part, which is now eroded. Rather than exploring all alternatives for which there is no geological evidence, our model is constructed on the basis of specific field observations indicating a high fracture permeability throughout the eastern low-grade-metamorphic block, including the mine area. Thus, we arrived at a specific model that is consistent with structural evidence and successfully explains all of the stringent mass-balance and isotopic evidence available on the regional and mine scale.

Wilde and Gessner also state that our model is based on an incorrect relative timing of fault movement relative to late-metamorphic ore formation. We used the observation that peak-metamorphic D2 folding predated the later fracture-accommodated D3 folding at mine (Swager et al., 1985) as well as district scale (Bain et al., 1992). D3 folding is contemporaneous with or possibly followed by copper mineralization and regional-scale iron-oxide carbonate alteration attending brine infiltration. A more recent attempt at absolute Ar-Ar dating (Perkins et al. 1999) yielded results that are consistent with this structural timing interpretation. One sample from the Mount Isa fault zone may indicate that part of the differential uplift postdated (but not predated, as Wilde and Gessner purport as a "widely accepted view") the copper-mobilizing hydrothermal event.

With respect to the usage of "free convection" versus "forced convection," Wilde and Gessner's objection actually serves to highlight why uplift of the western block is so important for copper ore genesis. Wilde and Gessner correctly identify that throughout our simulations convection occurs in the breccia body. It can be termed "free" because fluid cannot enter or leave this high permeability system (Freeze and Cherry, 1979, p. 508). Under "forced convection" fluid inflows and outflows are present and fluid motion in the flow volume is due to hydraulic forces acting on its boundaries (Freeze and Cherry, 1979). This is the flow regime in the breccia body that is conducive to the formation of copper ore. It only develops when there is uplift of the western block.

Wilde and Gessner's statement that "the simulation of heat transport appears to be at odds with analytical heat transport calculations" is a particularly serious critique and requires explicit rejection. Contrary to their claim, they provide no analytical calculations of heat transport at all and their simplistic analysis does not pertain to fluid circulation in the eastern block. Wilde and Gessner merely evaluate the dimensionless Peclet number, Pe, an estimator for the relative proportions of advective versus diffusive heat transport. To put the level of critique into perspective, we would first like to clarify a few misunderstandings about Pe in Wilde and Gessner's comment. Of the many equivalent definitions of Pe, Wilde and Gessner chose $Pe = lv/\kappa$, correctly assigning v to advection velocity and κ to thermal diffusivity. However, they incorrectly call l "the diffusion length of the system," when l is in fact the opposite, an advection length given by $l = vt$ (t denoting time). Using the correct definition for the characteristic diffusion length $L_\kappa = \sqrt{4\kappa t}$ instead, another well-known formulation can be derived, i.e., $Pe = 4l^2/L_\kappa^2$. Diffusion length now explicitly appears in the formula, but in the denominator rather than the numerator as stated by Wilde and Gessner. For Pe varying by a factor of 10, the ratio of these lengths will vary by a factor of $\sqrt{10} \approx 3.16$, i.e., the effect on heat transport is far less drastic than implied by Wilde and Gessner.

In an attempt to substantiate their argument, Wilde and Gessner refer to a paper by McKenzie and Bickle (1990). However, that paper discusses neither Pe nor advective versus diffusive transport, but rather deals with a mathematical formulation of eutectic mantle melting. We could not decipher what Wilde and Gessner wanted to imply with this and can therefore only very generally reply to what we think that Wilde and Gessner meant to say.

The only sensible explanation is that they used Pe for a rough estimate of heat diffusion across the fault as a function of fault slip velocity. This alone, however, is insufficient for the eastern block *after* the onset of fluid convection. It is the very nature of this problem that precludes the meaningful use of any standard analytical heat transport solutions and requires numerical simulations instead. Therefore, these cannot be considered "at odds" with each other, as implied by Wilde and Gessner.

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