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Significance of strain localization and fracturing in relation to hydrothermal mineralization at Mount Isa, Australia

Klaus Gessner [a,b,*], Peter A. Jones [c], Andy R. Wilde [d], Michael Kühn [a,1]

[a] *Earth Systems Modelling Group, School of Earth and Geographical Sciences, The University of Western Australia, Crawley WA 6009, Australia*
[b] *Computational Geoscience, CSIRO Exploration and Mining, PO Box 1120, Bentley WA 6102, Australia*
[c] *School of Earth Sciences, James Cook University, Townsville, QLD 4811, Australia*
[d] *School of Earth Sciences, Monash University, Clayton, VIC 3400, Australia*

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Abstract

The rheology of layered meta-sedimentary rocks, and their orientation and position relative to major fault systems were the key controls on Proterozoic hydrothermal copper mineralization at Mount Isa, Australia. Compositional layering in the host rock partitioned mechanical behavior and strain, leading to selective permeability generation and the focusing of fluid flow. Shale layers preferentially failed by plastic shearing, whereas meta-siltstones remained elastic or failed in tension depending on magnitude of deformation and fluid pressure. Numerical simulations support the hypothesis that the orientation of layering and the proximity to major fault systems controlled fracturing and permeability increase in the Urquhart shale. The dilating shale provided a pathway for an upward-flowing, reduced basement fluid, from which quartz was precipitated during cooling. During a later event, the reactivation of steep structures provided access to surface derived oxidized metal-bearing brine, causing the precipitation of dolomite followed by chalcopyrite ore in the brecciated silicified shale.

Keywords: Numerical models; Layered materials; Strain; Mount Isa; Hydrothermal systems; Copper deposits; Lead–zinc deposits

1. Introduction

Rock deformation is a crucial requirement for creating fluid pathways and precipitation sites in post-metamorphic hydrothermal ore systems, since metamorphism creates a low permeability wall rock. For structurally controlled hydrothermal deposits a number of studies have successfully used numerical models based on a continuous Darcy-flow approximation rock to simulate dilation in complex multi-material geometries during transient flow periods (e.g. Ord et al., 2002; Sorjonen-Ward et al., 2002). In this paper we will use this technique to investigate how deformation-related permeability changes on the meter- to kilometer-scale could affect hydrothermal mineralization at Mount Isa. It will be shown that the rheology of the host rock and the position and orientation of pre-existing faults controlled the location of the Mount Isa copper deposit.

* Corresponding author. Now at: Earth Systems Modelling, Centre for Exploration Targeting, School of Earth and Geographical Sciences, The University of Western Australia, Crawley WA 6009, Australia.
E-mail address: Klaus.Gessner@uwa.edu.au (K. Gessner).
[1] Now at: Angewandte Geophysik, RWTH Aachen, Lochnerstr. 4-20, D-52056 Aachen, Germany.

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2. Stratigraphy and tectonic framework

The Mount Isa copper deposit is located in the Mount Isa Inlier, an inverted and metamorphosed Proterozoic intra-continental rift zone in North-West Queensland, Australia. At the Mount Isa mine, copper was precipitated as chalcopyrite in a hydrothermal breccia located in a silicified portion of the metasedimentary Urquhart shale. The Urquhart shale differs from other members of the Middle Proterozoic Mount Isa Group by its characteristic layering of carbonaceous shales and dolomitic siltstones. This layering occurs at the 10 cm to meter scale, and dips steeply (~65°) to the West at the mine site. A number of detailed studies (Perkins, 1984; Swager, 1985; Bell et al., 1988) concluded that copper ore was deposited after the main tectono-metamorphic events of the Isan Orogeny, and postdates a large zone of lead–zinc–silver mineralization at the same location. Structural work in the mine and its vicinity outlined three major deformation events during the Isan orogeny: D_2 E–W shortening, D_3 top-to-E simple-shear, and D_4 dextral oblique slip. The basal part of the Urquhart shale, located immediately above a faulted contact with metamorphosed basalts and sediments of the Eastern Creek Volcanics, displays the most intense fracturing and the highest ore grade of up to 25% Cu. A salient feature of the copper ore bodies is that brecciation and chalcopyrite mineralization are spatially related to silicification, which affected large portions of the Urquhart shale above its footwall contact to the meta-volcanic basement. The highest ore grades occur predominantly in the siltstone layers of the Urquhart shale. Finer-grained beds in this proximal zone are altered to graphitic shale, which is rarely fractured but shows evidence for layer-parallel shear. Geochemical studies (Wilde et al., 2005) suggest that the chemical composition of the Urquhart shale does not vary significantly from other Mount Isa Group members. Hence the question is, if and how the layering of the Urquhart shale relates to the creation of deformation-related permeability during multiple hydrothermal fluid flow events.

3. Deformation-related permeability changes

Deformation-related permeability changes occur as a response of sediments and rocks to mechanical loading, which can lead to either the creation or the destruction of pore space. Destruction of pore space and, by inference permeability, is common in under-consolidated sediments affected by mechanical compaction or tectonic stresses. In an elastic-plastic Mohr–Coulomb constitutive model, the two end-member modes of mechanical failure are failure in tension and failure in shear (Jaeger and Cook, 1979). Each of these modes has a significant impact on the creation of volume and permeability, through either plastic dilation (Vermeer and de Borst, 1992) in the case of shearing, or through the opening of fractures (Zhang et al., 1994). While plastic shearing probably leads to an increase of one or two orders of magnitude in permeability, fracturing is expected to have a much more drastic effect, and increases permeability by at least three or four orders of magnitude (Oliver, 2001). In the Mohr–Coulomb constitutive model cohesion, tension limit, and friction angle determine if and how a rock fails under given stress and fluid pressure conditions. An increase in pore pressure because it lowers effective stresses, and can promote tensional failure even in regional compression (e.g. Cox et al., 2001).

4. Strain partitioning in the urquhart shale

Strain partitioning controlled by lithologic layering can be observed at many locations in the Mount Isa mine and in surface outcrops. Layer-parallel shearing in shales and selective fracturing of meta-siltstone layers point to differences in mechanical failure behavior due to variations of physical properties. Differences in physical property values between shale and siltstone can lead to a significant variation in deformation behavior and changes in deformation-related permeability. Dipping layers respond much better to contraction and extension than horizontal or vertical layers, since this orientation has the least mismatch to predicted angles of fault planes in homogeneous rocks. Also, a much larger volume of rock appears to be affected when strain or mechanical behavior is partitioned according to layering, whereas in the other cases strain is limited to small areas of localized shear zones that crosscut the layering. This difference could be critical for the permeability structure of a hydrothermal plumbing system, such that layering potentially allows much larger volumes of a stratigraphic unit to dilate.

5. 3D mine scale model

To investigate whether the anisotropic rheology of the Urquhart shale or its position within the geological architecture at the mine were the critical factors for providing strain localization and increased permeability, a number of numerical simulations of deformation and fluid flow have been carried out, using the finite difference code FLAC^{3D} (ITASCA, 1997–2003). Thermal transport and reactive transport mechanisms are not