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Active fault and shear processes and their implications for mineral deposit formation and discovery

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ABSTRACT

Mineralisation associated with fault, vein and shear zone systems can be related to processes that operated when those systems were active. Despite the complexity of processes that operate in faults, veins and shear zones, there are typically systematic patterns in geometry (e.g. segmentation and step-overs) and scaling, which are the cumulative result of multiple slip events. In turn, there are systematic patterns in individual slip events (e.g. earthquake-aftershock sequences, shear zone creep transients, earthquake swarms) with implications for permeability enhancement and mineral deposit formation. This review identifies three avenues for future research: (1) a need to improve constraints on the scaling characteristics of faults, shear zones and veins specifically related to mineralisation. (2) The integration of stress change and damage concepts with 3-D lithological observations and reactive transport modelling. (3) Understanding the impact of multiphase fluids (e.g. H_2O–CO_2–NaCl fluids) on fault mechanics and permeability. Static stress change modelling, damage mechanics modelling and fault/vein scaling concepts have promising predictive capabilities for the future discovery of mineral deposits. The review mostly refers to epithermal, mesothermal, and carlin-type gold deposits, but the principles could extend to any hydrothermal mineral deposit formed during faulting, fracturing and shearing.

1. Introduction

A fundamental aim of structural analysis applied to mineralisation is to identify how deformation influenced the enhancement or decrease of permeability in rocks, both spatially and over time. During the last 20 years, structural investigations have recognized the important role of transient, repeated, earthquake-related processes, in enhancing permeability and forming mineral deposits (e.g. Sibson, 1987; Sibson et al., 1988; Robert et al., 1995; Wilkinson and Johnston, 1996; Berger and Drew, 2003; Blundell et al., 2003; Muchez et al., 2005; Micklethwaite and Cox, 2004). In the same period of time, advances in seismology and geodesy, have helped identify a rich diversity of processes that operate in faults and shear zones, which result in both seismic and aseismic behaviour (e.g. Scholz, 2002; Freed, 2005; Schwarz and Rokosky, 2007). Understanding this variety of behaviour can help us constrain where and how permeability was generated around fault or shear zone systems that are no longer active. Similarly, numerical models initially developed to understand active fault behaviour have the potential to be applied to mineral exploration (Micklethwaite, 2007; Sheldon and Micklethwaite, 2007).

Before this review proceeds it is necessary to define a few terms. Mineralisation is a broad term, referring to naturally occurring processes that concentrate inorganic substances, especially metal ores. Strictly, 'mineral deposit' or its synonym 'ore deposit' are economic terms, because they describe ores that are so concentrated that the economics of extraction are feasible. Structural geology does not aim to predict the concentration of ores and therefore cannot predict the location of mineral deposits. Nonetheless, by understanding the spacing, geometry, development and mechanics of potentially mineralised structures, structural geology is an invaluable tool to mineral exploration.

The first part of this paper briefly discusses the temporal variability of permeability and the relationship between permeability, faulting and shearing. The second part outlines the geometries and scaling properties of well-constrained fault, vein and shear zone systems, in the context of observations from ore deposits. These properties are the cumulative result of multiple slip and fracture events (such as earthquakes) and in turn geometric features (such as step-overs) control the distribution of slip events. The third part of the paper discusses aspects of active fault and shear zone behaviour that relate to mineralisation. The fourth part of the paper

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covers recent modelling approaches advancing our understanding of active faulting, and fluid flow, which are also directly applicable as mineral exploration tools. This final section considers the relationship between CO_2 and seismicity, and the influence of CO_2-bearing aqueous fluids on the mechanics of faulting during mineralisation.

Closely related reviews include the relationship between earthquake processes and structural geology (Sibson, 1989, 2001), and the driving forces for fluid flow and permeability enhancement during ore deposit formation at depth in the crust (Cox, 2005). Oliver (2001) discusses the migration of metamorphic fluids and formation of ore deposits in and around faults or shear zones, and Blundell (2002) examines the geodynamic context of ore deposits and how earthquake processes contribute to deposit formation.

2. Deformation, permeability and mineralisation in the crust

Geological structure has a first-order spatial relationship with hydrothermal ore deposits. Examples include greenstone-hosted lode gold deposits, which typically form at mid-crustal depths (Fig. 1), within damage zone faults and veins, adjacent to regional-scale master faults or shear zones (Eisenlohr et al., 1989; Cox et al., 1995; Robert et al., 2005; Micklethwaite and Cox, 2006). Similarly, Carlin-type gold deposits are spatially associated with large normal fault systems (Cline et al., 2005) within the top 2 km of the crust (Fig. 1). Many types of epithermal gold deposit (Hedenquist and Lowenstern, 1994) are hosted within vein or dilatant fault networks (Simmons et al., 2005; Micklethwaite, 2009) at depths of less than 1 km.

A one-to-one correlation between structure and hydrothermal ore deposits is understandable when the metal budgets of deep hydrothermal solutions are examined, such as those from the geothermal environments of the Taupo Volcanic Zone, New Zealand (Simmons and Brown, 2007). The flux of gold and silver in solution (80–163 and 6800–13,850 kg Ag/yr) could easily account for the formation of the worlds largest hydrothermal ore deposits in a short time period of ~50,000 years. However, no deposits have been discovered in the Taupo Volcanic Zone, leading Simmons and Brown (2007) to conclude the most important processes for deposit formation are focussed fluid flow and efficient metal precipitation. Focussed fluid flow in particular is dependent on changes in permeability in and around structures, over time.

2.1. Permeability

Permeability is a measure of the ease with which fluid migrates through porous rock (Domenico and Schwarz, 1998). Permeability is not a material property but a parameter, dependent on hydraulic gradient and the physical or chemical controls affecting the porosity (Cox, 2005). In and around fault and shear systems, permeability is typically time-dependent, due to competition between various chemical and physical processes, as illustrated in Fig. 2.

Three important conclusions emerge from studies of fault, vein and shear zone related permeability. (1) Deformation can enhance permeability by many orders of magnitude. (2) Permeability can rapidly decrease post-slip or fracture. (3) Small components of structural networks in the brittle upper crust have elevated values of permeability, which persist over extended periods of time. Generally though, the formation of fault-related hydrothermal mineral deposits requires active deformation in order to sustain elevated values of permeability and enable focussed fluid flow. Evidence for these conclusions, permeability magnitudes and rates of decrease are outlined below.

2.2. Permeability and rates of variation

Permeability within fault zones potentially varies over ten orders of magnitude, from bulk rock values of $\sim 10^{-20}$ to $>10^{-16}$ m^2 (Manning and Ingebritsen, 1999; Townend and Zoback, 2000), up to co-seismic and postseismic values estimated at 10^{-13} to 10^{-11} m^2 (Koerner et al., 2004; Miller et al., 2004).

Rates of permeability reduction in fault gouges have been quantified by hydrothermal deformation experiments (e.g. Tenthorey et al., 2003; Tenthorey and Fitz Gerald, 2006; Giger et al., 2007; Kay et al., 2006), generally at high temperatures or specific fluid compositions, in order to enhance kinetics. The studies of Tenthorey and Fitz Gerald (2006), and Kay et al. (2006) are noteworthy because they involved reasonable crustal temperatures of 200–600 and 120 °C, respectively. Permeability decreases due to redistribution of material

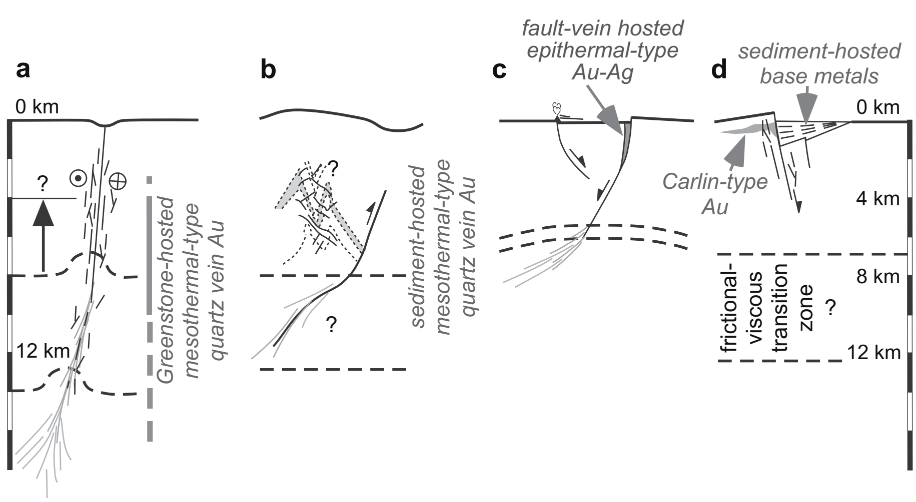

Fig. 1. Schematic diagram illustrating the approximate depths and structural environments interpreted for a small selection of different deposit types. (a) Mesothermal lode gold mineralisation associated with regional-scale strike-slip shear zones (e.g. Robert et al., 2005). (b) Mesothermal lode gold mineralisation hosted in veins within folded turbiditic sediments, associated with steep reverse dip faulting. (c) Fault or vein-hosted epithermal gold mineralisation. (d) Carlin-type gold mineralisation typically associated with large-scale normal dip-slip faults, close to the surface (Cline et al., 2005). Regional-scale structures in mesothermal environments are typically phyllosilicate-rich. Phyllosilicate-bearing fault rocks and/or slightly elevated geothermal gradients and could lead to shallow depths for the frictional–viscous transition zone, of ~5 km (Imber et al., 2001).