How should we model syntectonic hydrothermal fluid flow – some theoretical and empirical constraints

J Ridley

GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia, (email: jridley@laurel.ocs.mq.edu.au, phone: +61 2 9850 8371, fax: +61 2 9850 6904)

Abstract

Modelling of fluid pathways and flow histories in a complex segment of the Earth's crust is unlikely to be deterministic in an exploration prediction sense. We should limit effort to broad brush modelling, generalities or sub-problems. For the deeper crust, we need to consider distributions of fluid sources and sinks. Short time spans inferred for flow in lode-gold deposits suggests that rock strain can be neglected in simulations of flow for these deposits. Stress mapping with explicit modelling of all dilatant processes is proposed as an approach worth pursuing.

Issues

Full simulation of fluid flow in a segment of tectonically active crust would be a valuable exploration tool. A physically realistic simulation would incorporate parameters of the fluids – sources and sinks of both fluids and solutes – parameters and functions of the rocks – rock types, their structural history, rheological behaviour of each unit, permeability, – and, parameters of the imposed tectonic regime – temperature, stress fields, topography. Many of the relevant constitutive relations of rocks are imperfectly known. Many of the parameters are interrelated, in cases with strong non-linearity. For a complexly constructed and deformed segment of the Earth's crust, our information on conditions and geometry will always be imperfect, fluid flow is unlikely to be deterministic and, in particular, the robustness of a model will be difficult to guarantee or assess. Useful models are likely to be those which consider either generalities of flow, for instance through consideration of subsets of parameters, or broad brush regional patterns. I consider here three lines of theoretical and empirical constraint on fluid flow patterns that serve as guides to modelling.

Fluid pressure regimes

A number of lines of evidence, from metamorphism and from direct observations in sedimentary basins, show that tectonically active crust is typically hydrologically layered, with an upper layer at near hydrostatically pressured pore waters, a transitional zone and a lower layer with near lithostatically pressured fluids. Connolly and Podladchikov (2000) show that hydrological layering is essentially inevitable in compacting crust, hence in any crust with trapped fluids or in which fluids are being released in mineral reactions, and that layered fluid pressure regimes can be quasi steady state. This work reinforces earlier conclusions on fluid flow in the deeper crust during tectonism: that there is an overriding upward flux, that large scale lateral migration of fluids at these levels only occurs under specific circumstances, that topography has at most a second order influence, and that convection cells directly connected with near surface flow patterns are not expected. Densification and feedback between fluid pressure and permeability are critical processes to incorporate into models for the deeper crust. Feedback between densification, pore-fluid pressure and permeability mean that fluid pressure at depth is not a fully independent variable, but is strongly buffered by rock pressure. The overriding upward vector of flow means that the distribution of fluid sources and sinks is a critical control on the distribution of flow.

Time spans of hydrothermal fluid flow

Estimation of time spans of hydrothermal activity at an ore deposit have proven elusive. Although some works have shown evidence for fluid flow along a structure at different stages in its deformation history (e.g. McCaig et al., 2000), for many mesothermal gold deposits, the ore-forming hydrothermal event was restricted to a fraction of last phases of movement along the host shear zone or fault (e.g. Robert and Brown, 1986). Temperature fields potentially allow quantification of time span of hydrothermal activity where they reflect flux of upward migrating fluids. Lateral zonation of alteration and ore mineral assemblages across some larger mesothermal gold deposits are consistent with small but detectable temperature differences at the time of mineralisation. For the Mount Charlotte deposit, time spans of between 100 and 10000 years are estimated. Fluid flow was thus short lived compared to episodes of crustal deformation. For these deposits, it is suggested that models of transient fluid flow from specific sources in a quasi static rock volume are more applicable than those of time integrated crustal scale fluid flow throughout a deformation event.

Stress mapping: Which pararmeter is the best proxy for fluid flow?

Stress mapping simulates rock stress during loading of a rock volume under applied stress, and although is very simplistic modelling of crustal fluid flow, has had success as an exploration tool, and may be a useful basis for more thorough models. Proxies for the distribution of fluid flow across two dimensional stress models are the minimum principal stress (Holyland and Ojala, 1997), the mean stress (Ridley, 1993) and fracture aperture (Sanderson and Zhang, 1999). Inherent in the use of minimum stress and fracture aperture as proxies is the premise that fluid flow takes place when progressive change in a parameter causes a critical condition of permeability to be reached. Minimum stress is essentially a measure of the chances of dilation. Modelling of fracture dilation by itself has the disadvantages that fracture distribution and geometry is required to be known, and also that pervasive dilation, for instance along cleavage planes, and hydrofracture are not modelled. Mean stress is taken as a measure of fluid pressure and hence of vectors of fluid flow. Case examples show that each parameter can be the best proxy in specific situations. Mapping of all sources of dilatancy is proposed.

References

[1] Connolly, J.A.D., Podladchikov, Y.Y. 2000. Temperature-dependent viscoelastic compaction and compartmentalization in sedimentary basins. Tectonophysics 324, 137-168.

[2] McCaig, A.M., Wayne, D.M., Rosenbaum, J.M. 2000. Fluid expulsion and dilatancy pumping during thrusting in the Pyrenees: Pb and Sr isotope evidence. Geol. Soc. Am. Bull. 112, 1199-1208.

[3] Robert, F., Brown, A.C. 1986. Archean gold-bearing quartz veins at the Sigma mine, Abitibi greenstone belt, Quebec. Part I: Geologic relations and formation of the vein system. Economic Geology 81, 578-592.

[4] Ridley, J. 1993. The relations between mean rock stress and fluid flow in the crust: With reference to vein- and lode-style gold deposits. Ore Geol. Rev. 8, 23-37.

[5] Holyland, P.W., and Ojala, V.J. 1997. Computer-aided structural targeting in mineral exploration: two- and three-dimensional stress mapping. Aust. J. Earth Sciences 44, 421-432.

[6] Sanderson, D.J., Zhang, X. 1999. Critical stress localization of flow associated with deformation of well-fractured rock masses, with implication for mineral deposits. In: McCaffrey, K.J.W., Lonergan, L. and Wilkinson, J.J. (eds.) Fractures, Fluid Flow and Mineralization. Geol. Soc. London, Special Publication, 155, 69-81.