Multiscale dynamics of orebody formation

by

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The formation of large orebodies involves interlinked chemical and physical processes that operate from the nano to the lithospheric scale. In general, it is not possible to consider all these scales simultaneously to the same level of detail, so the processes that operate at one particular scale are often grouped or averaged to provide a basis for the next scale up. Equally, if one wants to understand what is happening at one particular scale, the physical conditions that operate at the next scale up can act as boundary conditions or constraints on what happens at the next scale down. We refer to this as a multiscale approach, and it results in an integrated, holistic approach to ore system analysis (Fig. 1). This project is an ARC Linkage project with funding from the GSWA, PIRSA (now DIMITRE), and the Silver Swan Group. The aim is to establish measurable parameters and indices that enable researchers to identify the differences between 'successful' and 'failed' hydrothermal systems from outcrops or drillcore, and to identify vectors to mineralization within 'successful' systems. This approach has led us to the conclusion that mineralizing systems operate far from equilibrium, and in fact never reach equilibrium (Ord et al., in press).

Here we concentrate on the lithospheric scale of an orebody, but also consider the outcrop and mine scales. The lithospheric-scale investigations are based on the observation that many large hydrothermal systems have their origins in intracratonic settings, far removed from any subduction zones. There are, of course, an important group of mineralizing systems associated directly with subduction zones, but these are not considered as part of this project. Examples of mineralized hydrothermal systems in intracratonic settings include the Olympic Dam iron oxide – copper – gold, Yilgarn orogenic gold, Carlin gold, and, arguably, the Mount Isa systems. Similar examples may emerge from the as yet unprospective Arunta Orogen and Musgrave Province.

For the moment, we are exploring the proposition (based largely on the work of Begg et al., 2009) that these mineral systems form within intracratonic orogens, coincident with zones of metasomatism in the subcontinental lithospheric mantle (SCLM) that have been reactivated at the time of mineralization. We show that tectonic deformation can cause spontaneous delamination of the SCLM in these zones, causing a concurrent and subsequent history of deformation, fluid infiltration from various depths within the SCLM, melting, and metamorphism, accompanied by surface processes such as erosion and sedimentation, all of which can last for 100 m.y. after a relatively rapid delamination. All of these processes leave their marks in the geological record, and can be indicative of an active mineralizing system (Gorczyk et al., 2012). Low-salinity fluids from relatively shallow depths, and CO_2-rich fluids from deep in the previously metasomatized SCLM are both involved. The delamination process is a new kind of Rayleigh–Taylor instability that forms in solids, rather than the classical Rayleigh–Taylor instability studied in viscous fluids by Houseman and Molnar (1997) and Elkins-Tanton (2007; see also Huismans and Beaumont, 2002). Delamination of the SCLM causes a thermal–mechanical disturbance producing types of deformation, metamorphism, melting, and fluid flow at least comparable with that produced at subducting margins. Such delamination events are being imaged increasingly in modern, or relatively recently mineralized, intracratonic settings (West et al., 2009; Guoming et al., 2011).

Recent results from the Albany–Fraser Orogen (Spaggiari et al., 2011) and the Western Australian part of the Musgrave Province (Howard et al., 2011; Smithies et al., 2012) provide tectono-thermal histories for these two regions; these data are summarized in Tables 1 and 2. The timescales associated with the tectono-thermal histories of these two regions are important. Since a thermal pulse diffuses (by conduction) through a rock thickness L (in metres), on a timescale given by 10^6L^2 (in seconds), timescales of 570 m.y. and 305 m.y. correspond to rock thicknesses of 135 km and 100 km, respectively, which are equivalent to lithospheric thicknesses. Conversely, the individual events lasting 100 m.y. and 40 m.y. are thermal events corresponding to rock thicknesses of 56 km and 35 km, respectively, corresponding to viable crustal thicknesses. The delamination process involves relatively rapid solid advection of SCLM through isotherms, and slow post-delamination tectonic relaxation. Thus, the timescales of 100 m.y. or less shown in Tables 1 and 2 can be explained by the delamination process, as

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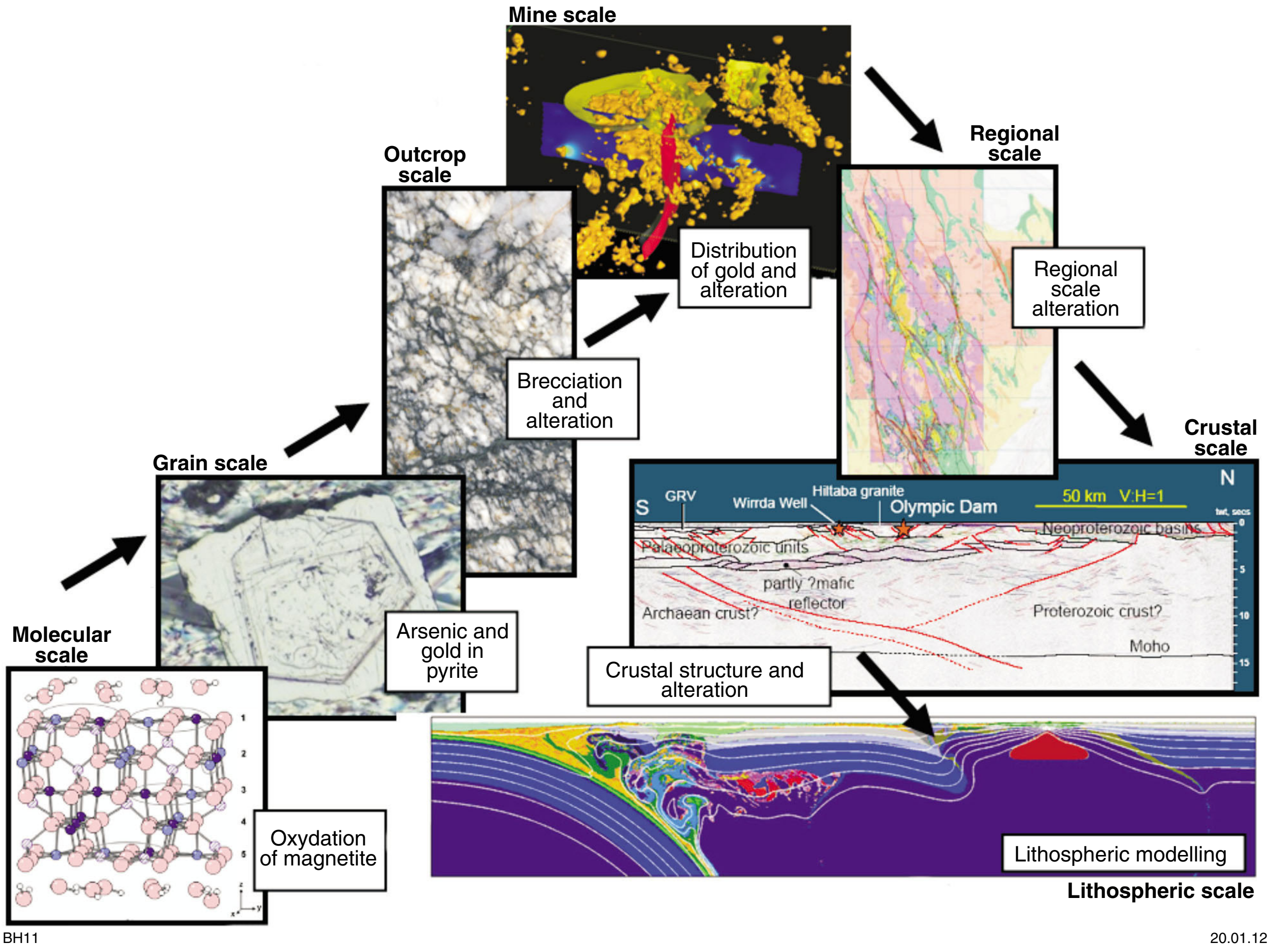


Figure 1. A multiscale approach to hydrothermal mineralizing systems

a result of which (at least) crustal material remains at high temperatures and pressures for extended periods corresponding to the post-delamination thermal relaxation.

Just as important as the tectono-thermal timescales is the width of the SCLM weak zone as an influence on patterns of deformation, melting, and fluid release that result during delamination (Fig. 4). After a critical width is exceeded, the pattern of deformation becomes localized, forming Y-shaped fault structures within the crust. The SCLM is advected into higher pressure–temperature regions below this structure, resulting in localized melting and devolatilization. We propose that the development of this localized deformation to one side of the delamination system is the primary focusing mechanism for large hydrothermal orebodies, and as such, the width of the delamination system is a prime criterion for failed-versus-successful mineralizing systems. Note that this asymmetry is reflected in the evolution of surface topography, so there will be a direct record in the stratigraphic history. This can be seen in the Albany–Fraser Orogen and Musgrave Province.

At the orebody scale, it is important to treat the development of these hydrothermal systems as open-flow chemical reactors (Ord et al., in press). Here, constraints imposed by the lithospheric-scale modelling presented above can be used to impose time and volumetric flow-rate constraints on the evolution of the system. This analysis results in a common history for all successful hydrothermal systems involving an initial stage of exothermic alteration (hydrous minerals, carbonates, and iron oxides) and the following endothermic precipitation of sulfides, metals, and silicates. The switch from one mode of operation to another requires a new mechanism for maintaining permeability, and this is commonly expressed as a stage (or several stages) of brecciation or vein formation. Also at this switch from one mode of operation to another, the most efficient systems must be localized, and this is seen as zoned mineralization or late stage alteration.

This non-equilibrium approach supplies several criteria for deciding whether a particular mineralizing system has been successful or not, based on drillcore or exposures.

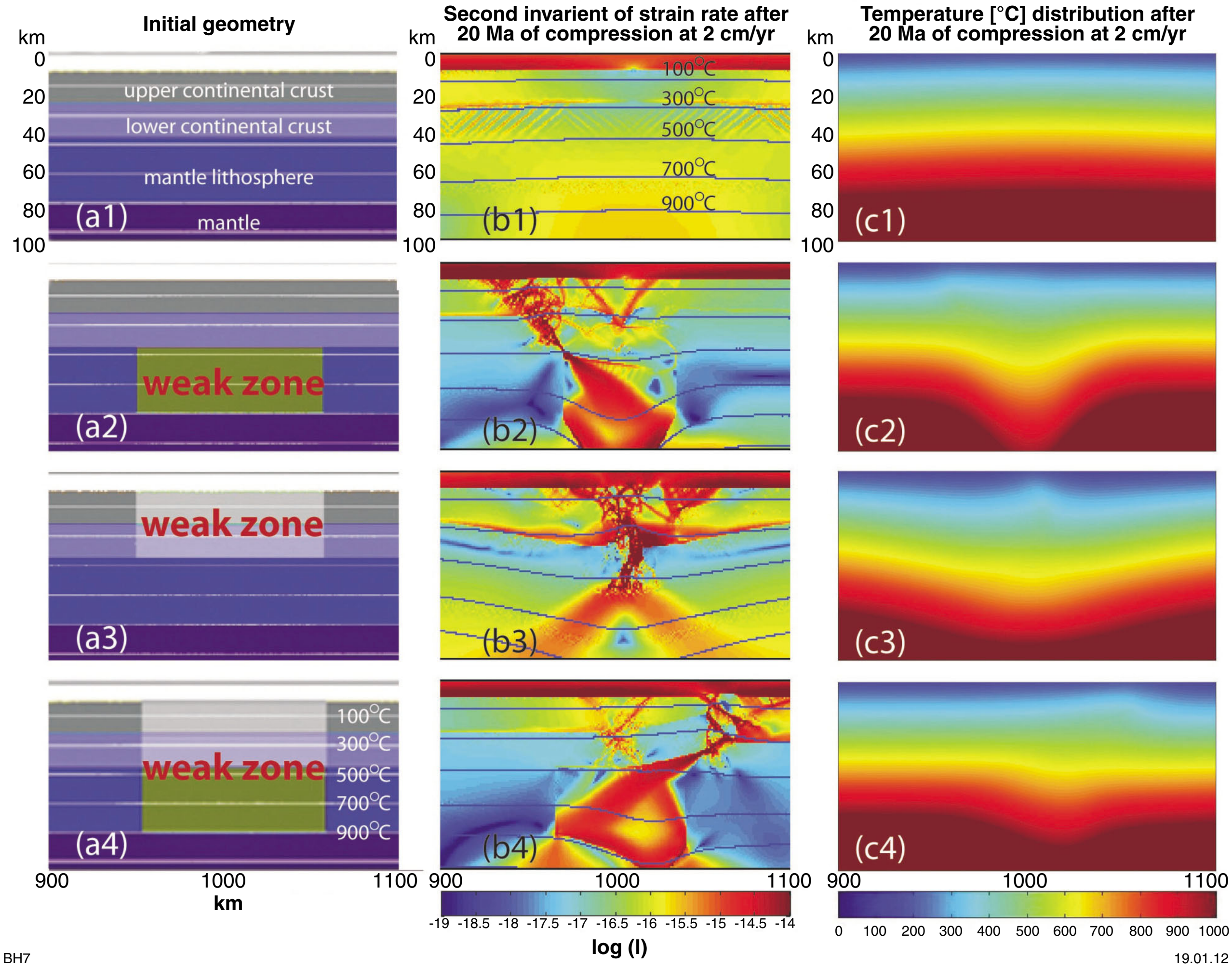


Figure 2. ***Results of four models with different initial geometries, showing: (a) initial geometry and bulk composition; (b) second strain rate invariant after 20 Ma of compression at rate of 2 cm/a; (c) temperature distribution after period of 20 Ma (from Gorczyk et al. 2012).***

Table 1. Albany–Fraser tectonic regime

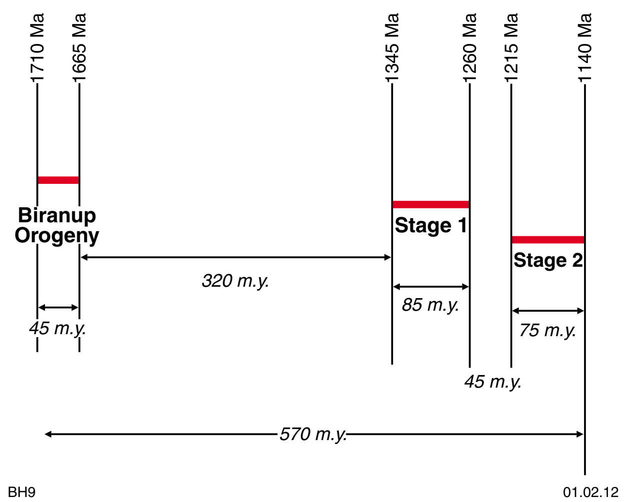
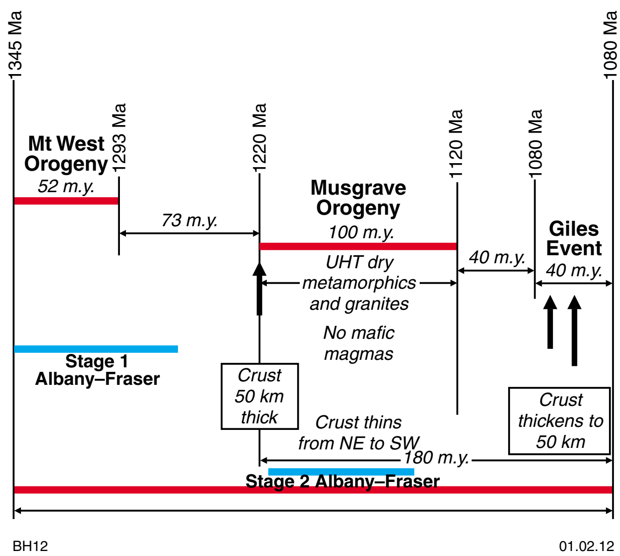


Table 2. Musgrave tectonic regime



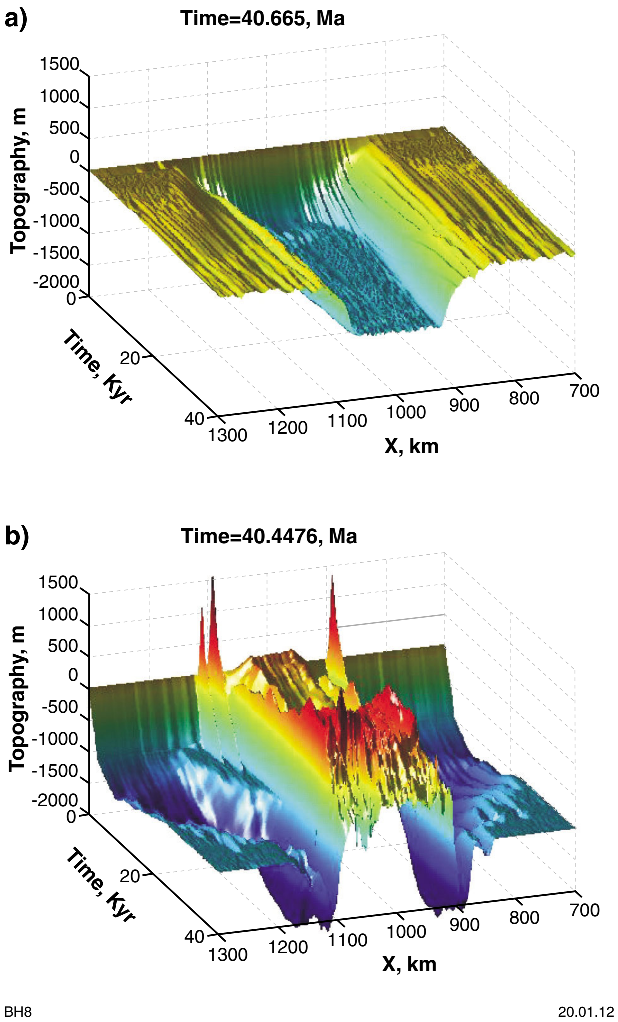


Figure 3. ***Dynamic evolution of the topography above the developing instability: (a) run with initial perturbation imposed only on mantle lithosphere; (b) run with initial perturbation imposed on whole lithosphere, with additional continental root. The initial peaks in topography on the sides of instability are due to the initial equilibration of topography. Further in the run, peaks above the downwelling correspond to intrusion of magma into the crust, plus mountain building processes, as a result of deep lithospheric detachment (from Gorczyk et al., 2012).***

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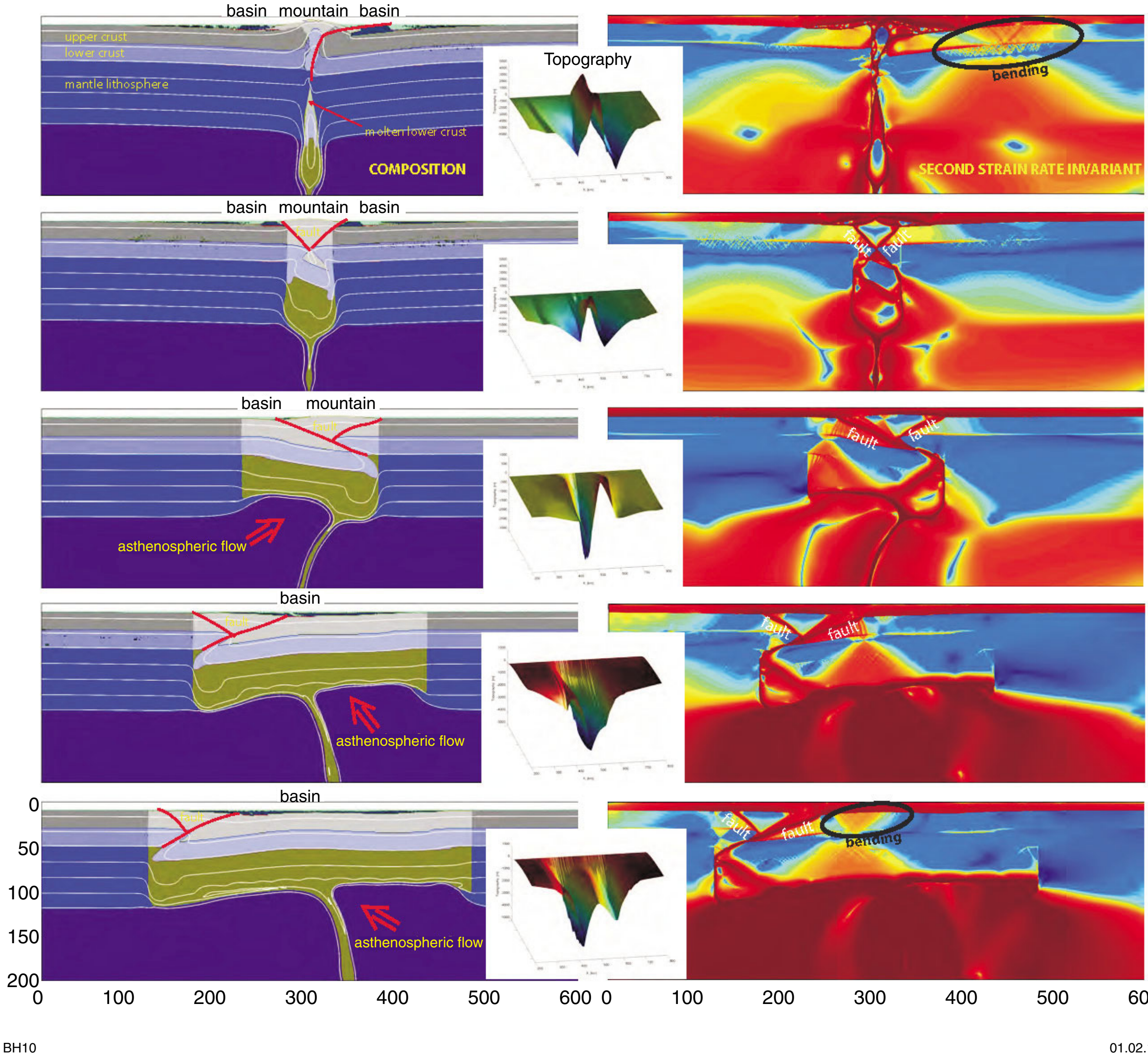

Figure 4. ***Influence of width of SCLM weak zone on the delamination process. Models are 300 km thick in all cases; width of weak zone varies from 50 km at the top to 400 km at the bottom; base of SCLM defined by 1300°C isotherm. Left-hand panel shows the geometry, with the development of Y-shaped fault systems shown in red; right-hand panel shows the distribution of strain rate. Inset shows the development of surface topographic relief.***