Metamorphic Dehydration and Fluid Transport: Laboratory Constraints and Hydrologic Modeling

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Fluids exert significant mechanical and chemical effects on crustal dynamics. H_2O-rich fluids are the most abundant type and are present in pores, dissolved in magmas, and structurally bound in hydrous minerals. Pore pressures generated by such fluids, whether by porosity reduction, degassing, or dehydration, can be very high and thus have a major effect on the mechanical behavior of the rocks. Numerous mechanisms for the generation and maintenance of overpressure in sedimentary, metamorphic and tectonic processes have been proposed [*Bredehoeft and Norton*,1990]. One important mechanism is the decomposition of hydrous minerals during prograde metamorphism, that may enhance the pore pressure and lower rock strength in accordance with Terzaghi's law of effective stress. The dehydration mechanism may also induce embrittlement.

Such dehydration weakening mechanism was documented in serpentinite, gypsum, chlorite, and clays in laboratory studies of *Raleigh and Paterson* [1965], *Heard and Rubey* [1966], and *Murrell and Ismail* [1976]. To dramatize the weakening and embrittlement effects, these experiments were mostly conducted under *undrained* conditions, such that the water released remained trapped within the sample assembly. In such a closed system, the pore pressure builds up to near the confining pressure and the strength of the sample drops to a value comparable to an unconfined sample. Since the sample is completely enclosed in an impermeable jacket, one does not have direct access to the sample and can not monitor the progress of dehydration and development of pore pressure. Furthermore such an undrained assemblage cannot be considered to be a realistic analogue of crustal setting that invariably involves finite permeability and fluid percolation [*Ferry*, 1994].

Some preliminary attempts were made to study samples under *drained* conditions. Little or no weakening was observed [*Raleigh and Paterson*, 1965; *Murrell and Ismail*, 1976] unless the transformation causes a change in deformation mechanism [*Rutter and Brodie*, 1992]. However, more comprehensive investigations recently conducted by *Ko et al.* [1997] on gypsum dehydration have demonstrated that the temporal evolution of pore pressure and strength in a drained dehydrating system are more complex than what were suggested by the previous work. This set of mechanical, hydrological and microstructural data highlights the interplay of fluid production, reaction-induced porosity change and permeability changes, and the dehydration kinetics in a dehydrating system. Gypsum was chosen for this study because the conditions for dehydration are more tractable to a quantitative laboratory investigation than those for other hydrous minerals. The conditions that control the development of excess pore pressures are similar for many hydrous minerals [*Murrell and Ismail*, 1976]. Therefore, although gypsum is tectonically important in its own right, it is also an excellent analogue for many other hydrous systems.

Motivated by these experimental observations, a hydrologic model was developed to analyze the evolution of pore pressure excess in a dehydrating system [*Wong et al*., 1997]. While the governing equation is based on Darcy's law and conservation of mass, this transient flow model is somewhat different from conventional models in that it incorporates two source terms (for dehydration and porosity production rates) and the permeability is assumed to have a strong dependence on porosity (that changes reversibly by elastic deformation and irreversibly by the dehydration reaction). The model satisfactorily explains why apparently contradictory conclusions on dehydration-induced weakening or strengthening were obtained, and it clarifies conditions under which pore pressure excess (and possibly weakening and embrittlement) can be generated and maintained in drained conditions through the interplay of dehydration, pore dilation and permeability.

Generation of pore pressure excess is likely if the Clapeyron curve (for the devolatization reaction boundary) in P-T space is such that $dP/dT > 0$, which implies that the total volume (solid+fluid) of the products (ΔV_{tot}) will be increased by the reaction. On the other hand, if $\Delta V_{tot} < 0$ then embrittlement and weakening can be ruled out. Indeed, for the latter case some have suggested the possibility of reaction-enhanced ductility associated with grain size sensitive diffusive mechanisms. Whether the anomalous pore pressure generated by the reaction can be maintained over time hinges on the hydromechanical responses of the dehydrating layer and its environment. In particular, if the permeability is lower than a critical threshold, then a significant pore pressure excess may be maintained over long duration. According to the law of effective stress, the dehydrating layer will undergo significant embrittlement and weakening, and hydraulic fracturing and pervasive development of veins are likely. On the other hand, if the environment is relatively permeable, then the development of pore pressure excess will occur as a transient peak that may result in episodic hydraulic fracturing. In the long run, the pore pressure will decay to the hydrostatic value.

The critical permeability required for maintaining pore pressure excess in a dehydrating system is sensitively dependent on the rates of fluid production and porosity change. The critical permeabilities so estimated for a number of dehydration reactions fall in the range of metamorphic permeabilities recently compiled by *Manning and Ingebritsen* [1999], who also emphasized the variation of permeability with depth that has not been systematically analyzed. Using an almost identical approach and focusing on the dehydration of serpentinite, *Ague et al*. [1998] suggested that repeated cycles of dehydration-induced seismicity are plausible in the mid-crust, and may be sustained throughout an orogenic episode if fresh hydrous minerals descend into the metamorphic zone.

In many respects, the hydrological process in a dehydrating system is similar to the development of pore pressure excess under drained conditions in seismogenic and sedimentary systems, that have been analyzed by *Rice* [1992] and *Neuzil* [1995], respectively. An assumption common to such models is that creep deformation and time-dependent compaction may be neglected. While such plastic deformation may not be important at relatively low temperatures or fast reaction rates (such as characteristic of contact metamorphism [*Hanson*, 1995]), it can be appreciable in other metamorphic environments. The coupling of deformation (in a creeping matrix) and fluid flow (in a pore space under near lithostatic pressure) in a system undergoing prograde regional metamorphism was recently considered by *Connolly* [1997]. In many respects, the fluid flow in such a metamorphic system is analogous to that in a partially molten system [*Stevenson and Scott*, 1991]. Continuous devolatization causes deformation-propagated fluid flow, that is upward and episodic. Such waves provide a mechanism for temporal focusing of metamorphic fluid fluxes with the potential to increase the efficacy of heat and mass transport.

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