Dynamics of Fluid Pathways and Fluid Flow in Intrusion-Related Hydrothermal Systems: Insights from Ore Deposits, Seismicity, and Numerical Modeling

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In low-permeability regimes, fluid migration in intrusion-related systems is controlled by permeability enhancement associated with episodic growth of extension fractures and repeated reactivation of faults. Opening of extension fractures is driven by fluid injection and pressurization of connected networks of hydraulic fractures at low differential stresses and severely overpressured fluid conditions. Vein orientations are controlled by near-field stress regimes. Faults are activated at higher differential stresses, and provide important fluid pathways. The internal structure of faults and veins in intrusion-related hydrothermal systems indicates that ore genesis involves hundreds to thousands of episodes of fluid migration and accompanying bursts of fluid-driven failure.

Seismicity styles in contemporary, overpressured, intrusion-related hydrothermal systems are dominated by injection-driven swarm sequences. Bursts of seismicity, associated with fluid-driven rupture propagation, involve up to thousands of slip events in the range $-1 < M_w < 3$ over days to weeks; slips range from 0.1 to 10 mm, over rupture lengths of several meters to several hundred meters. For example, a typical swarm at Hakone caldera (Japan) in 2009 exhibited intense seismicity over 8 days, and migrated through several small faults with strike lengths less than 2,000 m. Time migration of seismicity and the associated fluid pressure front occurred at rates up to several hundred meters per day. Total moment release during intrusion-related injection-driven swarm sequences indicates injection of approximately 10^4 to 10^5 m^3 of fluid over the duration of each swarm. Episodic swarm seismicity at Hakone in the period 1996 to 2006 occupied a volume of 10 km^3 over a depth interval of 3 km and illustrates the length scales on which episodic, fast, fault-controlled flow can occur in intrusion-related hydrothermal systems.

The dynamics of fluid-driven failure and propagation of fluid pressure fronts associated with injection of magmatic-hydrothermal fluids into low-permeability host rocks are explored using fully coupled hydromechanical simulations with continuum/discontinuum constitutive relations that incorporate the regional stress field, rock mechanical properties, mechanical heterogeneity associated with preexisting faults, and depth-dependent fluid properties. The models track dynamic changes in fluid pressure and stress states during fluid injection, along with permeability enhancement coupled with failure. The 3-D simulations also track evolution of fluid pathways, intensity of fracture damage, and fluid flux. The modeling closely simulates the formation of heavily fractured domains that host vein systems around cupolas in porphyry and some Sn-W systems, and allows exploration of how the dimensions of these domains and ore distribution are influenced by fluid production rates, initial permeability distributions, and far-field stress regimes. A major result is that nucleation of new faults and reactivation of suitably oriented, preexisting faults can generate fluid pathways that facilitate fast fluid transport up to several kilometers away from the injection source. Propagation of fracture networks through low-permeability domains into high-permeability, near-hydrostatic fluid regimes at shallow depths leads to rapid fluid depressurization, depletion of driving pressures in the fluid reservoir, and cessation of individual flow episodes. The results provide new insights about the dynamics of magmatic-hydrothermal systems and have implications for exploration for the distal footprints of these systems.