Shaken and stirred: Chilling the crust with earthquakes

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The long-documented hydrological response to earthquakes (Muir-Wood and King, 1993; Roeloffs 1996) has been whittled down to two prevailing underlying mechanisms (Wang2008): (1) the response of confined aquifers to volumetric strains in the near-field, with well-level increases in contraction and well-level decreases in dilation, and (2) enhanced permeability in both the near- and far-field resulting in both well-level changes and increased stream flow following earthquakes (Rojstaczer et al., 1995; Brodsky et al., 2003; Wang and Chia, 2008). One of the best documented hydrological responses to an earthquake was recorded in numerous wells in an alluvial fan at the toe of Taiwan's fold-and-thrust belt following the 1999 Mw = 7.6 Chi Chi earthquake, that also included substantial increases in stream flow (Wang et al., 2004). Although the hydrological response to earthquakes is well documented, its long-term significance is not often discussed. However, the reporting of changes in ground water temperature in aquifers near the Chi Chi epicenter (Wang et al., 2012, p. 119 in this issue of *Geology*), concomitant with the hydrological response, presents an opportunity to evaluate these findings in the larger context of fluids and the earthquake cycle. The additional observation of temperature changes supports the conceptual model of large-scale permeability increase as the primary mechanism responsible for increases in stream flow following earthquakes (Rojstaczer et al., 1995), and establishes a link to surface heat flow.

Heat flow measurements provide important information about the underlying thermal structure, but as an integrative measure of competing processes, it is not the strongest constraint on models. Heat flow measurements do, however, sometimes provide game-changing results. The most well-known is the absent heat flow anomaly expected from frictional heating around the San Andreas fault (California; Lachenbruch, 1980), with implications for the strength of seisomogenic faults. A temperature increase, presumably from frictional heating, was measured in a borehole drilled through a high slip patch of the Chi Chi earthquake, and was used to help constrain dynamic stresses during slip (Tanaka et al., 2006). In both cases, a primary assumption used to arrive at their respective conclusions was that conductive cooling was the primary heat transport mechanism. This assumption now comes into question by Wang et al. because it appears that the large-scale fluid flow following earthquakes can cool the mountain belt, erode the near-surface geothermal gradient, and eliminate shallow heat flow signals. Indeed, modeling by Wang et al. shows there should be no measurable surface heat flow as deep as 130 m 300 days after the earthquake, implying that heat flow measurements around active faults should be sampled at considerable depths to establish the existence or not of heat flow anomalies.

Heat flow is proportional to temperature gradients, and the thermal conductivity is the proportionality constant. Temperature changes with time by the relative contributions of heat conduction, heat sources (i.e., radioactivity, frictional heating, endothermic/exothermic reactions, etc.), and advective heat transport. In porous media, advective heat transport is controlled by the Darcy velocity of the fluid, which itself is governed primarily by the permeability. For a constant-viscosity fluid like water at shallow depths, the Darcy velocity can change by one of two mechanisms: either (1) from changes in the hydraulic head, or (2) from changes in the permeability of the medium. In a steady-state hydrological system such as that in Taiwan prior to the Chi Chi earthquake, the Darcy velocity was controlled by changes in hydraulic head associated with the seasons, at constant permeability. However, large-scale changes in (vertical) permeability following the earthquake would increase the Darcy velocity and thus the amount of heat transported by advection. This scenario is advanced by Wang et al., where seismically induced increases in the vertical permeability flushed trapped water in the mountains and transported substantial heat via advection. The advective heat transport is shown to have long-term consequences on the near-surface geothermal gradient, and thus heat flow around active mountain belts. Once the enhanced advection stops, heat transport is controlled primarily by the slow process of conduction, resulting in a durable temperature decrease and perturbed temperature gradients near the surface.

Of interest here is to explore whether the hydrological response to earthquakes near the surface can be extended to the crustal scale. Near the surface, confined aquifers are particularly good strain meters because they record the compressional or dilatational strains acting on the surrounding volume of the aquifer. Confined aquifers (reservoirs) in the deeper crust would respond in the same way, with pore pressure increases in contraction and decreases in dilation. This establishes pore pressure gradients that would drive Darcy flow and also create pore-elastic stresses. This scenario was first proposed as a mechanism for aftershock generation (Nur and Booker,1972), which was also suggested as an aftershock driver for the 1992 Landers (California) earthquake (Bosl and Nur, 2002), and as part of the 2009 L'Aquila (Italy) earthquake (Terakawa et al., 2010). Pore-elastic effects were also proposed for interpreting post-seismic surface deformation in Iceland (Jonsson et al., 2003) and also within the main step-over of Landers (Peltzer et al.,1996).

Large permeability increases near the surface affect fluid flow and thus advective heat flow, which may also apply to much deeper levels. All hydrogeological systems are controlled by the intrinsic permeability, but this essential parameter remains elusive because of its ability to change drastically in response to earthquakes or other tectonic processes (Miller and Nur, 2000). Co-seismically enhancing permeability on a large scale perturbs the pre-seismic steady-state system, triggering increased fluid flow and the concomitant advective transport of both heat and chemistry. Chemical precipitation along the flow path then shuts down the permeable network, resulting in large-scale but transient changes in the hydraulic properties. The results of Wang et al. suggest that the system is in steady-state for most of the earthquake cycle, but all the action occurs in a very short time span at the time of the earthquake, with long-term consequences on the system's measurable properties. In the case of Taiwan, the data suggest a recovery time to pre-earthquake hydraulic properties of about 2 years, and although large uncertainty exists in this estimate, it is still an instant relative to the earthquake cycle.

The depth to which permeability increases occur is not known, but recent studies of chemical weathering tracked in streams indicate that permeability increases may be quite deep, with a substantial geothermal component indicating deep weathering (Calmels et al., 2011). If large-scale changes in the aquifer-aquitard systems occur near the surface, then one might expect that when turned upside down, similar processes occur at the crustal scale. That is, just as increased permeability in the near surface allowed the escape and flow of water trapped in the mountains, increasing permeability or breaking a seal at depth could also allow the

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escape and flow of trapped high pressured fluids at depth. Evidence for co-seismic permeability increases at the crustal scale are indirect, but the recent observation of the injection of deeply derived CO_2 into a shallow aquifer near the 2009 L'Aquila earthquake (Chiodini et al., 2011) indicates rapid fluid flow along highly permeable pathways created during the earthquake. Earthquake related increases in ion concentrations prior to, and particularly after, the 1995 Kobe (Japan) earthquake add additional support to this mechanism (Hartmann and Levy, 2006).

If large-scale permeability increases at depth in response to earthquakes, then this provides an important mechanism for draining trapped high-pressure reservoirs at depth, analogous to the draining mountains reported by Wang et al. The difference at depth, however, is that once permeability is enhanced, the reservoir drains at significant overpressure, capable of generating aftershocks along the flow path because of the large reductions in the effective normal stress acting on incipient slip planes. This mechanism for aftershock generation has been proposed for earthquake sequences in Italy (Miller et al., 2004), a thrust sequence in Japan (Sibson, 2007), and some swarm seismicity (Cappa et al., 2009; Shelly and Hill, 2011). The complex interaction of fluid flow, fracture, and healing of flow networks via heat and chemical advection, both in the near-surface and at depth, should be the focus of future research. One drawback in the study of Wang et al. is that well temperatures were monitored infrequently, preventing any clear signal of the spatio-temporal evolution of the temperature field. Future targeted measurements should include geochemical and temperature measurements in aquifers in seismically active regions to provide robust baseline measurements for future investigations of the same aquifers after the earthquakes strike.

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