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The impact of earthquakes on fluids in the crust

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Abstract
The character of the hydrological changes that follow major earthquakes has been investigated and found to be critically dependent on the style of fault displacement. In areas where fracture-flow in the crystalline crust communicates uninterrupted with the surface the most significant response is found to accompany major normal fault earthquakes. Increases in spring and river discharges peak a few days after the earthquake and typically excess flow is sustained for a period of 4-12 months. Rainfall equivalent discharges, have been found to exceed 100 mm close to the fault and remain above 10 mm at distances greater than 50 km. The total volume of water released in two *M* 7 normal fault earthquakes in the Western U.S.A. was 0.3-0.5 km^3. In contrast, hydrological changes accompanying reverse fault earthquakes are either undetected or else involve falls in well-levels and spring-flows. The magnitude and distribution of the water-discharge for these events is compared with deformation models calibrated from seismic and geodetic information, and found to correlate with the crustal volume strain down to a depth of at least 5 km. Such relatively rapid drainage is only possible if the fluid was formerly contained in high aspect ratio fissures interconnected throughout much of the seismogenic upper crust. The rise and decay times of the discharge are shown to be critically dependent on crack widths, for which the «characteristic» or dominant cracks cannot be wider than 0.03 mm. These results suggest that fluid-filled cracks are ubiquitous throughout the brittle continental crust, and that these cracks open and close through the earthquake cycle. Seismohydraulic fluid flows have major implications for our understanding of the mechanical and chemical behaviour of crustal rocks, of the tectonic controls of fluid flow associated with petroleum migration, hydrothermal mineralisation and a significant hazard for underground waste disposal.

Key words *earthquake – water*

1. Introduction

A clear relationship can be demonstrated between the style of fault displacement and its hydrological «signature» (Muir Wood and Woo, 1992; Muir Wood and King, 1993). Co-seismic strain models can be shown broadly to explain the difference between the hydrological signatures of normal and reverse fault earthquakes, the geographical extent of the hydrological response and even, in general terms, the magnitude of the water-release.

In a region undergoing extensional faulting, continuing strain distributed through the crust causes appropriately oriented fractures to dilate, thereby increasing crustal porosity. Pore-pressures are sustained by slow infilling of the dilated fractures with water from the surface (see fig. 1a-d). At the time of a major normal fault rupture, strain formerly distributed through the crust becomes concentrated on the fault, and the surrounding crust undergoes elastic rebound in compression. In contrast, in a region undergoing compressional tectonic deformation, negative strain (volume decrease) in the crust closes fractures and reduces crustal porosity in the interseismic period. At the time of the fault rupture, as strain is transferred into

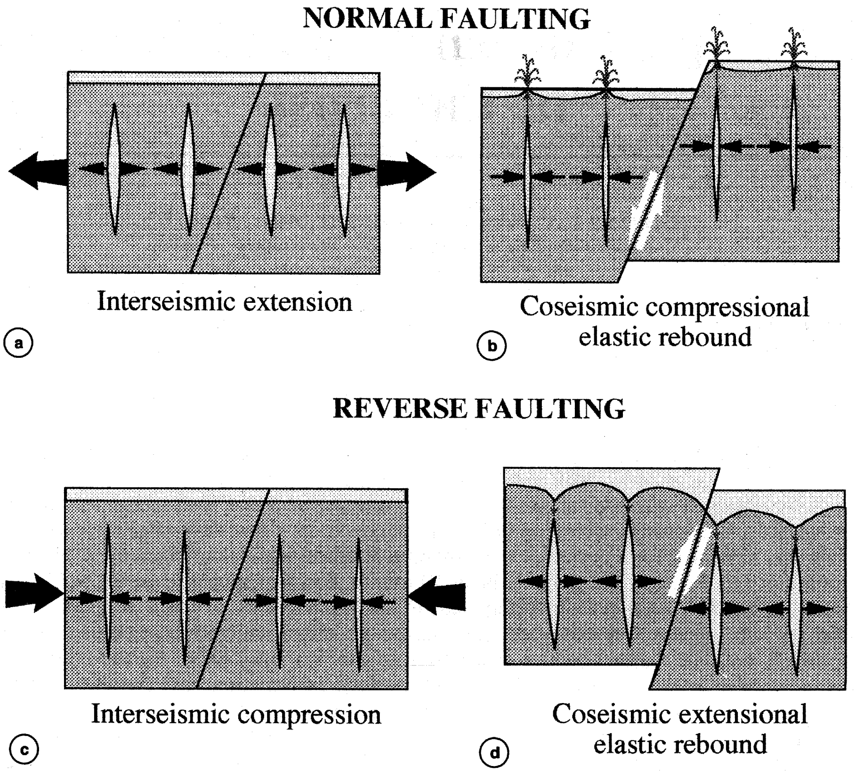

Fig. 1a-d. For extensional faulting the interseismic period (a) is associated with crack opening and increase in effective porosity. At the time of the earthquake (b) cracks close and water is expelled. For compressional faulting the interseismic period (c) is associated with crack closure and the expulsion of water. At the time of the earthquake (d) cracks open and water is drawn in.

fault displacement the surrounding crust undergoes elastic rebound in extension.

Hence in the region surrounding a normal fault rupture it is expected that the decrease in crustal porosity will lead to the expulsion of water following an earthquake. In the region surrounding a compressional fault rupture reduced hydraulic pressures should lead to water being drawn into the crustal volume. In both normal and reverse fault earthquakes the impact on the height of the water-table (and consequent well-levels and superficially sourced spring flows) will be dependent on how effectively this water-table is connected to the fracture-flow system at depth. Where the crystalline rocks of the crust communicate with the surface uninterrupted by the presence of any overlying impermeable sedimentary cover the superficial groundwater should respond to underlying changes in fluid pressures.

River flows provide the most important resource for quantifying these post-seismic changes. By sampling changes in discharge across catchments typically > 100 km^2 in area, it becomes possible to average the crust on a scale whose lateral dimension is of the same order as the hydraulically-conductive thickness of the crust. River discharge data can then be normalised for the area of the drainage basin to achieve a «rainfall equivalent» discharge either in the form of velocity (for a daily average) or cumulative linear «thickness».

2. Normal vs. reverse faults

We have documented changes in near-surface hydrology following a number of earthquakes in diverse tectonic environments. The form of these hydrological changes can be illustrated from two major high-angle dip-slip earthquakes: the 1959 *M* 7.3 normal fault Hebgen Lake earthquake and the *M* 7.2 1896 reverse fault Rikuu (North Honshu) earthquake (earthquakes associated with a significant strike-slip component of displacement reveal more complex hydrological signatures: Muir Wood and King, 1993).

Three river flow profiles (with entirely separate catchments) are shown in fig. 2 from the region of Southeast Montana for the period before and after August 18th, 1959 Hebgen Lake earthquake (data from USGS Water Supply Reports). For both sets of plots average monthly flows are shown for comparison. From the left-hand plots it can be seen that in all three rivers a peak in flow arrived within four days following the earthquake. There was no precipitation around this time to explain such a surge and the increase in flow that follows the earthquake can be seen to have been sustained relative to the trend of the monthly averaged flow curve for more than 60 days. From expected flow curves for these rivers (calibrated from river flows within the same region but outside the influence of the earthquake) it is possible to assess the overall volume of the water release in each catchment that appears to show an almost linear decay following the initial peak (Muir Wood and King, 1993). Typical decay times to half peak flow are 100-150 days. These cumulative flows, normalised for the individual drainage basins around the fault in terms of rainfall equivalent discharges, are shown in fig. 3. The individual catchments with more than a total of 1 mm excess discharge have been shaded in three tones corresponding to1-20 mm, 21-40 mm and > 40 mm. The total volume of water discharged across all the surrounding catchments is equivalent to ca. 0.5 km^3.

The Rikuu earthquake of August 31st, 1896 involved surface reverse fault rupture, over a distance of 36 km with a maximum uplift of 3.5 m. This was accompanied by an antithetic reverse fault rupture located some 15 km to the east and in the hanging wall of the main fault. Hence all the near-surface faulting appears to have been reverse implying that all near-surface elastic rebound was extensional. No changes in river flows were reported following the earthquake, but hot springs supplying bathhouses at Oshuku, Tsunagi and Osawa dried up after the earthquake, while there was a significant reduction in flow at the thermal springs at Namari and Yuda (see fig. 4). All of these lie in the hanging wall of the main fault, to the east and within 20 km of the principal antithetic fault. In contrast, close to the northern end of the main fault between the main fault and its antithetic a new hot spring formed at Sengan-Toge following the earthquake.

3. Coseismic strain models

In order to examine in more detail the expected magnitude and extent of strain induced hydrological effects, strain models of coseismic deformation have been generated using a boundary element programme in which a dislocation element is introduced into an elastic medium. Figure 5a,b is an illustration of the dilational strain changes that accompany a normal fault displacement, both in cross-section (fig. 5a) and a plan-view approximation (fig. 5b). The predominant strain changes are compressional. Strain changes of reverse fault earthquakes are largely equivalent although of opposite sign to those of normal fault earthquakes.

4. Percolation depth

In the case of the Hebgen Lake earthquake the observed discharge for a traverse perpendicular to the strike of each of the faults was compared with predicted discharge for a two dimensional coseismic strain model. For the Hebgen Lake earthquake the closest fit is with the 5 km depth prediction both in general shape and in amplitude. The fit with the data is remarkably good and the data is not very sensitive to where the profile is taken.

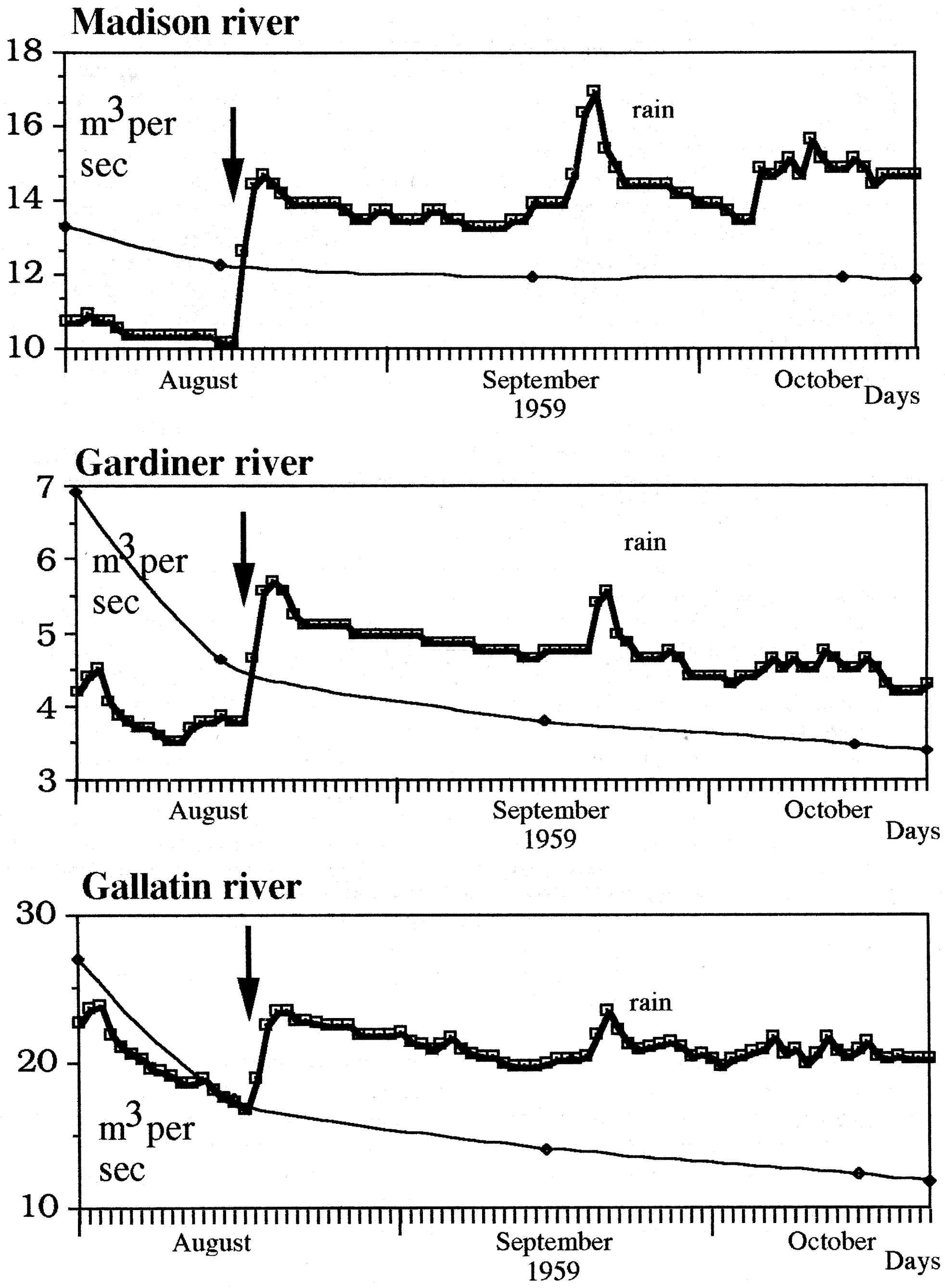

Fig. 2. River flow data for three rivers in the vicinity of the 1959, August 17th, Hebgen Lake, Montana earthquake, in the days around the time of the earthquake. Average monthly flows plotted as a thin line.

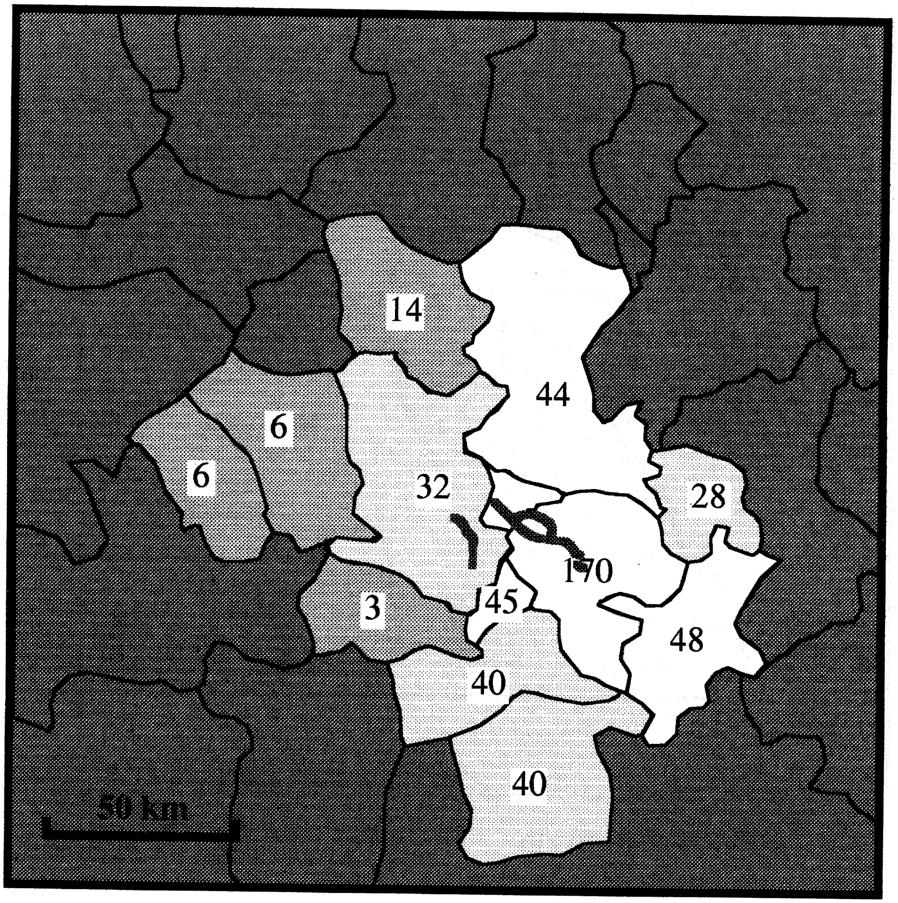

Fig. 3. Cumulative excess flow following the Hebgen Lake earthquake normalised for the area of the catchments into excess rainfall equivalent (mm). Mid-grey shading indicates catchments with less than a 1 mm excess flow; three lighter tones correspond to 1-20 mm, 20-40 mm and > 40 mm.

This comparison suggests that all the water that appears at the surface appears to be associated with fracture systems extending to considerable depth. A large part of the coseismic volumetric strain can be shown to be associated with the closure of cracks and expulsion of water.

5. Characteristic fracture apertures

The most straightforward way to describe the form of the observed flows is to assume that they result from a series of planar uniform cracks open at the surface and closed at some depth and subject to a pressure change over a depth range (Muir Wood and King, 1993). The crack width is found to be the parameter most strongly controlling the decay of the flow vs. time profile while the dead depth (depth to the top of the section of the crack undergoing a sudden strain) and the crack width together determine the rise time. Most of the observations are fit by models with crack widths of about 0.03 mm and effective dead depths of about 2 km.

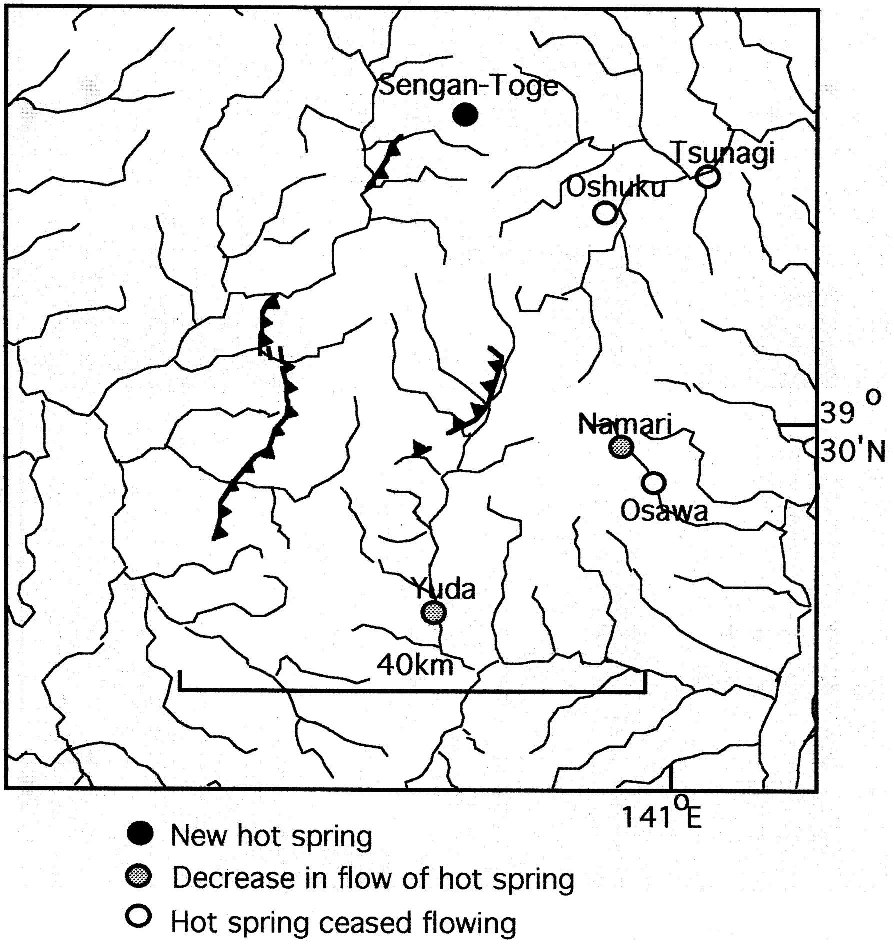

Fig. 4. Impact on hot-springs of the August 31st 1896 Rikuu (North Honshu) *M* 7.2 reverse fault earthquake. Barbed lines are surface-fault ruptures; barbs on upthrown side of the fault.

To obtain cumulative rainfall equivalent discharges of 20-40 mm implies characteristic crack separations of less than 4 m. The similarity that exists between the duration and rise-time of hydrological signatures in a wide variety of earthquakes suggests that this property is widespread.

6. Underground waste disposal

Hydrological changes that accompany earthquakes may significantly alter the ground water regime, potentially causing fractures to reverse their flow, or stagnant bodies of water to become involved in a sudden movement towards the surface. Where underground repositories for chemical or nuclear waste are constructed with the intention of relying on advantageous ground water flow, either in terms of rates or directions of fluid transport, coseismic changes in flow may have a deleterious impact, in the most extreme cases causing contaminated water to pass rapidly to the surface. Fluid flow measured in the interseismic period is likely to be entirely distinct from that which

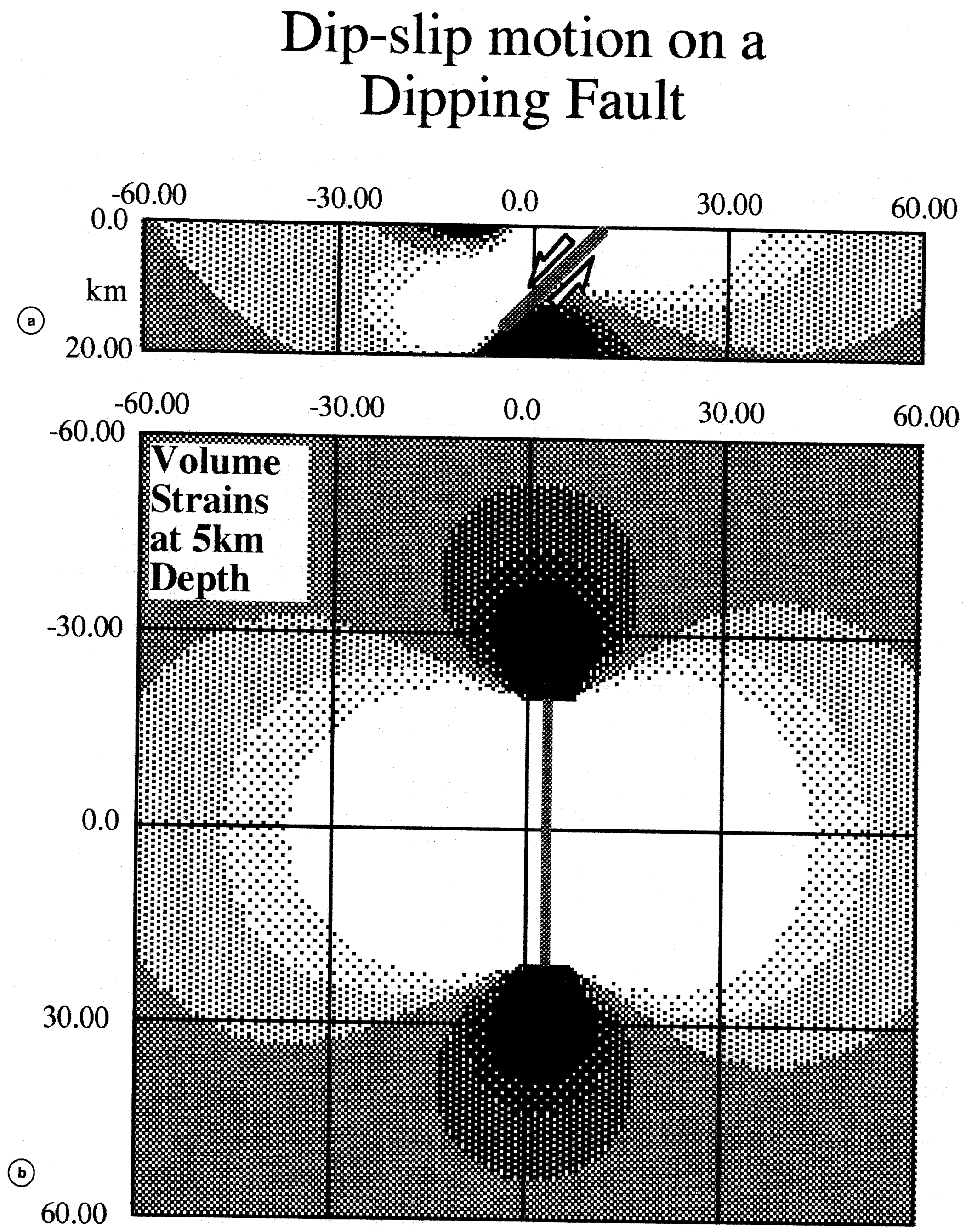

Fig. 5a,b. Cross-section (a) and plan-view (b) of strains modelled around a normal fault. The scale units are kilometers, slip for (a) is 1 m. Strain levels are shaded from a background grey, to lighter shades (negative strain) and to darker shades (positive strain): strain-steps of 2 × 10-5.

prevails immediately following the earthquake. Seismohydraulic processes need to be given particular consideration when planning the underground disposal of hazardous waste.

7. Mineralisation

The fundamental differences in strain cycling between extensional and compressional tectonic environments are likely to have a profound impact on the conditions and styles of mineralisation. In the extensional environment interseismic crustal dilation leads to an increase in crustal porosities which may be topped up from the surface water table. Repeated flushing of water through the top five kilometres of the crust, over the 1000 or more seismic cycles that make up the tectonic activity of a rift bounding fault, will significantly affect rock chemistry. For trace ionic species disseminated through the rockmass, reprecipitation to form concentrated vein mineral deposits is most likely to occur in the immediate aftermath of an earthquake when the watermass is squeezed to shallower and cooler levels in the crust.

In contrast, in a compressional tectonic environment fluid is squeezed out between earthquakes, producing such phenomena as mud-volcanoes. The rapid recharge of the dilated rock mass following a reverse fault displacement may be accomplished in part by the inflow of water from deep-sourced hydrothermal fluids already saturated with dissolved ionic species. Mineralisation is therefore most likely in the interseismic period.

8. Seismohydraulics and petroleum migration

Over a significant proportion of the crust there are extensive sedimentary cover sequences of very low permeability, that prevent, at least in the short-term, any connection between basement fluid pressures and near-surface aquifers. If increased fluid-pressures cannot be relieved through flow to the surface, then fluid flow will be lateral, either within the fractured crust, or more often within some overlying aquifer towards the base of the sedimentary cover.

Following a normal fault displacement fluids will tend to migrate away from the vicinity of the fault. The volumes of displaced fluid can be predicted to be comparable to those found emerging at the surface where there is no impermeable cover (*i.e.* ca. 0.5 km^3 of fluid migrating laterally from a region 10 000 km^2, in area). The flux on the margins of such an area, entirely covered by an impermeable overburden would be more than 1000 m^3/m of perimeter: in a 10 m thick aquifer with a 10% dynamic porosity this would move the fluid 1 km. Following a reverse fault displacement fluid flow would be drawn towards the fault. Such pulsed episodes of seismohydraulic fluid flow are likely to have a significant impact on the migration of hydrocarbons, in particular when tectonic activity is resumed fairly late in the evolution of a sedimentary basin.

The flows created by the large-scale sudden changes in pore-pressures accompanying seismic strain-cycling can oppose the prevailing fluid flow regimes created by gravitational or thermally-driven fluid flows. Tectonics could therefore drive fluids into reservoirs that might otherwise be discounted as potential drilling targets. Employing coseismic and interseismic strain models it is possible to predict the magnitude and extent of these multiple episodes of fluid flow as part of basin analysis. Coseismic and interseismic strain changes may also explain the development of zones of over- and under-pressurisation within confined fluid reservoirs.

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