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Using surface characteristics to infer the permeability structure of an active fault zone

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Abstract

Studies of fault hydraulic architecture have shown faults to be spatially and temporally heterogeneous, with the potential to act as conduits, barriers, or a combination of conduit and barrier to subsurface fluid flow. Here we present a model for the distribution of permeability in an active normal fault based on a geostatistical analysis of 702 spring and ground temperature measurements. The temperatures were measured at the land surface along the trace of a normal fault that cross-cuts alluvium and weakly lithified sediments in the Alvord Basin of Oregon, USA. For flow parallel to the plane of the fault our analysis shows that the fault zone is dominated by broad areas of low to moderate permeability, interspersed with a number of spatially discrete, high-permeability flow paths. These observations are in agreement with conceptual models for faults in crystalline and well-lithified sedimentary rocks, but diverge from expectations for faults in alluvium and weakly lithified sediments. Our analysis demonstrates the potential for faults to develop hydraulic architectures intermediate between the idealized conceptual models currently available, and illustrates the need to test hypothesized behavior against observations in active systems.

Keywords: Fault hydrology; Geostatistics; Geothermal systems

1. Introduction

The hydrologic properties of faults are important to professionals in a wide variety of disciplines. Fault controls on fluid movement are important for ore genesis (e.g., Craw, 2001; Gow et al., 2002), petroleum migration (e.g., Antonellini and Aydin, 1994; Garden et al., 2001), fault slip and propagation (e.g., Sibson, 2000), and nuclear waste disposal (Wittwer et al., 1995). In spite of its widespread applications, fault hydraulic structure is difficult to characterize, and the role of faults in subsurface fluid flow is still poorly understood (Gudmundsson, 2000).

In general terms, faults comprise sets of hydraulic elements with permeabilities less than, greater than, or equal to the surrounding host rock. The overall hydraulic architecture of a particular fault is determined by the type and spatial distribution of the elements present, which are in turn a function of the type of host rock and deformation history. Field studies have shown that faults develop hydraulic elements as a function of host rock type; as a result, faults in different rock types are likely to demonstrate contrasting hydraulic architectures. For example, faults cutting crystalline rocks generally consist of two basic elements: a core of low-permeability gouge or cataclasite that accommodates the majority of displacement, flanked by damage zones that often demonstrate higher-permeability

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than the surrounding host rock, owing to the presence of deformation-related fracturing and subsidiary faulting (Caine et al., 1996; Evans et al., 1997). Alternatively, it has been shown that faulting in porous sandstones results in the formation of narrow (~1 mm) zones of cataclasis known as deformation bands, each of which accommodates a small offset (~1 to 10 times its own width), and slip planes that accommodate larger displacements (>1 m; Antonellini and Aydin, 1994, 1995; Shipton and Cowie, 2001; Shipton et al., 2002). The decrease in porosity that accompanies deformation banding results in a proportionate decrease in permeability; similarly, displacement across slip planes can substantially reduce permeability normal to the plane of slip, but may result in the formation of a high-permeability pathway for fluid flow parallel to the slip plane (Antonellini and Aydin, 1994, 1995). A third type of fault hydraulic architecture has been proposed for faults cutting poorly lithified sediments, in which a central core of clay or gouge is separated from the flanking damage zones by "mixed zones" of sediments displaced during slip. In this case, the damage zones consist entirely of deformation bands, and none of the fault architectural elements (core, mixed zones, damage zones) host open fractures. As a result, faults in poorly lithified sediments are hypothesized to reduce permeability both normal and parallel to the plane of slip (Rawling et al., 2001).

Regardless of the architectural units constituting a fault zone, investigations of fault hydrology rely on one or a combination of methods from a common set of tools for estimating hydraulic properties. Fault hydraulic conductivity may be measured in boreholes (e.g., Shipton et al., 2002), by permeameter testing of exhumed fault exposures (e.g., Rawling et al., 2001), or by laboratory testing of intact samples (e.g., Antonellini and Aydin, 1994; Evans et al., 1997; Kato et al., 2004). Other methods used to infer the hydraulic behavior of faults include thermal or spinner surveys in open boreholes (e.g., Barton et al., 1995), borehole geophysics (e.g., Kiguchi et al., 2001; Shipton et al., 2002), textural studies (e.g., Vermilye and Scholz, 1998, 1999; Steen and Andresen, 1999; Shipton and Cowie, 2001) and estimation of permeability based on fracture aperture distributions measured in the field (e.g., Matthäi et al., 1998; Jourde et al., 2002).

The data collection methods described above yield valuable data on fault hydraulic architecture, including the magnitude and spatial variability of fault properties, the juxtaposition of similar or contrasting units across the fault zone, and the effects of confining pressure on permeability. From a hydrogeologic perspective, however, these methods only provide a partial picture of system functioning, because information on flow-field boundary conditions, fracture conductivity and connectivity, and temporal evolution of hydraulic architecture may be lost, or described incompletely. As with all models of physical systems, conceptual models of fluid flow in faults must be tested by comparing predicted behaviors against observations of active systems. In general, however, observations of flow in active faults are limited to a relatively small region surrounding one or more boreholes that penetrate the fault zone under study (e.g., Barton et al., 1995; Kiguchi et al., 2001).

Here we present a geostatistical analysis of temperature measurements taken along the trace of the Borax Lake fault in the Alvord Basin of southeast Oregon, USA. Approximately 175 visible geothermal springs discharge over the ~1 km trace of the fault, providing a unique opportunity to examine fault hydraulic architecture in an active, fault-controlled flow system. We use a geostatistical analysis because it allows the development of a quantitative, probabilistic model of heterogeneity; a deterministic model of fault heterogeneity based on exhaustive temperature sampling in the Borax Lake fault is also available (Fairley and Hinds, 2004b), but high-resolution sampling of this type is generally only practical within a spatially restricted area. The analysis presented below offers an approach to evaluating fault hydrology at the site scale that compliments the methods described above, and provides a useful tool for testing conceptual models of fault hydraulic architecture.

2. Geological setting

The study area is located along the Borax Lake fault in the Alvord Basin of southeast Oregon, USA (Fig. 1). The Alvord Basin comprises a roughly north south trending graben, bounded on the west by Steens Mountain and the Pueblo Mountains, and on the east by the Trout Creek Mountains. The stratigraphic sequence of igneous rocks that form the crystalline basement has been described by several authors, including Fuller (1931), Williams and Compton (1953), and Minor et al. (1987). These units consist of over 2500 m of rhyolites, tuffs, and andesitic and basaltic lavas that include the Alvord Creek Formation, Pike Creek Volcanics, Steens Mountain Volcanics, and the Steens Mountain Basalt (Fuller, 1931; Williams and Compton, 1953). On the basis of unpublished lithologic logs from exploration wells drilled by the Anadarko Production Company, we estimate ~400 m of tuffs and ~200 m of siltstones, claystones, and other lithified sedimentary