Geostatistical evaluation of permeability in an active fault zone

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1. Introduction

[1] This study presents a description of permeability in an active fault zone located in the Great Basin extensional province. The fault hydraulic structure is inferred from geostatistical analysis of temperatures in 143 geothermal springs, located along a fault trace in the Alvord Basin of southeast Oregon. Based on this analysis, we conclude that the fault zone is predominately low permeability, interspersed with relatively few, spatially-discrete, high-permeability channels. The conceptual model presented is in agreement with the findings of other investigators, but extends their work by offering a representation of fault properties at the tens to hundreds of meters scale. INDEX TERMS: 1829 Hydrology: Groundwater hydrology; 8010 Structural Geology: Fractures and faults; 8135 Tectonophysics: Hydrothermal systems (8424); 8045 Structural Geology: Role of fluids; 5104 Physical Properties of Rocks: Fracture and flow. Citation: Fairley, J., J. Heffner, and J. Hinds, Geostatistical evaluation of permeability in an active fault zone, Geophys. Res. Lett., 30(18), 1962, doi:10.1029/2003GL018064, 2003.

2. Site Description

[5] The study area is located on the north end of Borax Lake, in the Pueblo Valley of southeast Oregon (Figure 1). Pueblo Valley is a part of the larger Alvord Basin, a north-trending graben typical of the northern Great Basin extensional area. The basin is bounded on the west by Steens Mountain and the Pueblo Mountains, and on the east by the Trout Creek Mountains. Faults in the Alvord Basin are generally steeply dipping, striking north to northeast, and cut sequences of Miocene-age volcanics, including basalts, rhyolites, and tuffs. Smaller faults located within the basin are often obscured by overlying basin-fill material consisting of poorly lithified alluvial and lacustrine sediments, intermixed with nonwelded ash tuffs; the existence of these faults is often inferred from geophysical surveys, or from direct observation of north to northeast trending scarp.

[6] Approximately 190 vents define a linear, north-northeast trending structure north of Borax Lake; perhaps fifty of these vents have been noted by previous investigators [Schneider and McFarland, 1995]. The distribution of the geothermal springs clearly delineates a left-stepping echelon fault system (Figure 1), and major ion chemistries indicate a common source for the geothermal springs, with no detectable mixing with shallow, cool groundwater. Studies have shown that faulting is active along the western boundary of the Alvord Basin [Hemphill-Haley, 1987], and anecdotal evidence suggests that the geothermal springs near Borax Lake are influenced by tectonic activity in the area [Williams and Compton, 1953; Cleary, 1976]. Together, these characteristics convincingly demonstrate that the fault
models, values of range and sill were assigned to each sub-model. The mathematical descriptions of temperature variability also incorporated a “nugget” parameter that quantifies variability at a scale below the minimum separation distance. For a more detailed discussion of variogram models and parameters, the reader is referred to Deutsch and Journel [1998]. In the present study, at least four mathematical models adequately described the observed variability (Table 1). These models were used to generate high-resolution (1 m²/pixel on a 30 x 400 m grid) temperature distribution fields, conditioned on the existing data, using a Sequential Gaussian Simulation algorithm [Deutsch and Journel, 1998]. A representative composite temperature field, based on gridblock averages of 100 conditional realizations of a combined Gaussian and Spherical model of spatial variability, is shown in Figure 2.

4. Results and Discussion

[8] The simulation shown in Figure 2 provides important insight into the distribution of fault properties in the study area. All temperature simulations displayed a pattern in which high temperature areas appeared in discrete, spatially-restricted areas. Cooler spring temperatures tended to cluster in broad, distributed bands along the trend of the fault. The model defaults to the mean spring temperature far from conditioning points; conceptually, however, these areas can be interpreted as representing average ground temperature. This pattern of spatial distribution was observed regardless of the mathematical model used to represent temperature variability. Similarly, composite images of the North and South Groups showed identical behavior, although the relatively fewer data available for the North Group resulted in a somewhat larger uncertainty range. The persistence of this trend, and its independence from the model chosen to represent the spatial variability of the data, give confidence that the analysis provides an accurate portrayal of the distribution of water temperatures within the fault.

[9] Additionally, the composite temperature fields provide a surrogate description of hydraulic conductivity along the fault at Borax Lake. Assuming the lateral boundary temperatures driving cooling are approximately equal for all flowpaths, and spatially constant temperature and hydraulic potential in the reservoir, the primary control on spring temperature at the land surface is the travel time from the reservoir to the discharge point. Since the primary factors affecting travel time can be lumped within the description of permeability, higher permeability channels should demon-

| Table 1. Variogram Models of Temperature Variability in 149 Geothermal Springs at the Borax Lake geothermal area in the Alvord Valley, Oregon |
|---------------------------------|------------------|------------------|-------------|
| Model Type                     | Nugget (in °C)   | Sill (in °C)     | Range [m]  |
| Gaussian                       | 100 (46%)        | 90.00 (41%)      | 8.00       |
| + Spherical                    | 118.84 (64%)     | 78.84 (36%)      | 30.00      |
| Exponential                    | 118.84 (54%)     | 78.84 (36%)      | 30.00      |
| Gaussian                       | 160 (73%)        | 58.84 (27%)      | 30.00      |
| Spherical                      | 140 (64%)        | 78.84 (36%)      | 30.00      |

Parameters are shown for four different models, including a nested Gaussian/Spherical model. Values for the nugget and sill parameters are given as absolute and percentage contribution to the model variance.

Figure 1. Location of the study area in Harney County, southeast Oregon. The study domain included 149 geothermal springs, extending approximately one kilometer north of Borax Lake. The left-stepping en echelon fault trace delineated by individual springs is clearly visible in the inset diagram.

provides local structural control on the flow of heat and groundwater.

3. Data Collection and Analysis

[7] During July, 2002, temperature measurements were taken from 149 springs in the Borax Lake area. Temperature measurements were made with a handheld digital thermometer, and spatially referenced using a handheld GPS unit. All measurements were taken during a single day, to minimize the impact of atmospheric temperature fluctuations on spring temperatures. The data obtained were divided into two groups, designated the North Group and the South Group, depending on their location relative to the fault step-over (Figure 1). Six outliers were excluded from the data set; four whose spatial separation was too small to be accurately resolved by handheld GPS, and two believed to derive from shallow interflow rather than being directly connected with the fault trend. The remaining data points totaled 55 and 88 in the North and South Groups, respectively. Spring temperatures were found to be quite variable; two springs, separated by a few meters, could show differences of up to 30°C. To obtain a description of temperature variability along the fault trace, the square of the difference in water temperature between pairs of springs was plotted as a function of their separation distance. Standard geostatistical models of spatial variability (e.g., Gaussian, Spherical, Exponential, etc.), or linear combinations of acceptable models, were fit to the resulting “variogram” using two parameters: the “range,” or separation distance beyond which observations are uncorrelated, and the “sill,” or maximum value attained by the variogram. In the case of linear combinations of

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strate proportionally greater discharge rates and temperatures than lower permeability channels. Spring temperatures and fault permeability therefore share identical spatial correlation structures, and the simulated temperatures in Figure 2 are directly proportional to fault permeability.

The inferred permeability structure of the present study is in good qualitative agreement with other investigations of flow in faults and highly heterogeneous porous media. The core of a typical fault consists of fault gouge and breccia, materials that are much lower in permeability than the surrounding protolith [Caine et al., 1996; Evans et al., 1997], and the permeability of this material is further reduced by mineral precipitation from geothermal fluids. Systems in which flowpath permeability is maintained by fault slip develop highly anisotropic structure, with long correlation length scales parallel to the direction of fault slip [Curewitz and Karson, 1997]. Normal to the direction of slip correlation lengths are short, and isotopicgeochemistry studies support a conceptual model of discrete, highly conductive channels separated by extensive zones of low permeability [Fabryka-Martin et al., 1996]. Numerical studies have shown that similar “fast flow pathways” develop spontaneously in heterogeneous media with anisotropic correlation structure [Moreno and Tsang, 1991], and studies of faults exposed at the surface support such a hydraulic structure at depth [e.g., Doughty, 2003].

5. Conclusions

Although groundwater modelers often represent faults as planar features of finite thickness and uniform hydraulic properties, it is generally accepted that the permeability structure of faults is complex, and variable in both space and time [Curewitz and Karson, 1997; Evans et al., 1997]. Unfortunately, there is little field data available to guide groundwater modelers in developing realistic property sets for fault domains at a scale appropriate for numerical flow modeling, although recent investigations have begun to correct this situation [e.g., Jourde et al., 2002]. This study provides a two-dimensional (parallel to land surface) description of fault permeability in an active fault zone, based on geostatistical analysis of temperature in 143 geothermal springs in the Alvord Basin. We conclude that the hydraulic structure of the fault zone is dominated by broad areas of low-permeability, interspersed with relatively few, spatially-discrete, high permeability channels. The conceptual model presented is in agreement with the findings of other investigators [Caine et al., 1996; Curewitz and Karson, 1997; Gudmundsson, 2000; Jourde et al., 2002] and numerical studies of flow in heterogeneous media [Moreno and Tsang, 1991], but extends their work by offering a representation of fault properties at the tens to hundreds of meters scale. Future studies at the Borax Lake site using surrogate parameters to infer fault properties are expected to provide a more detailed picture of the relationship between fault mechanics and groundwater hydrology.

Figure 2. Borax Lake South Group spring locations (on left) and simulated temperature field (center). Simulated temperatures represent block-by-block averages of 100 conditional realizations using Sequential Gaussian Simulation and a combined Spherical and Gaussian model of spatial variability. The simulation background temperature is the average spring temperature, rather than the ground temperature.

References


