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Structural Fabric Of The Geysers

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ABSTRACT

A consistent means for comparing regional fracturing with that in The Geysers geothermal system was achieved using Thematic Mapper (TM) images. Linear features were defined by line traces that were bounded by disappearance or changes in strike, and the data was analyzed to document both trace length and strike. Using a Geographic Information System (GIS) the fracture trends are analyzed with respect to both the production zone and the Clear lake volcanic province as defined by heat flow. Statistical analysis of the data shows that the fracture pattern over the production zone is distinct from the regional fracture pattern. It is often stated that the principal strike-slip faults that bound the geothermal system are parallel the San Andreas fault system; however, their orientation is 10° to 30° more westerly. In addition, the northeast Cobb Creek and east-west Anderson Creek trends are strongly represented over the geothermal system. A major zone of fracturing extends from Pt. Arena to the east and passes through The Geysers. We propose that this zone reflects the location of the Mendocino Fracture Zone at approximately 3 Ma. The Geysers hydrothermal-magmatic system appears to be controlled by this family of faults and is located in the area of maximum flexure. Dextral strike-slip motion across this flexure resulted in northwest-southeast extension to the north and compression to the south. The orientation of the extension is consistent with the dominant fabric in The Geysers, the formation of the Clear Lake basin and the extensional zone of Stanley et al. (1997).

Introduction

Field mapping has been carried out over the Geysers geothermal field and surrounding areas for many years. However, rock exposure is often poor and access is often difficult because of steep terrain and dense brush as well as private property restrictions. Initial interpretation of satellite images showed that features mapped by previous workers could be identified. In addition, features could be seen that had not been discussed by other investigators, including our recognition of the northeast-trending Cobb Creek linear (Nielson and Nash, 1996; Hulen and Nielson, 1996).

A review of the literature on the relationship between fracturing and permeability controls in The Geysers field shows a wide variety of opinions that are outlined by Nielson and Hulen (in preparation). That review suggests that permeability is principally controlled by steeply-dipping faults and fractures related to the neo-tectonic setting.

A number of authors have suggested that formation of the Clear Lake volcanic province, now understood to include the Geysers felsite (Hulen and Nielson, 1996), was related either to the opening of a “slab window” (Dickinson and Snyder, 1979; Lachenbruch and Sass, 1980; Stanley and Rodriguez, 1995) or to the southwestward movement of the North American plate over a mantle plume (Hearn et al., 1981). The slab window is large and does not explain the unique location of the felsite and Clear Lake volcanic province. The northward migration of the Mendocino Fracture Zone (MFZ) is believed to be responsible for the northwest-ward decrease in age of volcanic centers in northern California (Dickinson and Snyder, 1979). Using estimates of the rate of northwest-ward progression of the MFZ, McLaughlin (1981) suggested that the MFZ was located at the approximate latitude of the Geysers at about 3 Ma. He also suggests that the presence of the MFZ was responsible for the formation of extensional basins such as Clear Lake basin.

The structural framework of The Geysers region could be interpreted by looking at studies of strike-slip faulting in areas

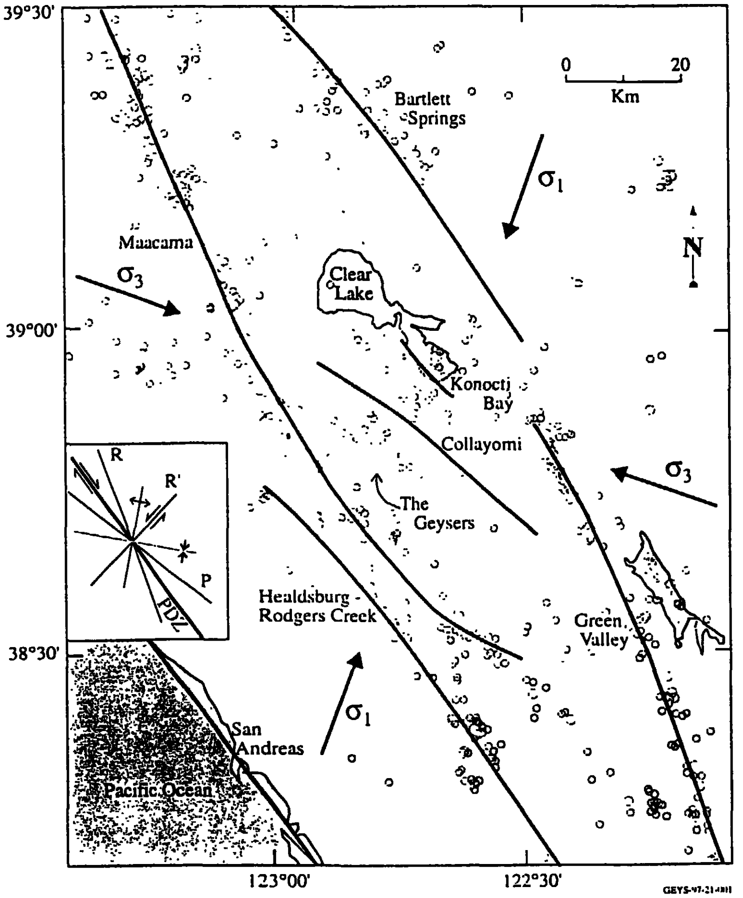

Figure 1. Seismic events, mapped faults and stress orientation in the vicinity of The Geysers geothermal field (Eberhart-Phillips, 1988). Insert shows geometric relationships between structures (Sylvester, 1988).

where the complexity of the geothermal system is not present (Aydin and Page, 1984; Sylvester, 1988). These authors present evidence that the geometry of strike-slip and associated faulting along the San Andreas system is compatible with a simple shear model; however, the similarities of fracture orientation with model studies are not perfect. The orientation of fractures that are observed in experiments are shown in the insert of Figure 1. The insert shows the Principal Displacement zone (PDZ) oriented N36°W which is the general orientation of the boundary between the Pacific and North American plates (Aydin and Page, 1984). R and R' are synthetic (dextral) and antithetic (sinistral) faults respectively. P faults are known as strike-slip shears, but they may have a component of reverse faulting (Aydin and Page, 1984). These authors compiled maps of the San Francisco Bay region, and found that many of the minor faults and folds mapped between the strike-slip faults have orientations similar to P fractures. Theoretically, compressional structures will be oriented about N80°W, and extensional structures will be oriented normal to this at N10°E.

Within The Geysers geothermal field, a number of publications have made reference to the reservoir controls exhibited by the Mercuryville and Big Sulphur Creek faults and parallel zones (McLaughlin, 1981; Evans et al., 1995). In the northern part of The Geysers field, these faults are oriented N55° to 70°W. The Geysers felsite is highly elongated along a N55°W to N60°W trend (Hulen and Nielson, 1996). The contoured depth to first steam entry shows a similar elongation oriented about N55°W to N60°W (Thomas et al., 1981; Unocal et al., 1992). These observations, compared with regional seismic maps (Figure 1), suggest that the fracture trends that are present in The Geysers field are oriented more westerly than the regional faults that parallel the San Andreas system (Oppenheimer, 1986; Eberhardt-Phillips, 1988). One possible conclusion is that these orientations are P fractures. Alternatively, Stanley and Rodriguez (1995) noted the similarity of the felsite orientation with thrust faults mapped by McLaughlin (1981) and proposed that the felsite was injected along these thrusts following the passage of the Mendocino Triple Junction.

A number of studies have recently drawn attention to the presence and significance of northeast trending fractures in The Geysers-Clear Lake region. Stanley and Rodriguez (1995) and Stanley et al. (1997) have shown that geophysical interpretations indicate a northeast trending zone of extension located between The Geysers production area and the southern end of Clear Lake. Walters (1996) has reviewed a large amount of literature for the area and demonstrates the importance of the northeast structural fabric in the control of mineralization and volcanism. Hulen and Nielson (1996) discussed the northeast trending Cobb Creek zone that falls within the extensional zone of Stanley et al. (1997).

In geothermal systems in the Imperial Valley, that are also associated with strike-slip faulting, a strong case has been made for the importance of step-overs between strike-slip zones in controlling permeability in wells (Elders et al., 1972; Halfman et al., 1984). While in other geothermal systems of the strike-slip association, the orientation of structures is permissive for such an interpretation (Alvis-Isidro et al., 1993). The present study was undertaken to evaluate the structural controls on the development of permeability in The Geysers with respect to the regional tectonics.

Method

Landsat thematic Mapper (TM) imagery offers several advantages in regional and local fracture analysis including (1) large areal coverage per individual scene (~185 km x 185 km), (2) relatively high spatial resolution (30 m x 30 m/pixel), (3) nearly world-wide coverage, (4) low cost, and (5) six visible/near infrared/short-wave infrared bands which can be used in various combinations on the computer screen to emphasize different features. For this study a virtually cloud-free TM image was used. Prior to fracture analysis, the image was resampled to UTM coordinates using the nearest neighbor technique, to allow the registration of other data, such as digital elevation models (DEMs), to the image in a geographic information (GIS) environment. Other preprocessing included the use of a histogram adjustment (Jensen, 1986) to help correct atmospheric effects on the visible and near infrared TM bands. No further preprocessing was done as the quality of the image was excellent and amenable to fracture analysis.

A number of spatial enhancement techniques are available for fracture analysis including several standard convolution filtering techniques and automated methods (Vincent, 1997, Karnieli et al., 1993). However, all of these methods are expensive in computer time and storage space especially when working on large data sets such as entire TM scenes. Another drawback is that geomorphic features are difficult to discern on most spatially enhanced images increasing the chance of mapping error. Although the problems mentioned above can be overcome, the authors have found that good results can be obtained from analyzing TM data with minimal preprocessing and displaying the image on the computer monitor as a false-color composite. It was found for this study that a false-color composite of TM bands 5, 7, 1, assigned to the red, green, and blue color guns respectively, gave good contrast over the area of interest. The image was analyzed visually at different scales to determine the existence of fractures and faults. This type of analysis oversamples steeply-dipping faults and fractures; however, steeply dipping features predominate in a strike-slip tectonic environment.

The fractures and faults were mapped as lines, in a vector GIS format, directly from the TM false-color composite. The GIS graphic-user-interface was enhanced with object-oriented utility software that allowed the extraction of the start- and end-points of the fracture/fault segments, the segment length, the strike azimuth and quadrant, and the concatenation of this data into a single file for addition to the GIS as attributes or to import into other software for specific processing.

The GIS environment allowed the use of heat-flow unit contours, discussed below, to constrain areas of interest for their specific analysis. The GIS will also act as a permanent archive for the data generated and utilized in this study. Metadata, or descriptive files, were also included in the GIS to act as a guide for future users unfamiliar with the data. This paper and related graphics will also be scanned and included in the GIS for future digital retrieval.

Fracture Analysis

A data base was compiled from the fracture orientations measured on the TM images. It was clear during the definition of the linear features on the workstation that the scale of the image was often responsible for the features that could be defined. As was expected, more features were visible on the images that covered smaller areas than were visible on the larger-scale images. However, it was also the case that major regional features were identifiable on the larger images when no coherent pattern could be distinguished on the more detailed images. In order to evaluate the effect of scale on the image analysis, the satellite images were analyzed at three different scales. These were 1:1,400,000, 1:1,000,000 and 1:640,000. In addition, another analysis was done at a scale of 1:480,000 and smaller over the geothermal field and adjacent areas including the Clear Lake basin. In this fourth analysis, the scale was varied down to the limit of resolution of the images. The data is displayed on frequency rose diagrams showing the number of features of an orientation regardless of length. In general, frequency diagrams of fault length show similar orientations to the rose diagrams shown here.

The orientations of fractures for the region measured at a scale of 1:1,400,000 are shown in Figure 2a. There is a maximum concentration of fracturing oriented N25°W to N45°W, which is generally consistent with the San Andreas and parallel faults. A plot of the length of the traces versus azimuth shows that the longest features are also associated with this trend. A secondary concentration of frequency and length occurs between N70° to 75°W. We feel that this is a very significant trend, and it will be discussed in greater detail below. Figure 2b shows the orientations of features at a scale of 1:1,000,000. The results are similar to those discussed above with a concentration of fractures oriented N30° to 45°W. The N70° to 75°W trend is also present, and it appears more significant than it did at the larger scale. The results of the analysis at a scale of

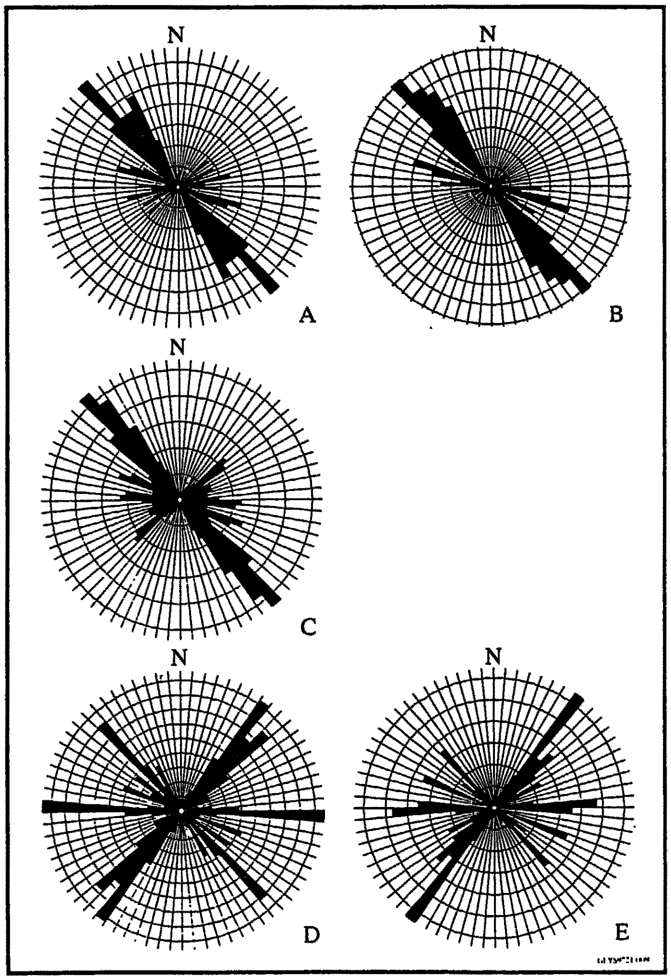

Figure 2. Rose diagrams showing the frequency of linears mapped on TM images in the vicinity of the Geysers. A. regional data at a scale of 1:1,400,000, n=98, 2% interval. B. Regional data at a scale of 1:1,000,000, n=82, 2% interval. C. Regional data at a scale of 1:640,000, n=241, 2% interval. D. Local data at a scale of 1:480,000 and less within the 4 hfu contour, n=259, 1% interval. E. Local data at a scale of 1:480,000 and less within the 12 hfu contour, n=85, 2% interval.

1:640,000 (Figure 2c) is similar to the 1:1,000,000 with an increase in the frequency of N45° to 55°E faulting. This is the approximate trend of the Cobb Creek lineament and the extensional zone.

In order to determine the structural fabric of The Geysers field and vicinity two methods were employed. First linear elements were identified on the TM images at a scale of 1:480,000 and smaller. The workstation was used to zoom in on the image to the limit of its resolution, and linear features were compiled at the scale where they could be clearly seen. Second, in order to define the outlines of the producing area, heat flow contours (Walters, 1996) were mapped into a GIS system. The fracture orientations were analyzed with respect to the area encompassed by the 12 and 4 heat flow unit (hfu) contours (Figure 3).

The 4 hfu contour surrounds the steam reservoir and areas to the northeast past the southern end of Clear Lake and defines accurately the distribution of the Clear Lake volcanics (Figure 3). The fractures present in the area encircled by the 4 hfu contour are shown in Figure 2d. This figure shows the predominance of the northeast fracture trend that is associated with the Cobb Creek structure (Hulen and Nielson, 1996) and the northeast extensional zone of Stanley and Rodriguez (1995) and Stanley et al. (1997). A trend of secondary importance strikes approximately east-west. Another prominent trend is N40-45°W.

The 12 hfu contour is a proxy for the outline of the producing zone. The fractures identified within this area are shown in Figure 2e. Here again, northeast fracturing, parallel the Cobb Creek structure is prominent. A trend of secondary frequency is oriented approximately east-west. Other important orientations are N40°-45°W, and N65°-70°W.

Regional Fault Distribution

Analysis of the 1:1,400,000 and 1:1,000,000 scale TM images identified several unique regional features that are important and suggest a new model for structural controls on The Geysers geothermal system. A series of fractures, with a nearly east-west to southwest arcuate trend, can be mapped from just north of Pt. Arena on the coast into The Geysers field (Figure 3). This is a trend that was identified, but not discussed, on the regional image interpretation of Rich and Steele (1974). The southern boundary of this trend is defined by the Mercuryville and Big Sulphur Creek faults in the vicinity of The Geysers. The geometry of this regional series of faults is remarkably similar to the modern MFZ as shown in Stanley et al. (1997). The Geysers geothermal system is located in the area of greatest curvature of this zone, and it is largely bounded on the south by the Big Sulphur Creek fault (Figure 4).

Other similarities with the present configuration of the MFZ include the faults oriented to the northeast, sedimentary basins developed through extension and complex interactions of thrust, strike-slip and normal faulting (Kelsey and Carver, 1988). The present zone of seismicity immediately south of the Gorda slab has a width of 5-10 km (Castillo and Ellsworth, 1993) which is similar to the width of the Pt. Arena - Geysers structural trend (Fig. 3). Also, the Pt. Arena - Geysers trend is probably responsible for the off-trend earthquakes with hypocenter depths restricted to the upper 10 km defined by Castillo and Ellsworth (1993).

Figure 4 shows a more detailed map of fracturing in the area of the geothermal field. The 12 hfu contour is closely aligned with the Big Sulphur Creek fault, which largely marks the southern extent of geothermal production. Note that the BSC fault has distinct change in strike from N70°W in the western part of the geothermal area to N45°W in the east. This change occurs where the Cobb Creek linear intersects BSC. We infer that the BSC fault was the southern extent of dextral strike-slip motion above the MFZ. The curvature of the MFZ to the south is reflected in the bends of the BSC fault, and results in tensional features to the northeast of the BSC fault and compression to the southwest (Figure 5). The results are consistent with the observed and calculated stress distribution across the zone of maximum curvature of the present MFZ (Spence, 1989). The extension to the northeast is consistent with a normal fault interpretation for the Cobb Creek structure and the northeast extensional zone of Stanley et al. (1997).

Connecting the point of maximum curvature of the BSC fault with the point of maximum curvature of the present MFZ (Stanley et al., 1997) is also a test of the model we are presenting here. Magmatic activity on The Geysers probably began about 3 Ma (Hulen and Nielson, 1996; McLaughlin, 1981) as did the formation of the Clear Lake basin as inferred from the age of deposition of the Cashe Formation (Rymer, 1981). Thus, we will assume that the MFZ was present at 3 Ma. Connecting the points of maximum curvature indicates that the MFZ has migrated 171 km at an azimuth of N34°W. This yields a velocity of 57mm/a. The azimuth is consistent with the overall boundary between the North American and Pacific plates of N36°W (Aydin and Page, 1988). The calculated velocity is also consistent with measured migration rates (Castillo and Ellsworth, 1993; Spence, 1989).

A zone of similar orientation, although less well defined, is present to the south of the Pt. Arena - Geysers zone and trends through the city of Healdsburg. Another zone trends generally eastward from the mouth of the Navarro River through Lake Mendocino. A fourth zone starts along the coast at Fort Bragg and trends inland to the east to east-northeast. In other words, these zones are not pervasive in northern California but are found in distinct areas. The Point Arena - Geysers trend is the widest and best defined of those observed.

Since the development of structures related to the presence of the MFZ, the stress orientations have changed (Fig. 5). The present stress orientation will tend to close the faults of the Pt. Arena-Geysers zone while opening or shearing the northeast faults of the Cobb Creek trend and extensional zone of Stanley et al. (1997).

Conclusions

The structural history of The Geysers field is complex, resulting from the superposition of Cretaceous subduction and

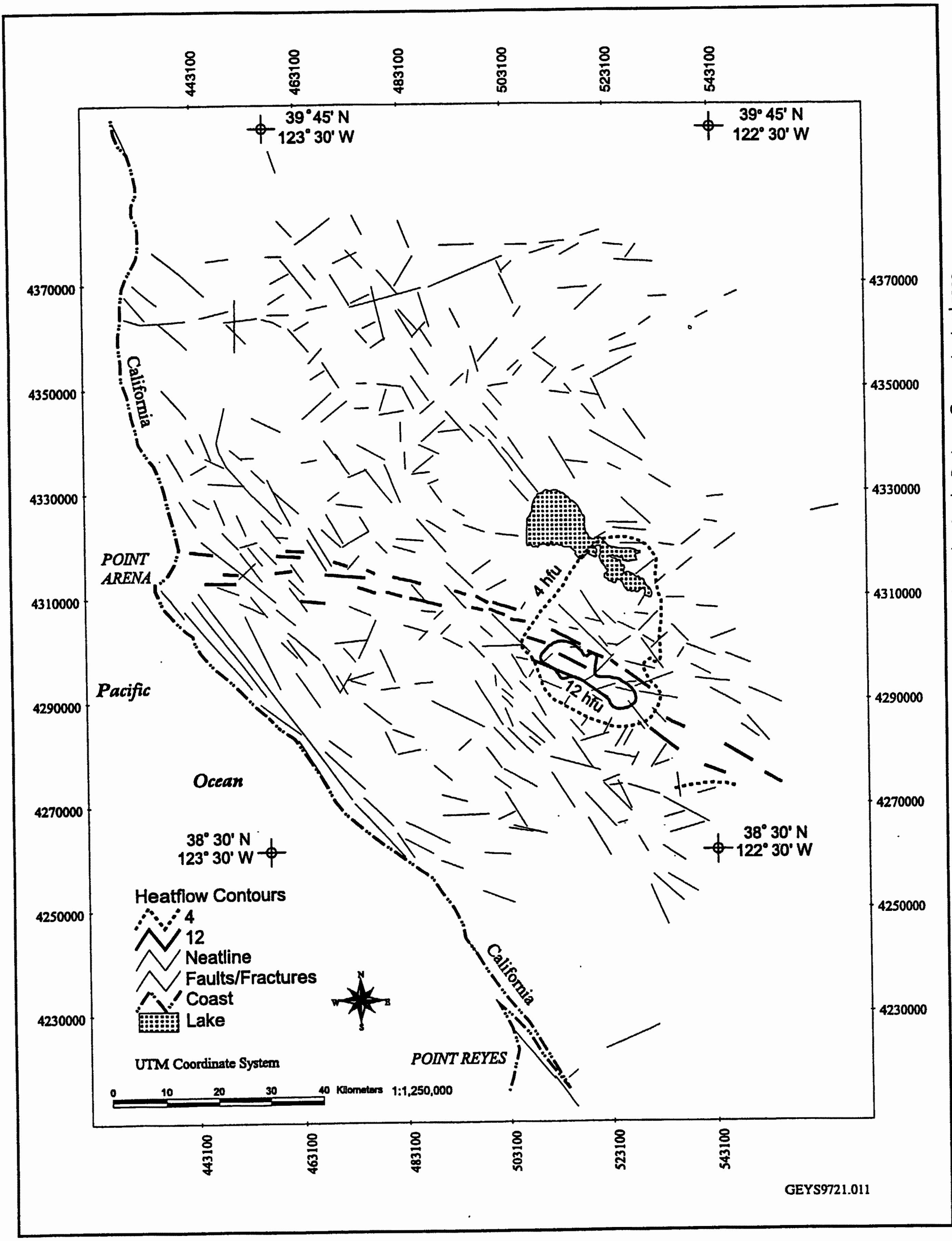

Figure 3. Regional linear elements for northern California showing the Pt. Arena-Geysers structural zone.

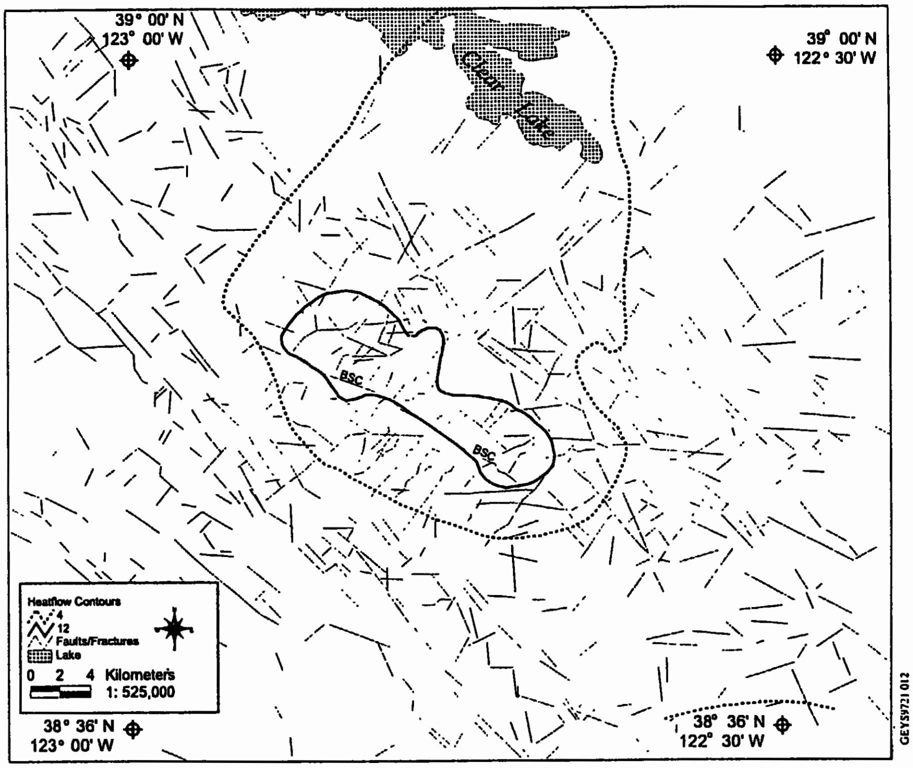

Figure 4. Fracture orientations for The Geysers area. Contours of 4 and 12 hfu (Walters, 1996) are added for reference. BSC is the Big Sulphur Creek fault.

thrusting, deformation related to the Mendocino Fracture Zone, deformation resulting from intrusion of the felsite and strike-slip faulting related to the San Andreas system. Although the fracture trends can be interpreted in terms of a simple shear model, we prefer an interpretation that involves changing deformational style.

The analysis of structural trends with respect to heat flow demonstrates that the structural trends within the geothermal field are statistically different from the regional fault trends. Over The Geysers system, there is a predominance of faults oriented N35° to 40°E, coincident with and parallel to the Cobb Creek linear, as well as the broader extensional zone of Stanley et al. (1997). This northeast trend is reflected in reservoir data such as pressure declines and tracer flow paths (Stanley et al., 1997; Nielson and Hulen, in preparation). This trend is also prominently represented in mining properties in the area (Walters, 1996).

Analysis of satellite imagery shows that the southern boundary fault of the Geysers geothermal system, located along Big Sulphur Creek, is part of an arcuate zone of faults that can be followed to the Pt. Arena area. The geometry of this zone is similar to that exhibited by the MFZ landward of the Mendocino Triple Junction. The Geysers system is located in a zone of maximum curvature of these faults. The presence of the Clear Lake basin, Clear Lake volcanic field and northeast trending Cobb Creek linear (Hulen and Nielson, 1996) and northeast trending extensional zone (Stanley and Rodriguez, 1995) show other similarities with the present configuration of the MFZ as it bends to join the San Andreas system of faults.

The passage of the MFZ left a deep-seated flaw in the crust that continues to be seismically active and serve as a conduit for magmas. The unique nature of the Pt Arena - Geysers zone suggests either that the MFZ was resident at this location for an unusually long period of time or that the MFZ was particularly well coupled mechanically to the North American plate. We also believe that fracture permeability in the reservoir has been influenced by emplacement of the Felsite. Subsequent to the passage of the MFZ, The Geysers has been under the influence of the San Andreas fault system. The model for the location of The Geysers proposed here does explain the location and much of the structural character of this unique hydrothermal-magmatic system.

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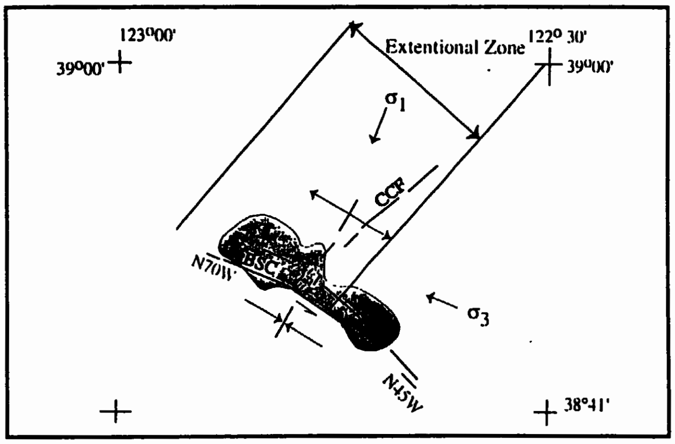

Figure 5. Structural interpretation of the Geysers area showing the Big Sulphur Creek fault (BSC) and the Cobb Creek fault (CCF); The Geysers production zone is outlined by the 12 hfu contour. The extensional zone is from Stanley et al. (1997), and s1 and s3 represent the present orientation of the greatest and least principal stresses (Eberhart-Phillips, 1988). Convergent and divergent arrows show the compressive and extensional forces associated with dextral movement across the flexure in the paleo-Mendocino Fracture Zone.

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