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FRACTURE SYSTEM IN THE KAKKONDA AND OYASU GEOTHERMAL FIELDS, NORTHEASTERN HONSHU, JAPAN

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ABSTRACT

Hydrothermal veins and minor faults associated with geothermal activities in the Kakkonda and Oyasu geothermal fields, northeastern Honshu, Japan, are investigated to clarify the developmental process of fractures and the relationship between fracture systems and path of geothermal water. Many of hydrothermal veins are characterized by the combined structure of shear fractures and tensile fractures, that is, jog structure. This structure is used to determine the sense of shear along the shear fracture and to reconstruct the associated stress field. In the Kakkonda geothermal field, these fractures are classified into four systems on the basis of their dominant orientation and sense of shear, which are NNW-SSE to NW-SE strike and moderate dip system (NW-moderate dip system), NW-SE strike and steep dip system (NW-steep dip system), NE-SW to E-W strike and steep dip system (NE to E-W system), and horizontal system. The NE to E-W system consists of veins and faults with lateral and normal displacement, both of which were formed by the stress field with horizontal minimum principal axis trending NNE-SSW to ENE-WSW, though fractures belonging to the NW-moderate dip and NW-steep dip systems were also formed by lateral or normal fault type stress field. The present paths of geothermal water are controlled by the NE to E-W and horizontal systems. Fractures developed in the Oyasu geothermal field are also classified into four systems, which are NNW-SSE through N-S to NNE-SSW strike and steep dip system (N-S system), N-W strike and steep dip system (NW system), NNE-SSW through E-W to WNW-ESE strike and steep dip system (NE to E-W system), and horizontal system. Lateral slip type fractures are dominant in the former three systems. The NE to E-W system and horizontal system in this field are considered to play an important role on the present paths of geothermal water. The geothermal reservoir in both fields are characterized by lateral slip type fractures accompanied with horizontal fractures, though the regional stress field in northeastern Honshu is believed to be a reverse fault type.

1. INTRODUCTION

Fractures, in which geothermal fluid flows, have been considered to form geothermal reservoir in some fields. These fractures are frequently filled with precipitated minerals from geothermal water to be hydrothermal veins. The veins are characterized by their orientation, geometry, sense of displacement and/or mineral fillings. This study concentrates on the population systematics of veins and the reconstruction of associated stress field in the Kakkonda and Oyasu geothermal field, northeast Honshu, Japan. The development of hydrothermal fracture zone, that is, geothermal reservoir is also discussed.

2. FRACTURE ANALYSIS

The geometrical feature of fractures, such as conjugate relationship of shear fractures or jog structure, were frequently observed both in the Kakkonda and Oyasu geothermal field. Sense of displacement and associated stress field can be deduced from these structures. In the case of conjugate relationship of shear fractures, it is assumed that intermediate principal axis is parallel to the intersection of shear fractures, and that maximum principal stress axis is perpendicular to the intermediate axis and is on a plane bisecting the acute angle between shear fractures. The jog structure consists of two kind of fractures; a shear component dominant fracture and a tensional component dominant fracture (Fig. 1). Though most of tensional component dominant fractures are filled with such precipitated minerals from geothermal fluid as quartz , calcite, zeolite and so on, there is sometime no fillings in shear component dominant fractures. If a tensional component dominant fracture is assumed to be perpendicular to minimum principal stress axis and the intersection of both fractures is parallel to intermediate axis, then principal axes' orientation of the associate stress field with the jog structure and the sense of displacement along the shear component dominant fracture can be determined.

In the field survey, orientation, width, displacement and cross-cut relation to another fracture, as well as the geometrical feature mentioned above, are described in detail for each fracture. At this time, fractures are subdivided into four types based on their fillings; hydrothermal vein filled with such white minerals as quartz, calcite, and/or zeolite (named as white vein), fracture with euhedral pyrite grains and without white colored minerals (pyrite vein), fracture only having gouge or breccia in it and displacing offset markers (fault), and fracture displaying no displacement with no fillings (joint). Joints will be discussed no more in the following section, because they are thought to be little relevant to geothermal activity.

3. KAKKONDA GEOTHERMAL FIELD

The geology in the Kakkonda geothermal field consists of pre-Tertiary formation, Miocene Obonai formation, Kunimitoge formation, Takinoue-onsen formation, Osuke formation, Yamatsuda formation, Pliocene Kitashirasawa formation, Minamishirasawa formation, Plio-Pleistocene Tamagawa Welded Tuffs, Pleistocene Matsukawa Andesite and Iwate Volcanic Products, in ascending order, and some intrusions including Quaternary Kakkonda Granite (Sato, 1982; Koshiya *et al.*, 1993; Doi *et al.*, 1995). Formations above the Takinoue-onsen formation are exposed in a ground surface. Formations form Takinoue-onsen formation to Kitashirasawa formation and Tamagawa Welded Tuffs are mainly composed of volcaniclastic rocks. Minamishirasawa formation consists of dacitic lava and lava-dome. Hydrothermal veins are well developed in these formations, though they are rarely observed in Matsukawa Andesite and Iwate Volcanic Products.

Dominant orientations of white veins, faults and pyrite veins in the whole field are NE-SW to E-W in strike and steep in dip (NE to E-W system), and N-S to NW-SE in strike and shallow in dip (NW moderate dip system) (Fig. 2). Faults and pyrite veins also trend NW-SE and dip steeply (NW steep dip system). The NW steep dip system of white veins are developed in many of subarea of the field (Koshiya *et al.*, 1993). Therefore, NE to E-W system, NW moderate dip system and NW steep dip system can be observed for all types of fracture, that is, white veins, faults and pyrite veins, though orientation distribution frequency is different for fracture types and subareas. Moreover for white veins, very low angle dipping fractures (horizontal system), which dip less than 30 degree, are distributed in the central area of the field.

Most of shear fractures belonging to all the systems except the horizontal system show lateral slip and/or normal slip in sense of displacement (Fig. 3). Inferred stress fields for the NW moderate dip system and the NW steep dip system based on geometry of each set of fractures are lateral fault type (F2L) and normal fault type (F2N) with horizontal minimum principal stress axis trending range from NNE-SSW to ENE-WSW (Fig. 4). For the NE to E-W system, it is estimated that stress field for each set of fractures belonging to this system is lateral fault type (F3L) or normal fault type (F3N) with horizontal principal stress axis trending range from NNE-SSW to ENE-WSW, which is almost perpendicular to the previous one, though the lateral fault type stress field is predominant.

Preliminary analysis by inversion technique of Etchecopar et al. (1981) and Gephart and Forsyth (1984) for the NE to E-W system shows that the stress field is lateral fault type with minimum principal axis trending NNW-SSE, and that stress ratio R is very high, where R is the ratio of $\sigma_1 - \sigma_2$ to $\sigma_1 - \sigma_3$, and σ_1, σ_2 and σ_3 are principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$).

The NE to E-W system is inferred to be younger than the both NW systems from cross-cut or displaced relationship between fractures. It was observed in the field that 83 percent of fractures belonging to the horizontal system cross-cut fractures of the NE to E-W system and 17 percent are cross-cut by the NE to E-W system fracture. However, focal mechanisms due to microearthquakes observed in the Kakkonda field show lateral fault type stress field with p-axis of ENE-WSW (Kaneshima *et al.*, 1988). And the propagation of fracture during hydraulic fracturing is NE-SW to E-W in orientation (Doi *et al.*, 1988a). Judging from these observation, it is strongly suggested that the NE to E-W system is latest. Therefore, it is concluded that the NE to E-W system and the horizontal system are synchronously formed. The K-Ar dating indicates 0.2 Ma for fractures of the NE to E-W system. The associated stress field with the system has possibly continued to the present time.

The distribution of these fractures concentrates on the zonal area trending NW-SE along River Kakkonda, and this area almost coincides with distribution area of neutral to alkaline altered minerals (Koshiya et al., 1996). Moreover, this zonal area is concordant with subsurface permeable zone (Doi *et al.*, 1988b). Therefore it is concluded that the zonal area, namely fractured zone, delineates the geothermal reservoir of the Kakkonda geothermal area, and that its constituent fractures belong to the NE to E-W and horizontal systems.

4. OYASU GEOTHERMAL FIELD

The Oyasu geothermal field is in the Tertiary Sanzugawa caldera. The geology of the field consists of pre-Tertiary granites and green schist, Miocene Doroyu formation, Mio-Pliocene Minasegawa formation and Sanzugawa formation, Pliocene Kabutoyama formation and Takamatsu-dake volcanics, and intrusions. Minasegawa formation comprises dacitic pyroclastics regarded as syn-caldera volcanic deposits, and Sanzugawa formation is lacastrine deposits as caldera fillings. Hydrothermal veins are well developed in these two formations.

Fractures, especially white veins, developed in the field are divided into four systems, namely NE to E-W system, horizontal system, N-S system and NW system in order of the number of measurements. The NE to E-W system consists of steeply dipping veins trending range from

NNE-SSW through E-W to WNW-ESE, the N-S system steeply dipping veins trending range from NNW-SSE through N-S to NNE-SSW, the NW system steeply dipping veins trending NW-SE, and the horizontal system veins dipping very low angle (Fig.5).

White veins of these steeply dipping systems are mainly composed of tensional fractures and lateral slip type shear fractures, though a small part of shear fractures have normal or reverse slip component (Fig. 6). Inferred Stress field for each set of fractures belonging to the NE to E-W system are lateral fault type (S1L) with horizontal minimum principal axis trending range from NW-SE to N-S and horizontal maximum axis trending range from NE-SW to E-W, normal fault type (S1N) with minimum axis trending the same direction as in the lateral slip type, and reverse fault type (S1R) with maximum axis trending the same direction as in the lateral slip type (Fig. 7). Stress fields due to sets of fractures of the N-S system similarly includes lateral fault type (S2L), normal fault type (S2N) and reverse fault type (S2R), but their maximum or minimum principal axis is approximately perpendicular to those for the NE to E-W system. Stress field inferred from sets of fractures of the NW system comprises lateral fault type (S3L) and normal fault type (S3N) with minimum principal axis trending range from N-S to NE-SW, which is oblique to that either in the NE to E-W system or in the N-S system.

Among these three steeply dipping systems, the NE to E-W system is predominant, and the horizontal system is more dominant than the N-S system and the NW system. Internal structure within hydrothermal veins, e.g. zonal structure of filling minerals, of the NE to E-W system is observed to continue to that of horizontal system in several places. This evidence means that the NE to E-W system was formed synchronously to the horizontal system. ESR ages of quartz in the horizontal hydrothermal veins show ranging from 13 to 18ka (Mizugaki et al., 1996). This strongly suggests that the horizontal system, and also the NE to E-W system are formed in the latest stage up to recent age.

The fractures of all the systems are mainly distributed in the zone which trends NW-SE along River Minase in the northern area, in turn, NE-SW in the southern area (Fig. 8). Especially the distribution of the fractures of the horizontal system concentrates on the central part of the zone. This zone is possibly bounded by the major fault and concordant with the horst. Similarly in the Kakkonda geothermal field, dominant orientation of fractures, which is characterized by the NE to E-W system and the horizontal system, is different to the zone.

5. SUMMARY

The predominant and latest fracture systems both in the Kakkonda and Oyasu geothermal field were formed by the lateral fault type stress field; F3L in Kakkonda and S1L in Oyasu, though the regional stress field in northeastern Honshu is believed to be a reverse fault type with E-W trending compressional axis. And the systems ,which is the NE to E-W system both in the fields, are evidently accompanied with the horizontal system. The mechanism that lateral slip type fracture and horizontal fracture are synchronously formed in the same stage has not yet established, though the mechanism of synchronous formation of reverse fault type fracture and horizontal fracture was reported by Sibson (1990), who considered such a horizontal fracture as a tensile fracture by referring to fault-valve behaviour. Preliminary stress inversion analysis in the Kakkonda field suggests very high value of stress ratio R for the NE to E-W system. This means that the lateral fault type stress field F3L is closed to reverse fault type stress field. This is possibly the reason why both types of fractures were simultaneously formed.

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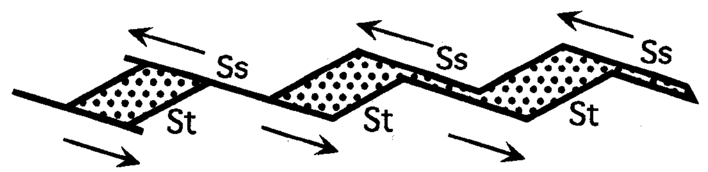

Figure 1. Schematic sketch showing jog structure in hydrothermal veins. Ss: shear fracture, St: tensional fracture, stippled area: mineral fillings precipitated from geothermal fluid.

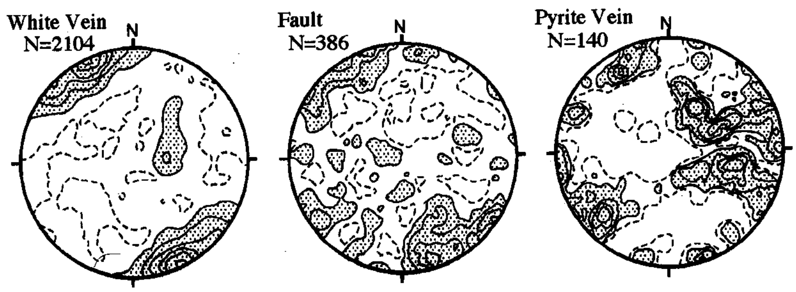

Figure 2. Orientation of poles of fractures in the Kakkonda geothermal field (after Koshiya et al., 1993). Contour: 0.5%(broken line), 1%, 2%, 3%, 4%, 5%. Stippled area: >1%. Equal-area, lower hemisphere projection.

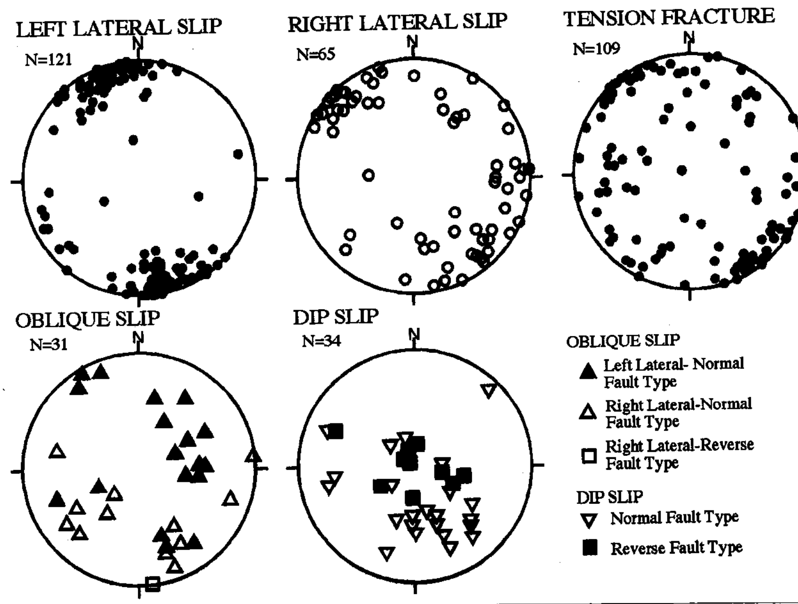

Figure 3. Sense of displacement for white veins in the Kakkonda geothermal field (after Koshiya et al., 1993). Equal-area, lower hemisphere projection.

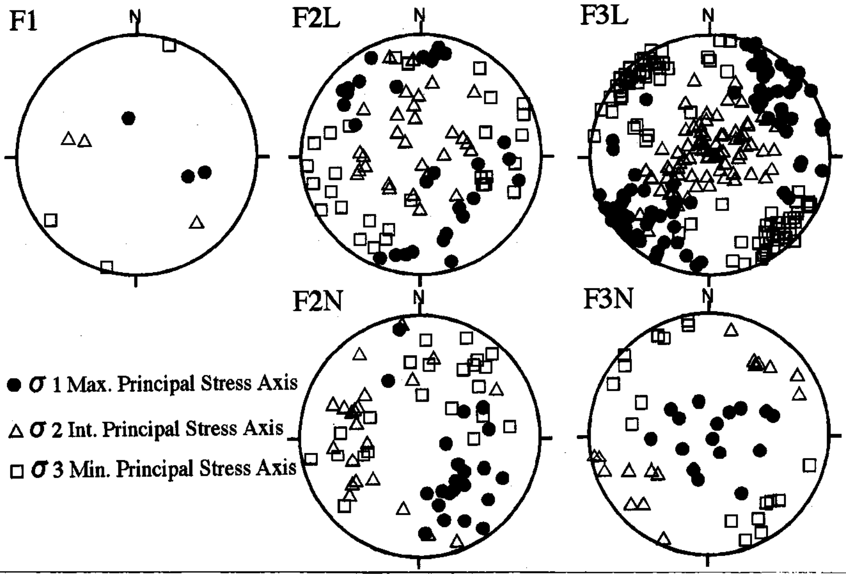

Figure 4. Orientation of inferred principal stress axes from each conjugate set of fractures or jog structure in the Kakkonda geothermal field (after Koshiya et al., 1993). F1 is the oldest normal fault type fracture system. The other abbreviations are referred in the text. Equal-area, lower hemisphere projection.

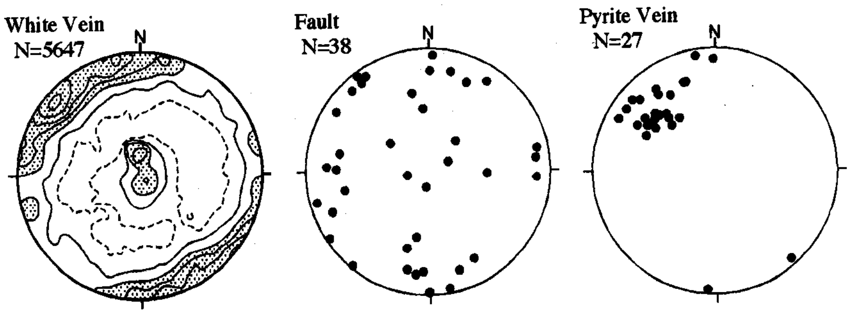

Figure 5. Orientation of poles of fractures in the Oyasu geothermal field. Contour: 0.4%(broken line), 0.9%, 1.4%, 1.9%, 2.4%, 2.9%, 3.4%. Stippled area: >1.4%. Equal-area, lower hemisphere projection.

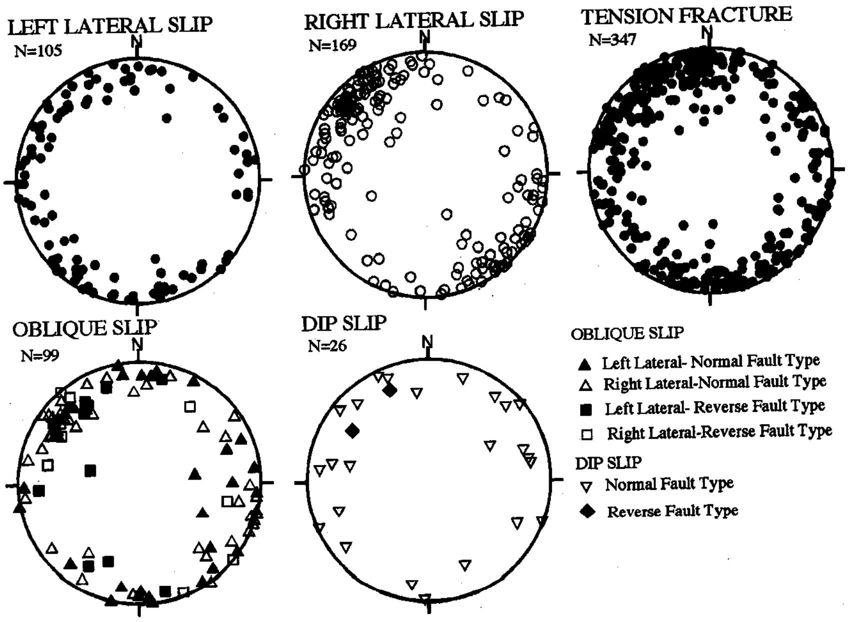

Figure 6. Sense of displacement for white veins in the Oyasu geothermal field. Equal-area, lower hemisphere projection.

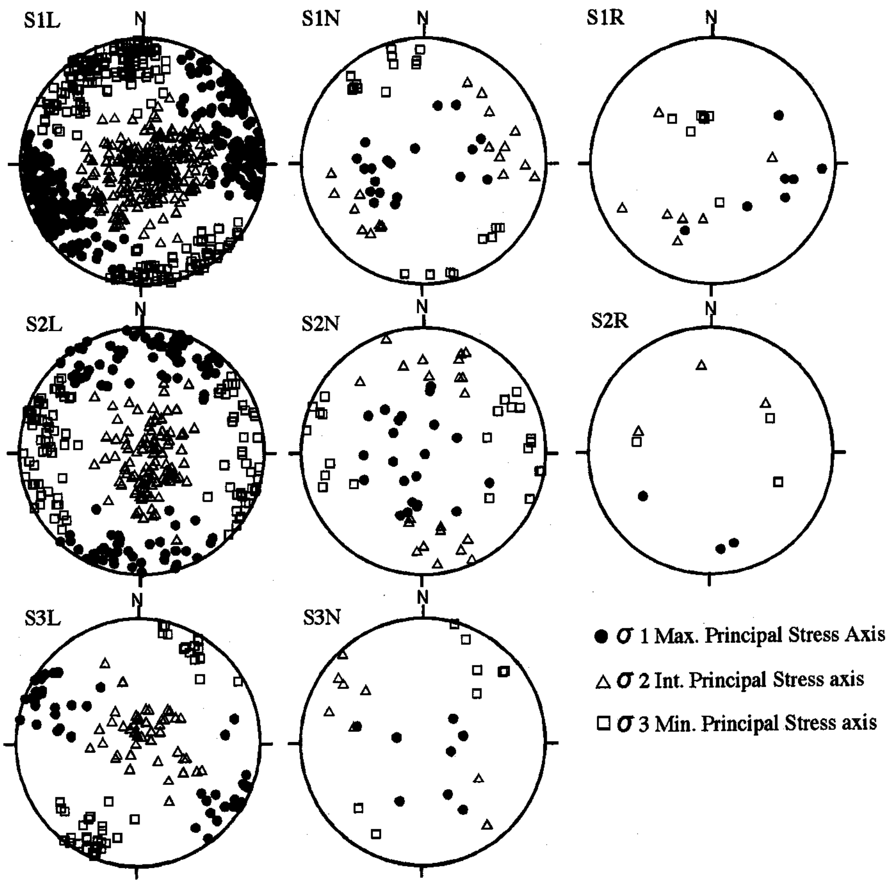

Figure 7. Orientation of inferred principal stress axes in the Oyasu geothermal field. Equal-area, lower hemisphere projection.

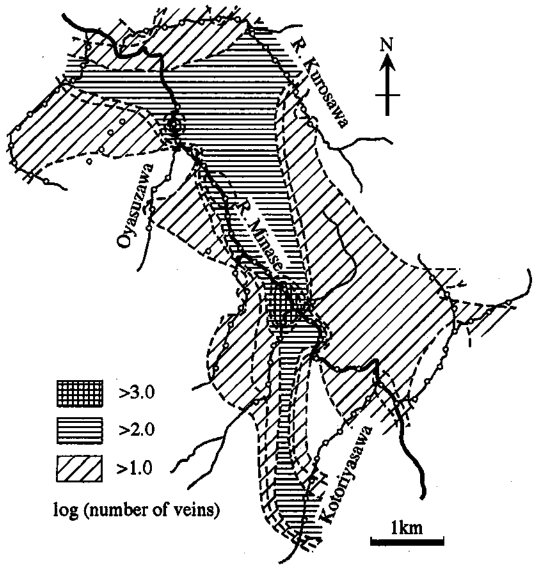

Figure 8. Distribution of hydrothermal vein. The density of veins is calculated as the number of veins per a circle centered at white small circle with 250m radius.