STRUCTURAL EVOLUTION OF GEOTHERMAL FIELDS IN JAPAN

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ABSTRACT

Hot springs usually are situated in the volcanic belt of a convergent zone and are used as indicators of possible geothermal potential in an area. This paper discusses a study which examined the locations of hot springs (i.e., with temperatures > 90°C) in Japan, along with such other characteristics as Na/K ratio, flow rate, and rate of volcanic activity in the area, to determine the influence that plate underthrusting exerts in determining the locations of these hot springs. The results indicate that hot springs in Japan are situated in clusters in the volcanic areas along the extension of zones which mark discontinuities in plate underthrusting. Geothermal fields that have been exploited to date are located in the vicinity of these clusters of hot springs. Measured heat flow in many of these zones is higher than average for volcanic areas. Such zones, with higher-than-average crustal temperatures, may be favorable for the development of productive geothermal fields if local geological and hydrological conditions permit.

INTRODUCTION

Hot springs are used as indicators of geothermal fields in an area. Hot springs in volcanic areas indicate the existence of a heat source and ground water availability. If, in such areas, temperatures at shallow depth (< 2 km) are high (> 180°C) and rock permeability is satisfactory, then geothermal energy can be exploited (1). Examination of hot springs is therefore always the first step in a geothermal exploration program, as the development history of almost all productive fields worldwide testifies. The objective of an exploration program is to locate the hottest part of the system and to understand the structural and hydrological regime in the area.

The relationship between hot springs and geothermal fields is complex and not completely understood. The hottest part of the system may be a few kilometers away from the location of hot springs. Hot springs may reflect conditions at depth directly or indirectly depending on the extent to which the thermal system is marked by overlying nonthermal groundwater horizon. The existence of hot springs does not guarantee sufficient permeability to define an economically viable field. Hot springs may be a sign of impermeable material along relatively permeable cracks of very limited volume.

Sugimura and Uyeda (2) have noted that in Japan, springs yielding water warmer than 30°C (i.e., warm springs) are distributed almost exclusively in the volcanic belt of the arc, thereby suggesting some influence of plate underthrusting. Muffler (3) noted that most of the geothermal fields in the world are associated with either convergent or divergent plate movements. Acharya (4, 5) has pointed out that many geothermal fields in the circum Pacific area are located along the landward extension of zones which mark discontinuities in the underthrusting plate. The database for this study was small; the number of productive geothermal fields in the circum Pacific area is small to date because of the tremendous expense involved in exploration. Hot springs, on the other hand, are abundant in island arcs and their temperatures can be measured inexpensively.

This paper discusses a study of various characteristics of hot springs, including the location and distribution of hot springs and of geothermal fields in Japan, their temperature, geochemical makeup, flow rates, relation to volcanic activity in the area, etc. This study was performed to identify the characteristics of hot springs which are located near productive geothermal fields to determine the influence of plate underthrusting on the locations of these hot springs and on the structural evolution of both hot springs and geothermal fields in Japan.

DATA

The plate tectonic setting of Japan is well understood (2) and is shown in Figure 1. Tectonic activity in and near northern and central Japan is influenced by the underthrusting of the Pacific Plate along the Japan and Kurile Trenches. Tectonic activity in southwest Japan is influenced by the underthrusting of the Philippine Plate along the Ryukyu Trench and the Nankai Trough. Figure 1 also shows the locations of active volcanoes (6) and the

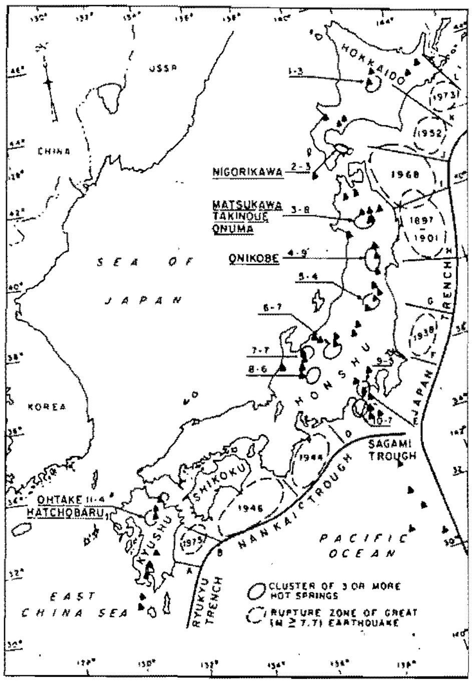

Fig. 1 Hot springs, geothermal fields and plate configuration in Japan. Locations of clusters with three or more hot springs (open circles) from Sumi (8) and geothermal fields (names underlined) from Nakamura (11). Base map showing volcanoes (filled triangles) and plate boundaries from Simkin et al. (6) and McCann et al. (7). Rupture zones of great earthquakes, including the year of rupture from Mogi (13) and Seno (14, 15). A cluster is three or more springs with temperature $\geq 90°C$ within a 15 km x 15 km area. Clusters are numbered 1 to 11 from north to south. The second number for each cluster is the number of very hot springs in that cluster.

rupture zones of great earthquakes (i.e., magnitude > 7.7) associated with underthrusting (7).

There are numerous springs in Japan and their temperatures have been measured by scientists of the Geological Survey of Japan. Sumi (8) shows the distribution of these springs in Japan based on the temperature of water; the temperature intervals are < 25°C, < 25°-42°C, 42°-60°C, 60°-90°C, and > 90°C. The locations of all the springs, as well as other characteristics such as temperature, flow rate, associated rock type, and pH value, also are listed by Sumi (8).

Scientists of the Geological Survey of Japan also have examined 45 areas in Japan that show potential for exploitation of geothermal energy and the chemical compositions of the thermal waters from these main Japanese geothermal fields have been published (9, 10). Nakamura (11) shows the locations of productive geothermal fields in Japan (see Figure 1). These data form the basis of the study reported herein.

It is reasonable to assume that springs with water temperatures > 90°C are more indicative of higher subsurface temperatures than springs with temperatures < 25°C. Springs with water temperatures > 90°C will hereafter be referred to as very hot springs. An examination of Figure 1 shows that while hot springs are located in many parts of Japan, in a number of areas there is a concentration of hot springs. For the purpose of this study it was assumed that clusters of very hot springs in a small area suggest the existence of high subsurface temperatures in the area and the availability of groundwater for heat transfer. It was further assumed that three or more very hot springs situated within a few kilometers (e.g., < 10 km) of one another are an indication that the geothermal reservoir may be of sufficient volume (>2 km^3) to be economically productive. Figure 1 shows the locations where three or more very hot springs occur within a few kilometers of one another.

To determine if the springs with temperatures >90°C reflect the high subsurface temperatures necessary for geothermal exploration, geochemical data from all geothermal areas in Japan were used to compute subsurface temperatures. The subsurface temperatures were computed based on Na/K ratios using the following relationship developed by Fournier (12):

$$t = \frac{1217}{\log (Na/K) + 1.483} - 273.15 \qquad (1)$$

where Na/K is the ratio measured and t is the temperature in °C.

Hirukawa et al. (9, 10) list the Na/K ratio for all hot springs in a given geothermal area. Some 45 geothermal areas have been investigated in this manner and the number of hot springs in a given thermal area vary from 10 to 275. For each geothermal area an average Na/K ratio was computed from all measured ratios. This average ratio was then used in Equation 1 to compute average subsurface temperatures in that geothermal area. Locations of these geothermal areas with subsurface temperatures >150°C are shown in Figure 2.

The relationship of these locations of high subsurface temperatures to the active volcanoes in Japan was investigated to establish if the frequency of volcanic activity influences the subsurface temperatures. All volcanoes with five or more eruptions per century during the last 200 years were identified (see Figure 2). The activity rate was computed from data on volcanic activity (6).

The locations (8) of all natural springs (irrespective of temperature) in Japan were examined to determine if the distribution of these springs suggests a uniform or a nonuniform pattern. The number of springs per unit degree and tenth of a degree in both latitude and longitude were computed.

Exploitation of geothermal energy requires not only high temperatures over a certain volume of reservoir but also a minimum flow rate to generate power on a consistent basis; therefore, flow rates of all springs were examined to identify hot springs with high flow rates. For each prefecture in Japan, an average flow rate was computed from the flow rates of all springs in that prefecture. All very hot springs in any prefecture with flow rates higher than the average for that prefecture were identified; these very hot springs are shown in Figure 2. These data enable examination of the spatial relationship between very hot springs with high flow rates and geothermal fields.

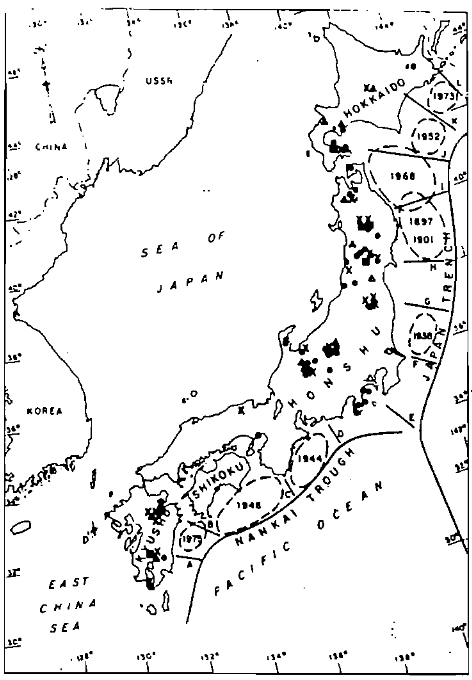

Fig. 2 Indicators of high crustal temperatures in the volcanic area of Japan. Active volcanoes with 5 or more eruptions per century during last two hundred years are shown as solid triangles. Productive geothermal fields are shown as solid squares. Locations of geothermal areas where subsurface temperature is estimated to be >150°C from geochemical data are shown as crosses. Locations of very hot springs with flow rates higher than the average flow rates for that prefecture are shown as filled circles. Also shown are the rupture zones of great earthquakes and the transverse zones discussed earlier.

RESULTS

Figure 1 shows that all proven geothermal fields are situated in the vicinity of some of these very hot springs. As a temperature of about 180°C is required at a geothermal field for power production, this casual spatial association between the two suggests that crustal temperatures are high over a wide area in the vicinity of these fields. This result supports the earlier assumption that very hot springs are indicative of high subsurface temperatures.

As noted previously, warm springs are distributed all along the volcanic arc. Figure 1 shows that clusters of three or more very hot springs which are located within a few kilometers of one another do not occur all along the volcanic belt but are spaced about 100 to 150 km apart. Southwest Honshu is an exception to this configuration. A cluster of hot springs exists in only one area. There are no volcanoes in the area that have shown activity over the last 10,000 years, although older inactive volcanoes do exist along the northern coast (6). It is clear that very hot springs and geothermal fields do not occur all along the arc. This discrepancy between the distribution of warm springs, very hot springs, and geothermal fields suggests that the high temperatures necessary to exploit geothermal energy may not be prevalent at shallow depths all along the volcanic belt but may result from certain special conditions.

An examination of Figure 1 suggests that very hot spring clusters are not randomly distributed but appear to have some relationship with plate underthrusting. Many of these clusters appear to be situated in volcanic areas which correspond to one end of the rupture zone of great earthquakes (i.e., magnitude ≥ 7.7). For example, Clusters 1 and 2 are situated near the two ends of the 1952 earthquake. Clusters 2 and 3 are situated near the terminations of 1968 rupture. Clusters 3 and 4 are similarly situated with respect to the zone which ruptured in 1897 to 1901. There are a number of clusters (i.e., Clusters 6, 7, and 8) which are situated in an area corresponding to the triple junction. Clusters 9 and 10 are located near the junction of the Sagami Trough (a transform fault) and the Nankai Trough. Cluster 11 is situated near the intersection of the Nankai and the Ryukyu Troughs.

Kelleher et al. (12) noted that the rupture zones of great earthquakes in Japan have an average length of about 150 km. It is therefore possible that locations of very hot springs may be influenced by the rupture zones of large earthquakes. Mogi (13) has noted that the aftershock zones of great earthquakes occur in nonoverlapping units separated by structural discontinuities in the arc. Seno (14) divided northern Japan into provinces on the basis of landward extension of these structural discontinuities (see Figure 1). Figure 1 also shows province boundaries for southern Japan that were established on the same basis using rupture zone data from Mogi (13) and Seno (15). Transverse zones B, D, E, and J mark the lateral termination of plate boundary segments. Transverse zones A, C, F, G, H, I, K, and L mark the structural discontinuities in the arc. These transverse zones are parallel to the slip vector determined by Seno (14, 15) from fault plane solutions for all plate boundary segments near Japan.

Figure 1 shows that clusters of very hot springs in Japan, in general, appear to be situated along the extension of transverse zones or province boundaries. Clusters are located in zones A, B, C, E, F, G, H, I, J, K, and L. The correlation between the locations of the hot springs and the presence of transverse zones is 1.0, while the correlation between the transverse zones and locations of hot springs is 0.91. Only along the extension of zone D are there no clusters of very hot springs. It is interesting to note that there are no active volcanoes in southwest Honshu (6) and hot springs are situated in only one area, along the extension of zone C, which separates the rupture zones of the 1944 and 1946 great earthquakes.

The locations of some of the transverse zones shown in Figure 1 may involve some error because they are based on the aftershock zones of great earthquakes, and the orientation of some of the zones may be arbitrary. Figure 1, however, still shows a good correlation between the locations of hot springs and the ends of the aftershock zones of great earthquakes. This suggests that proper conditions (i.e., fractures, fluids, etc.) exist for the development of very hot springs in these transverse zones.

The discrepancy between the distributions of very hot springs, geothermal fields, and active volcanoes is obvious from an examination of Figure 1, which shows six clusters of three or more very hot springs in the volcanic belt which can be associated with underthrusting along the Japan Trench. Simkin et al. (6) show 27 active volcanoes in this belt that are distributed more or less uniformly along the middle of the Honshu island. These data suggest that areas with high subsurface temperature are not uniformly located all along the belt of active volcanoes but develop only in certain areas.

This observation also is supported by an examination of Figure 2. Hirukawa et al (9, 10) examined 45 geothermal areas in Japan and yet geochemical data suggest subsurface temperatures greater than 150°C in only a few areas. Figure 2 also suggests, like Figure 1, that these areas are not randomly distributed across Japan but appear to be spaced along the extension of zones which terminate the rupture of great earthquakes. Figure 2 also confirms the obvious: that productive geothermal fields are located in areas with subsurface temperatures >150°C. This suggests that areas with subsurface temperatures >150°C will be good targets for geothermal exploration studies.

A comparison of the locations of active volcanoes having more than 5 eruptions per century over the last 200 years with locations with subsurface temperatures >150°C suggests that in some areas high subsurface temperatures may exist because of active volcanism. However, there are no active volcanoes in the vicinity of many locations with high subsurface temperatures. Active volcanism may be a sufficient but not a necessary condition for the existence of high subsurface temperatures in the shallow part of the crust.

Examination of the locations of very hot springs with flow rates higher than average (see Figure 2) also suggests that a majority of these very hot springs are in the vicinity of clusters of three or more very hot springs. As to be expected, all known geothermal fields in Japan are located near hot springs with higher-than-average flow rates for the area. Closer examination of Figure 2 suggests that in most cases, these hot springs with high flow rates appear to be on the landward extension of zones which terminate the rupture zones of great earthquakes.

Finally, an examination of the distribution of all springs in Japan (regardless of temperature) shows that the density (i.e., number of springs per unit area) is highest along the extension of these zones. Also in many cases the clusters of three or more very hot springs are located in areas with an overall high density for springs with different temperatures. Assuming that a spring is an indication of some type of fracture or fault near by, the distribution of all springs may in some way reflect the subsurface distribution of fractures. This examination therefore suggests that the density of subsurface fractures is high in these volcanic areas located along the extension of zones which terminate the rupture zones of great earthquakes.

DISCUSSION

The results of this study suggest that, in Japan, the locations where three or more hot springs occur within a few kms of one another appear to be spatially related to the landward extension of transverse zones which separate an underthrusting plate into different blocks. It is possible that differential shear between the two blocks may lead to higher heat flow in the transverse zones. Limited data available on heat flow in Japan support this suggestion (see Figure 3). The average heat flow in the volcanic areas of Japan is 1.5 heat flow units (HFU). Heat flow along the extension of zones A, E, I, J, L, and M is indeed very high (3.5 HFU) as compared to the average of 1.5 HFU. No heat flow data are available along zones B, F, H, and K. Heat flow along zone G is about 1.5-2.5 HFU. Heat flow along zones C and D is about 1.5-2.0 HFU. As southwest Honshu is not volcanic, the heat flow in transverse zones C and D is therefore higher than is to be expected in a nonvolcanic area. These observations suggest that heat flow is higher than average in the transverse zones. It is likely that crustal temperatures are higher in the transverse zones.

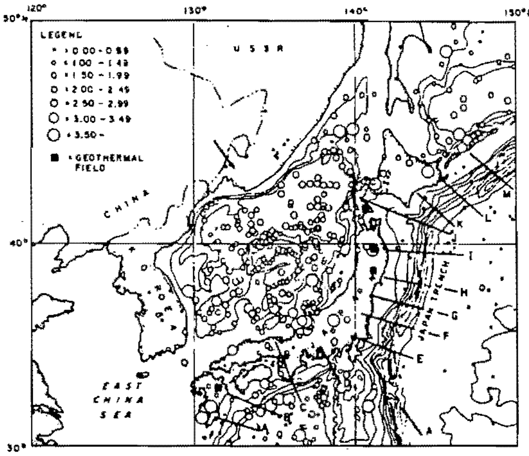

Fig. 3 Heat flow in Japan and vicinity in relation to the location of geothermal fields and transverse zones. Basic heat flow map from Watanabe et al. (17). Locations of geothermal fields (filled squares) from Nakamura (11). Transverse zones A-L as in Figure 1. Zones L and M outline a block which ruptured in 1973 and had ruptured earlier in 1984.

Acharya (4, 5) examined the locations of geothermal fields in the circum Pacific area and observed that most of the geothermal fields are situated along the extension of zones which mark a break in the lateral continuity of the underthrusting plate. The breaks noted were: (1) terminal ends of several plate boundary segments (such as B, D, E, and J in Figure 1); and (2) transverse zones which divide plates into several independent blocks on the basis of rupture zones (such as A, C, F, G, H, I, K, and L in Figure 1). Based on these data Acharya (5) suggested that such transverse zones are favorable areas for the development of productive geothermal fields. Although geothermal fields are indicative of high temperatures at shallow depths, their absence does not mean low crustal temperatures. The expense involved in geothermal exploration is sufficiently high so that only few locations are thoroughly investigated. Hot springs, on the other hand, are abundant in island arcs and temperatures of hot springs can be measured inexpensively. The distribution of hot springs in Japan suggests that shallow crustal temperatures may indeed be higher in these zones.

Data on the locations of clusters of very hot springs, the locations of geothermal fields, and the locations with subsurface temperatures >150°C suggest subsurface temperatures in volcanic areas along the extension of the transverse zones are higher than normal. Available data on heat flow in Japan also support this observation. The cause of these increased temperatures may not be so simple, particularly as they do not arise from high volcanic activity in the area. It also is not immediately clear how transverse zones in the underthrusting plate will affect shallow crustal temperatures in Japan. The observation that features in the underthrusting plate affect the tectonics in the other plate is not unique; it has been noted that the volcanic chain in Central America changes its orientation in response to discontinuities in the underthrusting plate (16). The transverse zones divide the underthrusting plate into different segments. These different segments slip at different times and the resulting differential shear can lead to the generation of additional heat in these zones. The observation that heat flow and subsurface temperatures are higher along the extension of these zones suggest that differential shear may lead to development of numerous fractures along their extension. These fractures then lead to fluid flow which permits efficient transfer of heat from the subsurface to the near surface. The existence of numerous fractures also can enhance the direct flow of heat from subsurface to near surface. This may explain the clustering of very hot springs in these areas. However, only detailed geophysical surveys can determine if these areas have greater number of fractures per unit area than other areas in Japan.

The presence of volcanoes is certainly an indication of the possibility of several paths existing in the subsurface for the migration of magma. But the clusters of very hot springs are not associated with every volcano in Japan. Furthermore, not all locations with subsurface temperatures >150°C are situated near active volcanoes with more than 5 eruptions per century over the last 200 years. Locations of subsurface crustal areas in Japan with temperatures >150°C near very active volcanoes is therefore not a necessary condition for clusters of very hot springs. It is likely that along the extension of these zones there are a greater number of fractures in the subsurface than fractures generated by a volcano. Spatial proximity of the areas with an overall high density of hot springs and areas with clusters of three or more very hot springs suggests that these clusters can develop because of the ease of heat and mass transfer in these zones. The locations of these clusters along the extension of zones along which great earthquake ruptures terminated suggest some sort of influence of the geometry of underthrusting. This study therefore supports the results of an earlier study by Acharya (5) that showed that productive geothermal fields are located along the extension of zones which terminate the ruptures of great earthquakes. The data base in this study is much larger.

The precise relationship between hot springs and geothermal fields can only be understood on the basis of a comprehensive exploration program, and may vary from field to field. At the same time, the absence of hot springs does not necessarily mean the absence of high temperatures at shallow depth, for heat could be carried away laterally beneath an impermeable cap, even though high temperatures may exist there. Nevertheless, the great majority of geothermal systems known and explored to date are associated with extensive, deep circulatory systems which result in discharges of hot water and steam at the surface; such surface manifestations are the most obvious criterion to justify an exploration program. The distribution of hot springs in Japan suggests that hot springs in transverse zones may be the most favorable indication of higher temperatures at shallow depths in the crust. If local geological and hydrological conditions are favorable, then a productive geothermal reservoir may develop in these transverse zones.

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