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QUATERNARY GRANITIC PLUTON INFERRED FROM SUBSURFACE TEMPERATURE DISTRIBUTION AT THE SENGAN (HACHIMANTAI) GEOTHERMAL AREA, JAPAN

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ABSTRACT

A Quaternary granite has been confirmed below 2,860 to 3,729 m depth by the drill hole in the Kakkonda field in the Sengan (Hachimantai) geothermal area, Japan, and is regarded as the heat source of the present geothermal reservoir. The temperature exceeds 350°C around the rim of the granitic body and reaches to more than 500°C at 1 km inside. The thermal gradient of this interval is very steep and constant (30°C/100m). This evidence suggests that the confirmed granite corresponds to the consolidated outer zone of a magmatic pluton which is adjacent to a Pliocene dacite intrusive body and not associated with any extrusive volcanics. The Quaternary granite could be subdivided into cupola-shaped smaller intrusions separated from an underlying big pluton, and the big pluton itself. This expectation arouses new interest in the existence of cupola-shaped smaller intrusions at other geothermal fields and an underlying big pluton for the whole area. The Sengan geothermal area includes many geothermal fields such as the Sumikawa, Ohnuma, Toshichi, Matsukawa, and Nyuto fields, besides Kakkonda. The Quaternary granite has not been confirmed at any other fields except Kakkonda, but Tertiary granite has been identified at Sumikawa, a Pliocene dacite intrusive body at Nyuto, and a Pleistocene porphyrite at Matsukawa. Subsurface temperature contour maps are described for whole Sengan area, based on a calculation by the relaxation method using bore hole temperature logging data. These maps indicate that a high-temperature zone (HTZ) forms the shape of an eastward-convex horseshoe. The total area over 200°C at -2 km with reference to mean sea level (msl) reaches 390 km^2. The HTZ is generally consistent with the distribution of younger (< 0.5 Ma) Quaternary volcanics. The HTZ is also consistent with a geologic upheaval structure and a shallow gravity basement. These mean that the HTZ has been formed by tectonic uplift associated with younger Quaternary magmatism (0.5 Ma to present), which not only produced extrusive volcanics but also concealed intrusive magma bodies. The expected intrusive bodies must be very extensive and/or composed of many bodies to account for the extensive HTZ. The intrusion of Quaternary granite may be enhanced through fracture zones and/or density contrast around intrusions provided by pre-existent intrusive bodies, because the intrusive bodies tend to swarm in spite of intrusion age. The HTZ seems to have been formed and sustained by multiple intrusions of young Quaternary granite during 0.5 Ma to present. Further deep drill holes are expected to prove the emplacement of the Quaternary granite.

1. INTRODUCTION

The Sengan (Hachimantai) area is located on the backbone range of Northern Honshu, and it extends along the border between Senpoku county, Akita prefecture, and Iwate county, Iwate prefecture. Its total area is about 600 km^2. The Sengan area includes many geothermal fields, such as Kakkonda, Sumikawa, Ohnuma, Toshichi, Matsukawa, and Nyuto. Many surface surveys and drillings have been carried out in the Sengan area for national projects, such as "Confirmation study of the effectiveness of prospecting techniques for deep geothermal resources" (1980-1988) and others. The temperature gradient curves of 53 drill holes in these fields were summarized and used as the data base for estimation of subsurface isothermal contour maps. Most of the temperature profiles were measured after 120 hours of standing time, and can be nearly regarded as formation equilibrium temperature.

The Kakkonda area is located in southeastern part of the Sengan, about 10 km west from the N-S trending Quaternary volcanic front of Northern Honshu. This is the first field in Japan where it has been proved that a young Quaternary granite acts as the heat source for the present geothermal system. The New Energy and Industrial Technology Development Organization (NEDO) has carried out the project "Deep-Seated Geothermal Resources Survey" as part of the New Sunshine project in Kakkonda since 1992. This project aims to understand the overall geothermal environment including the shallow systems, and to evaluate the possibility of utilizing hydrothermal fluids from deeper than 3,000 m. Exploration well WD-1a, drilled to a depth of 3,729 m, encountered Quaternary granite from 2,860 to the bottom (e.g., Yagi *et al.*, 1995; Muraoka, *et al.,* 1998).

2. EXTRAPOLATION METHOD OF SUBSURFACE TEMPERATURE

It is generally difficult to estimate accurately deep subsurface temperature beyond the bottoms of drill holes, because the thermal gradient changes greatly with depth and horizontal distance. However, deep subsurface temperature based on temperature logging data from shallow drill holes may be estimated by the relaxation method for the purpose of obtaining more accurate subsurface temperature distribution at the fields where many temperature profiles of drill holes are available (Tamanyu, 1993; Tamanyu, *et al.,* 1995). First, the temperature at -5,000 m msl is estimated by a smooth downward extrapolation of the temperature profile of the drill holes. The temperatures at 0, -500, -1,000 m msl are estimated by manually contouring at each level and digitizing these contours. The temperatures in the subsurface space, divided as a cubic lattice with 250-m grid spacing, are calculated by the relaxation method in two steps. First, the temperatures at surface, 0, -500, -1,000 and -5,000 m msl are fixed; and second, the temperatures at surface, -5,000 m and at the lattice points which have corresponding measured temperatures are fixed. In the relaxation method, the temperature at a point of a cubic lattice is calculated from temperature values at 6 lattice points on x-, y-, z-axes surrounding the central point. Then repetition of this calculation provides the equilibrium temperature in the whole field on the assumption that heat transfer is wholly controlled by conduction. These calculations result in an overall subsurface temperature distribution pattern.

3. DATA PROCESSING

The subsurface equilibrium temperature, divided by a 250-m interval, is calculated by the relaxation method separated into first and second steps. The first step is carried out using the following three sets of fixed initial grid data. The first fixed data set is the grid data for surface temperature that is assumed as 10°C. The second fixed data set is the temperature at -5,000m msl, which is estimated from extrapolation of the temperature-depth curve of drill hole based upon the assumption of either convective or conductive upflow (Fig. 1). The third fixed data set is the temperature at 0, -500, -1,000 m msl estimated by manual contouring. The grid data close to drill hole are assumed to be the same as actual logging data. The temperature values for all grids are obtained by the first step of the relaxation calculation. This means that the outline of the subsurface equilibrium temperature can be estimated generally by the first step of the calculation. However, the second step of the calculation is carried out in order to get more detail in the equilibrium temperature. The temperature values obtained by the first step of the calculation are partly replaced by actually measured temperatures at some grids, and then calculated repeatedly until the equilibrium temperature can be obtained by the second step of the relaxation calculation. The most appropriate number of repetitions should be decided by good continuity between calculated grid data and actual logging data. A flow chart of data processing is presented in Fig. 2.

4. SUBSURFACE TEMPERATURE DISTRIBUTION MAPS IN THE SENGAN AREA

The subsurface temperature distribution maps at four levels (0, -500, -1000, -2000 m msl) were described for the Sengan geothermal area on the basis of bore hole temperature logging data (Tamanyu, et al., 1996). The temperature profiles of drill holes were classified into 3 categories: upflow type, downflow type and conduction type. Upflow type profiles are common in zones dominated by hydrothermal convection, whereas conduction type profiles occur in both high- and low-temperature zones where hydrothermal convection does not occur. Downflow type profiles are very rare and are regarded as evidence of recharge of meteoric water. The location of drill holes and geothermal and hot spring fields are shown in Fig. 3. The temperature distribution map at -2,000 m, and a cross section of isothermal contours along X-Y are also shown in Fig. 3. The map indicates that the high-temperature zone forms the shape of eastward-convex horseshoe that is generally consistent with the distribution of Quaternary volcanics. The total area over 200°C at -2 km msl reaches 390 km^2 and is almost equivalent to the high-temperature zones of The Geysers in USA, Larderello in Italy and greater Tongonan in Philippine under the same conditions (Tamanyu, 1995). The temperature distribution maps are also described at 0, -500 and -1,000 m msl, and indicate that the high-temperature zone is extensive and located at the same position as on the map at -2,000 m msl. This means that the Sengan area is thermally controlled from shallow to deep not by local convection but overall by extensive conductive heat transfer.

5. COMPARISON BETWEEN EXTRACTED HIGH-TEMPERATURE ZONES (HTZ) AND OTHER ANOMALIES

The author is interested in the interpretation of the extracted high-temperature zone (HTZ) from the viewpoint of the underlying heat source. The HTZ is defined as the zone surrounded by the 300°C isotherm at -2,000 m msl. The comparison between the HTZ and surface and subsurface geology is described in the following sections.

5.1 Comparison between the HTZ and surface geology

The HTZ is very extensive and includes most Quaternary volcanic terrains such as Yakeyama, Hachimantai, Iwate-san and Nyuto-san covered with their volcanic products. The only exception is the Bunamori volcanic terrain which is dated older (1.0 - 0.5 Ma) than the others (0.5 Ma - present). The eastern parts of the Hachimantai and Iwate volcanic terrains, and the southwestern part of the Akita-Komagatake terrain are also outside the HTZ. It can be interpreted that these parts are composed of the youngest volcanic products, and therefore, heat propagation has not been enough yet. It is also worth noting that the HTZ is not restricted to volcanic vents but is spread widely toward the neighboring volcanic terrains. This suggests that heat propagation from a deep-seated heat source to the surface occurs not linearly along vents but radially from horizontally spread heat sources.

5.2 Comparison between the HTZ and subsurface geology

The HTZ can be compared with geologic maps and geologic cross sections, and with the distribution map of depths of the gravity basement. Some of the comparison has been presented provisionally by Tamanyu *et al.* (1999). The geologic cross sections (Research group for the geological map of Sengan Geothermal Area, 1985) indicate that most parts of the HTZ are correlative with a geologic upheaval in Quaternary time, which corresponds to the eastern part of the backbone range in Northern Honshu. The SAR (Synthetic Aperture Radar) interferometer data from JERS-1 revealed a recent surface deformation of about 10 cm from May to July 1998, with a volcanic micro-earthquake swarm around Mt. Iwate (*e.g.,* NASDA/EORC and Nagoya Univ., 1999; GSI, 1999; Kobayashi, *et al.*, 1999; and Nishimura, *et al.*, 1999), and its detected extent almost corresponds to the HTZ. This means that the above-mentioned geologic upheaval is still continuing intermittently, even at present. The depths of gravity basement were calculated by three-dimensional analysis of gravity data, with the assumption of three layers of which densities are 2.2 g/cm^3 for the upper layer, 2.45 g/cm^3 for the middle layer, and 2.65 g/cm^3 for the lower layer (Komazawa *et al*, 1987). The gravity basement is generally regarded as lower Tertiary and pre-Tertiary basement based on a comparison with geologic sequences of drill holes. The HTZ is correlative with shallow depths of gravity basement in most areas, but not correlative at the middle part of the Hachimantai and Yakeyama areas where the southward extension of Hanawa graben interrupts. The comparison results in good correspondence on the whole among the HTZ, the geologic upheaval structure and the shallow gravity basement. This indicates that the HTZ has been formed by a tectonic uplift associated with younger Quaternary magmatism (0.5 Ma to present) which produced not only extrusive volcanics but also concealed intrusive magma bodies. The expected intrusive bodies must be very extensive and/or composed of many bodies to account for the extensive HTZ.

6. QUATERNARY GRANITIC PLUTON INFERRED FROM SUBSURFACE TEMPERATURE DISTRIBUTION

The conceptual geothermal model along the Kakkonda area to Mt. Iwate is presented in Fig. 4 (Tamanyu, 1991, partly revised), showing the relationship between neo-granite-related and young volcano-related geothermal systems. This model indicates that neo-granite intrusions occur west of the young volcanic front, and that neo-granite intrusions provide more potential geothermal fields rather than do the young volcanoes. The neo-granite could be subdivided into cupola-shaped smaller intrusions separated from underlying big pluton, and the big pluton itself. Neo-granite is categorized as Quaternary granite. The neo-granite named Kakkonda granite is a stock several tens of square kilometers in area with an upper contact about 1.5-3 km deep, and it is a composite pluton varying from tonalite to granite (Doi, *et al*., 1999). The Kakkonda granite intruded to the top of the pre-Tertiary basement, while the Pliocene dacite of Torigoenotaki reached to the top of Tertiary formations in the Kakkonda field. These emplacement depths seem to be controlled by the density balance between host rocks and intruded bodies in the case of solid intrusion. The intrusion of Quaternary granite may be enhanced through fracture zones and/or density contrasts around intrusions provided by pre-existing intrusive bodies, because the intrusive bodies tend to swarm.

The presence of Quaternary granite has not yet been proved at other fields besides Kakkonda. However, the extensive HTZ suggests strongly that a Quaternary granite should be concealed at depth as the heat source. Pliocene dacite intrusions are recognized in the Nyuto and the Matsukawa fields, besides Kakkonda. Tertiary granite is recognized at the Sumikawa field. These pre-existing intrusive bodies may provide the appropriate condition for the intrusion of cupola-shaped stocks of Quaternary granite. Further deep drill holes are expected to demonstrate the presence of the underlying pluton beneath the Kakkonda granite at Kakkonda and beneath Quaternary granite at other fields (Fig. 5). As the result of the comparison with available geologic and geophysical data, the HTZ seems to have been formed and sustained by multiple intrusions of young Quaternary granite during 0.5 Ma to present.

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*written in Japanese with English abstract.

**written in Japanese without English abstract.

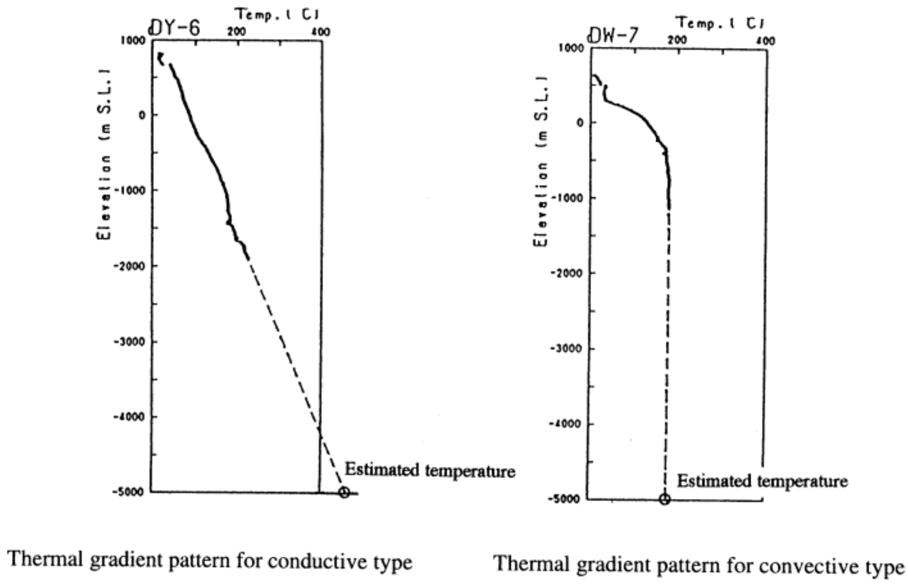


Figure 1. Estimation of the temperature at -5,000 m msl by extrapolation of thermal gradients

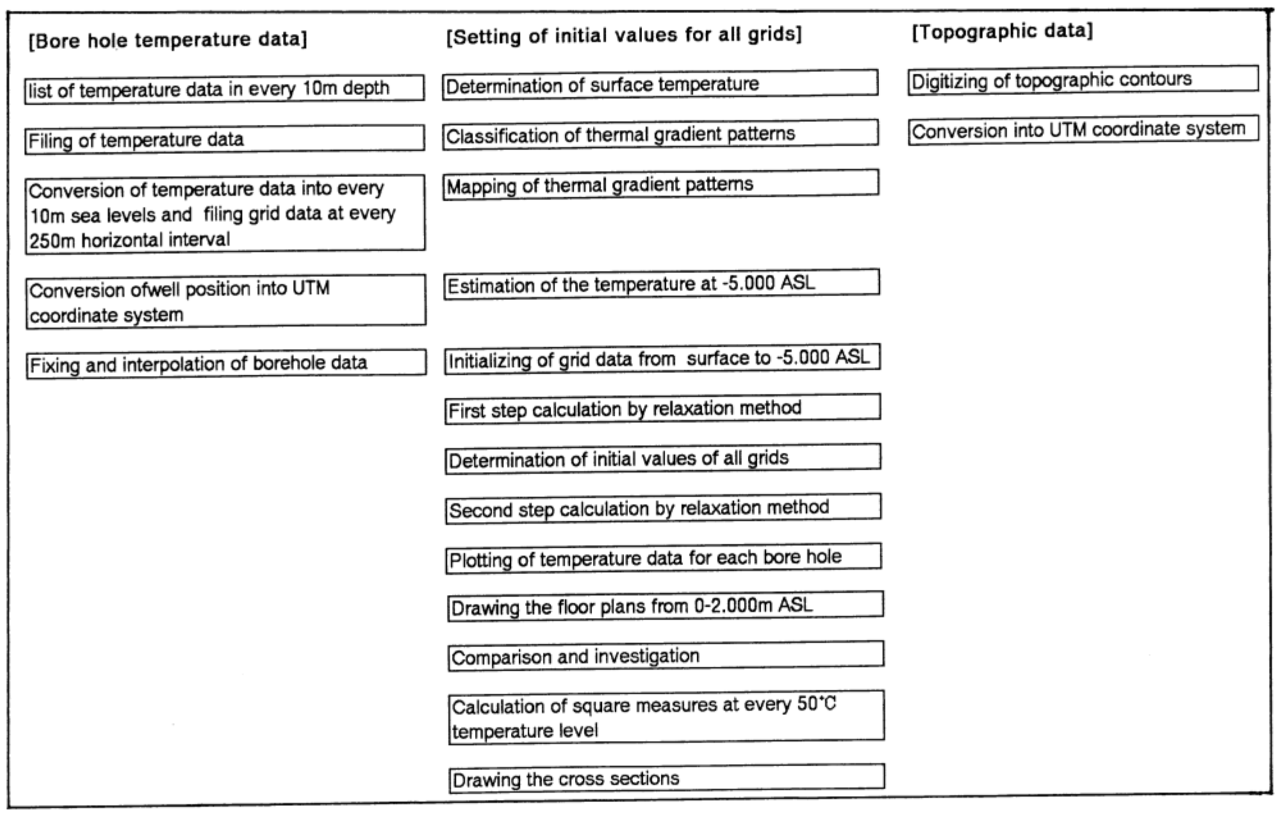


Figure 2. Flow chart of data processing

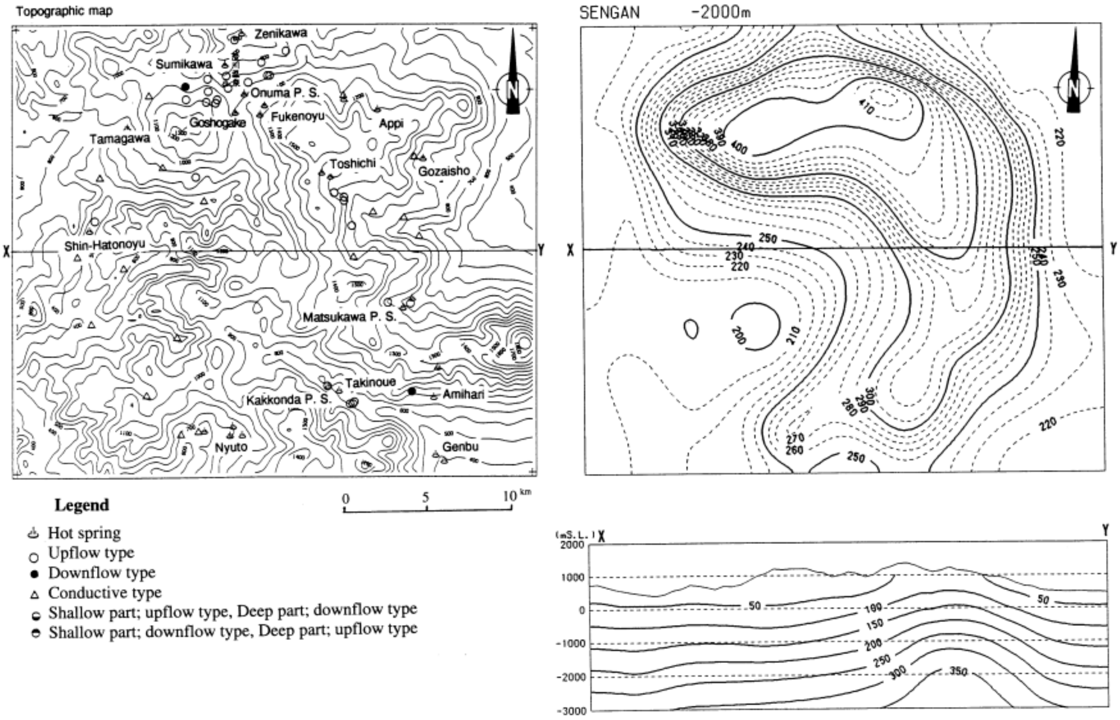
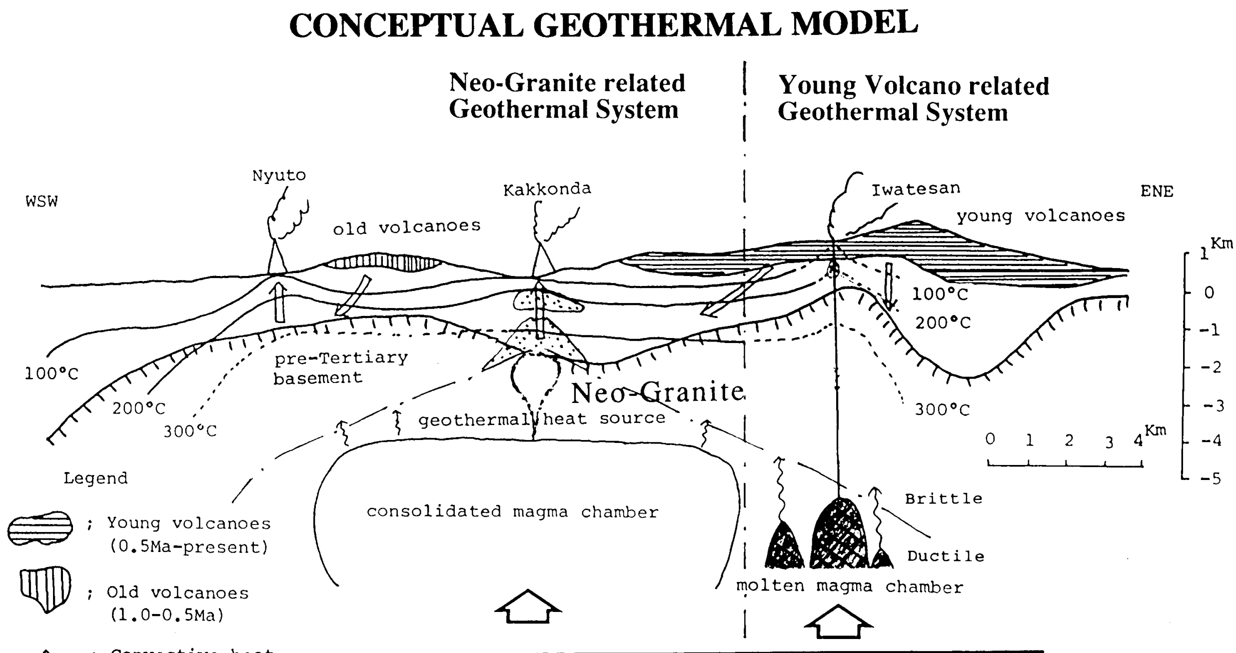


Figure 3. Location maps of drill holes, and temperature distribution maps at -2,000 m asl on the second relaxation method in the Sengan Geothermal area



	Neo-Granite Type	Volcanic Type
Heat Source	Neo-Granite and underlying Batholith	Deep and Small Magma Chamber
Heat Transfer	Heat Conduction	Volcanic Gas
Heat Potential	High and Broad	Low and Narrow
Chemistry	Neutral pH	Low pH
Main Structure	Upheaval Zone	Transitional Zone

Figure 4. Geothermal model in the Sengan geothermal area with special reference to heat source (Tamanyu, 1991, partly revised)

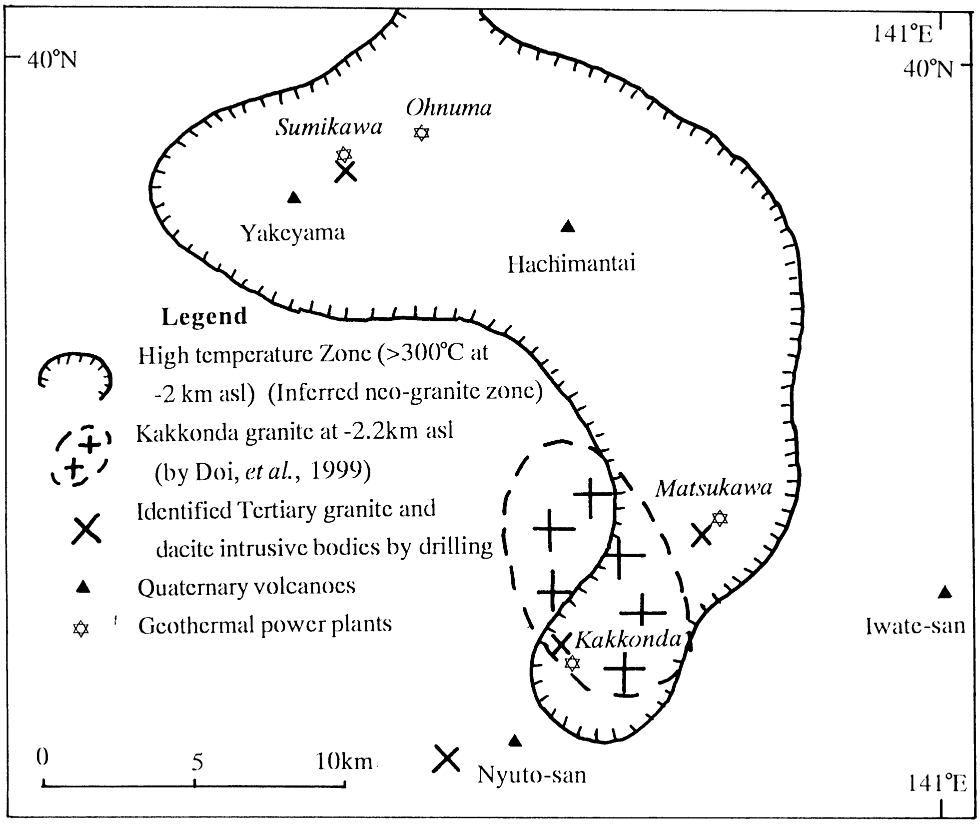


Figure 5. Inferred Quaternary granite in the Sengan geothermal area