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THE HOHI GEOTHERMAL AREA, KYUSHU, JAPAN

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ABSTRACT

Geophysical data from surface measurements and downhole pressure/temperature data in exploratory wells for a 112 km^2 region in northern Kyushu centered around Mount Waita are examined. The study area includes the geothermal fields supplying steam for the Hatchobaru and Ohtake power stations, but also extends a considerable distance to the northwest. Evidence from drilling logs, magnetotelluric surveys, lost-circulation horizons, downhole temperature surveys, and thermal and chemical properties of surface hot-spring discharge suggests the presence of a large geothermal reservoir north of the towns of Takenoyu and Hagenoyu.

BACKGROUND

The Hohi geothermal area lies in a mountainous region of north-central Kyushu island in Japan. Since 1978, the New Energy Development Organization (NEDO) has been engaged in a geothermal field assessment project in the area. NEDO has carried out various geophysical surveys and has drilled a number of deep wells in the area including ten 500 meter class "DB" series heat flow holes, seven "DW" series structural wells (1100 to 1800 meters depth) and three deep exploratory wells (2300 to 2600 meter "DY" series). Figure 1 shows the irregular topography of the study area (112 km^2; 8 km east-west by 14 km north-south), along with the locations of the various wells and natural hot springs in the vicinity.

In addition to the NEDO wells mentioned above, two wells (TY-1, 1000 m; K-7, 1500 m) belonging to the Kumamoto Prefecture are located near the hot springs at Takenoyu and Hagenoyu, and the 3000 meter HT5-1 well (belonging to the Kyushu Electric Power Company) is located near Hatchobaru, as shown in Figure 1. Two geothermal power stations operated by Kyushu Electric Power Company (Ohtake, 11 MW and Hatchobaru, 55 MW) have been both producing and injecting fluids for a number of years in a relatively small area (~ 1 km^2) in the southeastern part of the study area. These power stations employ a number of shallow production and injection wells (500 to 1500 meters) that are not shown in Figure 1.

The study area has an average elevation about 700 to 800 meters above sea level ("ASL"), and is dominated by the 1500 m Mount Waita. Just 10 km to the southeast is Mount Kuju (almost 1800 m), the highest mountain on Kyushu. Both are recently active volcanoes. Some 20 km south of the study area is Mount Aso, an active caldera. The presence of the numerous hot springs and attractive mountainous terrain has rendered the Hohi region a popular tourist resort area. NEDO's objective in studying the area is to assess the potential of the field for electrical power production using deep geothermal energy (in contrast to the shallow reservoirs at Hatchobaru/Ohtake) in a manner consistent with conserving the natural beauty and recreational attractiveness of the region.

In the present paper, we summarize our understanding of the reservoir mechanics of the Hohi geothermal field in its natural state. This understanding was acquired in an iterative fashion, combining available data to develop a quantitative model using a three-dimensional numerical reservoir simulator, and then systematically adjusting available free parameters (mainly permeabilities) in the numerical model to optimize agreement with measurements. The final numerical model is quite successful, in that it accurately reproduces measured downhole pressures and temperatures in wells as well as the locations and approximate discharge rates of natural hot spring areas. In this paper, however, we will restrict the discussion to the conceptual model itself and the fundamental field information upon which it is based (rather than the numerical simulation used to synthesize the various data sets) in the interests of brevity.

GEOLOGICAL STRUCTURE

The basic structure of the Hohi study area consists of a granitic basement of

Cretaceous age overlain by a succession of volcanic rocks over 2 km thick. Our knowledge of the structure arises mainly from seismic refraction surveys, gravity measurements, and drilling logs. The geophysical surveys (seismic, gravity) have been principally useful in locating the top of the granitic basement (which has been penetrated by only three deep wells; DY-2, DY-3 and HT5-1). In the southern part of the study area, these wells encountered basement rock 500 to 1000 meters below sea level. To the north, however, well DY-1 reached 1800 meters below sea level without encountering basement. The gravity survey likewise indicates a rapid increase in depth-to-basement in the northern part of the study area.

Figure 2 shows a south-north vertical section through the study area which passes through wells DW-4, DW-1, and DY-1. This sequence is typical of the study area as a whole. Overlying the granitic basement are the Pre-Kusu volcanics, which are relatively thin to the south but thicken greatly to the north where the basement drops away. A relatively thick section of Hohi volcanic rocks lies atop the Pre-Kusu formation; this Hohi group interfingers with members of the Kusu group to the north, which are nearly contemporaneous in time but of quite different lithology. In particular, the Kusu group contains substantial amounts of virtually impervious mudstones. Finally, the most recent element is the Kuju volcanic group which overlies the southern part of the area as a relatively thin layer. Each of the formations described above consists in reality of a succession of distinct lithologic units, each laid down in a separate volcanic event. An extensive collection of core samples has been obtained from the NEDO drilling program -- the reservoir samples exhibit typical properties for volcanic rocks, but the porosities generally are on the low side (10 to 15 percent).

UNDERGROUND TEMPERATURE DISTRIBUTION

Our knowledge of the distribution of temperature in the study area arises from two sources -- a magnetotelluric survey covering much of the northern part of the study area, and downhole temperature measurements in shut-in wells. Essentially, the magnetotelluric survey reveals two important features. First, in the general vicinity of wells DW-7, DW-2, DB-4 and DW-6, there is a buried high-conductivity zone extending downwards from about sea level depth. This conductive zone ends about 0.5 to 1 km to the east of well DW-6. Second, a narrow vertical zone of exceedingly high conductivity, oriented east-west, probably no more than a few hundred meters thick and at most 2 to 3 km long, is located roughly between wells TY-1 and DB-9, in the vicinity of the Takenoyu/Hagenoyu hot springs. The survey cannot provide the maximum depth reached by this feature, but it extends at least 3 km down. This suggests that hot fluid may be rising from depth in this area. It is noteworthy that this deep conductive feature coincides spatially with the abrupt deepening of the granitic basement. It seems likely that this change in basement depth is manifested as a set of east-west subparallel faults. If so, these faults could provide conduits for hot water recharge from depth.

Repeated downhole temperature-depth surveys were performed for at least several days after cold-wafer circulation stopped in each of the NEDO wells to observe the buildup of temperature. These surveys have proved useful in identifying the permeable horizons of the various wells and (in conjunction with observations of the simultaneous equilibration of the standing water level in the well) have also helped determine reservoir pressures, as will be seen. Figure 3 shows, for each of the wells in the study area, the formation temperature estimated to prevafl at a depth of 500 meters. For the DB-serfes (500 meters depth) wells, these are stable bottomhole temperatures; for the deeper wells, they are based on shut-in profiles. Two regions characterized by high temperatures at this shallow hdrizon may be discerned. The first is in the southeast quadrant of the study area, centered in the neighborhood of the Hatchobaru/Ohtake power stations. As mentioned above, this vicinity is already being explaited for electrical power. The other high-temperature zone is in the northwest, and corresponds spatially to the shallow conductive zone located by the magnetotelluric survey. Numerous wells have explored this northern hot zone, including the shallow wells DB-4 and DB-9, the intermediate-depth wells TY-1, K-7, DW-2, DW-6 and DW-7, and the deep DY-1 well. It is this northern high-temperature region that is of primary interest for the present study.

Figures 4 and 5 show, respectivkly, estimated formation temperature distributions in the vertical planes corresponding to Sections A-A' and B-B' of Figure 3, respectively. Figure 4 clearly shows an abrupt rise in temperature at depth as one moves north beyond well DY-2. The highest temperatures are found in the neighborhood of well K-7, and then temperatures decline slowly as one moves further north. This rise in the isotherms coincides spatially with the deep east-west conductive feature extending to great depth revealed by the magnetotelluric survey, and also corresponds to the abrupt drop in the basement elevation, as discussed above. It is also noteworthy that a temperature inversion is present in the north. Highest temperatures are found in the range 0 to -500 meters ASL ("above sea level"), with lower temperatures below. Figure 5 (corresponding to Section B-B') also exhibits this temperature inversion, and shows clearly that the hot anamoly is 3 to 4 km wide in the east-west direction, reaching at least from well DW-7 in the west to DW-6 in the east.

It seems clear that a very large volume of hot reservoir rock is present, extending from well K-7 in the south to well DW-6 to the north (a distance of 2.5 km) and probably a considerable distance beyond -- the northward extent of the hot zone has not yet been established by drilling, but may extend as far as the Kabeyu hot springs to the north of the study area (about 6 km north of well K-7). On the other hand, temperatures in this reservoir are not exceedingly high. The highest downhole recorded temperature is ~ 220°C (in well K-7 at ~ -500 m ASL), and most of the other wells in the area exhibit temperature maxima in the range 180°C to 205°C. These are significantly lower than the maximum downhole temperatures recorded in the Hatchobaru area (>250°C) and definitely indicate that the reservoir is (and always will be) a single-phase liquid system.

DISTRIBUTION OF RESERVOIR PRESSURES

As mentioned above, downhole temperature surveys were made in each well during heat-up and the standing water level in the well was simultaneously monitored. If the elevation of the feedpoint (Z_D, meters ASL) is known and the standing water surface level elevation (Z_W) is also known, the reservoir pressure at the feedpoint elevation may be computed from:

$$P_D = 1 \text{ atmosphere} + \int_{Z_W}^{Z_D} \rho\, g\, dz$$

where $\rho = \rho(P, T)$ and $T(z)$ is the measured temperature profile. The fluid density (ρ) may be taken to be that of pure H_2O for practical purposes; total dissolved materials in the Hohi fluids are generally about 0.001 by mass or less. No direct measurements of downhole pressures (with downhole gauges) have been made in any of the Hohi wells, but it is felt that the above indirect procedure may be used to obtain reservoir pressures accurate within a bar or so.

In this way, each well in the area contributes a single pressure value (P_D, Z_D). Figure 6 shows all these results for the various NEDO wells in the study area. The Kumamoto Prefecture wells (TY-1 and K-7) are also included. Although these data show a clear trend of increasing pressure with decreasing elevation, substantial scatter is present -- a least-squares straight line fit to all the points has a standard deviation (σ) of ±11 bars. It is noteworthy, however, that the wells in the northern high-temperature zone discussed previously (DB-4, TY-1, DW-2, K-7, DW-6, DW-7 and DY-1) all lie on a straight line and, further, that this straight line comprises a lower bound on all the data. In other words, all the other wells in the study area are characterized by higher pressures than the above set. Note that well DB-9, located along the southern boundary of the hot zone, appears to be transitional in that it has high downhole temperatures but also has pressures Some 14 bats higher than the straight line.

These data suggest that the seven wells in the northern area are in good pressure communication with each other. The remaining wells are not particularly well correlated, however. Even if the above seven wells are removed than the data set, a straight-line fit to the remaining data still yields $\sigma = \pm 9$ bars. We note, however, that wells located in regions of relatively high terrain (such as DB-3, DW-1 and DW-5) tend to be characterized by higher pressures than those in lower areas (DB-7, DB-8, DW-3 and DW-4). This suggests trying a two-parameter correlation of the form:

$$P = P_0 + \alpha Z_S - \beta Z_D$$

where Z_S is the elevation of the wellhead above sea level. The least-square fit which results (again excluding the northern wells) is:

$$P = 10.8 + 0.06585\ Z_S - 0.08806\ Z_D$$

where P is in bars and Z_S, Z_D are in meters ASL. This fit results in $\sigma = \pm 4$ bars; if the shallowest (DB-series) wells are excluded, σ declines to ±1 bar. Therefore, we believe that the above correlation adequately represents the pressure distribution outside the northern area, at least in the deeper parts of the system. Applying the same two-parameter fit approach to the seven northern wells alone yields:

$$P = 51.2 + 0.00255\ Z_S - 0.08715\ Z_D$$

(with $\sigma = \pm 1$ bar) which exhibits a much smaller influence of surface elevation (0.00255 compared to 0.06585).

The average vertical pressure gradients found above (0.08715 bars/meter in the northern area; 0.08806 bars/meter elsewhere) correspond to hydrostatic gradients (at 100 bars average pressure). for water columns at temperatures of 183 C and 174 C respectively. The implications are that regions with average temperatures below these values will in general be regions of downward cold-water recharge, whereas those regions at higher temperatures will tend to be regions of upflow.

FLOW CHANNELS AND PERMEABILITY

The NEDO wells in the study area were drilled primarily to provide structural information and core samples for geological studies. Occasionally, permeable horizons were encountered during drilling and were manifested by mud losses; as a general rule, these permeable zones were cemented and cased to facilitate further drilling. No long-term pressure transient testing has so far been perfonned at Hohi. Shortly after completion, each NEDO well was subjected to a short-term (one to two hour) cold water injection test; wellhead pressure was monitored during injection and subsequent falloff. Owing to the absence of downhole instrumentation in these tests and their short durations, results are unreliable and the measurements were frequently uninterpretable (water level sometimes continued to rise during falloff, for example). In one case, repeat measurements yielded permeability-thickness products for the same well that differed by an order of magnitude. Lacking other information, however, an attempt was made to determine an approximate permeability-thickness product from each such test record that was amenable to interpretation.

Generally speaking, these measurements yielded permeability-thickness products for the various DB and DW wells that are rather low -- between 0.03 and 0.5 darcy-meter. The length of the open interval in these wells is typically a few hundred meters, yielding average permeabilities in the range 0.1 to 1 millidarcy. Well DY-2 would not accept fluid unless wellhead pressures were raised to very high values; under normal circumstances it appears to be impermeable. Well DY-3 yielded a permeability-thickness product of 0.6 darcy-meter (with 1100 meters of open hole; average permeability = 0.5 millidarcy). DY-1 is far more permeable; with a permeability-thickness product of 8 darcy-meters and an open-hole length of 700 meters, we obtain a permeability exceeding 10 millidarcies. As mentioned abave, these values are highly uncertain and are probably significantly low on the average due to the practice of cementing aff permeable zones, at least for those wells for which major mud losses occured.

No records of drilling mud losses are available for the shallow (DB series) wells, but the remainder have good drilling documentation. By far the greatest problems with circulation loss ocdured in drilling the northern series of wells: DW-7, DW-2, TY-1, DY-1, K-7 and DW-6. The remaining wells were characterized by only minor and infrequent mud circulation losses. The pattern of mud loss is remarkably consistent among these six wells: upon drilling, major circulation losses were encountered starting about 100 to 200 meters below sea level and persisting for about 500 meters depth below that. At greater depths, circulation losses were occasionally recorded, but were less frequent. Apparently, a major fracture zone exists in this deptn interval which extends laterally several kilometers -- it was encountered in all six wells. The zone furthermore consists of numerous individual fractures, not simply one large crack; typically, major mud losses in this region were encountered every 50 to 100 meters, on the average. Unfortunately, no direct information is available concerning the transmissivity of this fracture zone. In wells DW-6 and DW-7, the cemented casing extends below the fracture zone. No cold water injection results are available for wells DW-2, TY-1 or K-7. In well DY-1, the cemented casing extends below the major part of the fracture zone (to -1100 m ASL), but, as noted above, even the few remaining feedpoints below the casing provide a permeability-thickness product estimated at 8 darcy-meters.

DY-1 is the only project well that has been produced. Since June 1982, DY-1 has been discharging continuously with occasional interruptions (about every nine months) for calcite cleanout. Unfortunately, no downhole measurements have been made under flowing conditions nor have wellhead measurements been made with sufficient temporal resolution to permit interpretation as a pressure-transient test. Discharge rates have been deliberately varied between 15 and 60 kg/s (with an average value of about 25 kg/s) to establish the well's flowing characteristics. Flowing wellhead pressures vary between 0.5 and 1.5 bars gauge, depending on discharge rate. No systematic degradation of wellhead pressure or flow-rate has been observed except that due to periodic calcite plugging. After cleanout, well performance returns to normal. Wellhead fluid properties are consistent with a bottomhole fluid temperature of 185°C (the same as the shut-in static value). It is impossible to interpret the available measurements to obtain quantitative permeability values, but the mere fact that the well will discharge at a high rate without measurable degradation for a long period of time suggests that substantial permeability must be present in the neighborhood of well DY-1.

Twenty major hot spring areas lie within the study area or immediately adjacent to it. The total natural discharge rate for these springs is in the range 150 to 200 kg/s. Roughly one-half of this discharge comes from springs in the extreme northern part of the study area (Kushino, Kawazoko, Hosenji, Ikiryu and Kabeyu). Numerous chemical analyses have been performed on the fluids discharged from these springs. Total dissolved solids are quite low. Three major anions are present: chloride (Cl^-), sulfate ($SO_4^{=}$) and carbonate (reported as H_2CO_3, HCO_3^- and $CO_3^{=}$). A clear spatial pattern can be discerned in the distribution of these anions among the various hot springs. If the "relative sulfur content' is defined as:

$$\frac{\text{moles sulfate}}{\text{moles sulfate+moles carbonate+moles chloride}}$$

the results for the various hot springs are distributed as shown in Figure 7, which also indicates the approximate temperature of the discharging fluid in each case. Sulfur contents for deep fluids discharged from well DY-1 and a nearby shallow water well (K-6) are also shown. At least three distinct regions are present. In the north, the "low sulfur region" contains the hot springs at Takenoyu, Hagenoyu, Kawazoko, Kushino, Hosenji, Ikiryu and Kabeyu as well as the two deep samples. All these fluids have sulfur contents of 0.07 or less. Immediately adjacent to the southwest is the "high sulfur region" with sulfur contents exceeding 0.6 including Yamakawa, Nuruyu, Oguni-Kozan and Teraono. The remainder of the hot springs (the "moderate sulfur region') lie in an arc along the southern and southeastern borders of the study area, and (with one exception) are characterized by sulfur contents in the range 0.2 to 0.5.

The implications of these chemical results are as follows. There is a possible hydrological connection between the hot springs near Hatchobaru and those along the southern boundary (Manganji, Tanoharu, Kurokawa). The very low sulfur content of the springs in the extreme north is reflected at Takenoyu/Hagenoyu, implying a common source for these waters, and this region of low sulfur content in the north extends to great depth, as shown by the sample from well DY-1 (2 km deep). Finally, despite their relative proximity, there is a dramatic difference in water chemistry between the springs at Takenoyu/Hagenoyu and those near Yamakawa, implying differing fluid sources.

Both airborne side-looking radar and satellite surveys have been made of the study area, revealing numerous surface lineament features as indicated in Figure 8. These lineaments may represent the surface expressions of faults and/or fracture zones which could provide conduits for fluid flow. Several major features may be discerned. A long lineament trending north-northeast in the southeast area connects the Hatchobaru/Ohtake area with the vicinity of the Suzumeno-Jigoku fumerole, where it intersects a pronounced system of lineaments running east-west along the southern boundary which surround the hot springs at Tanoharu, Manganji and Kurokawa. Since all these springs discharge chemically similar waters, it seems possible that these lineaments represent underground flow channels. Along the southern boundary, flow must be from east to west based on the surface topography and its observed influence on underground pressures; it is noteworthy that hot spring discharge temperature declines as one moves west. In the Hatchobaru area, a similar gradient in discharge temperature is present, with temperatures highest at Hatchobaru itself and declining northward. Whether a single deep source of hot fluid underlying Suzumeno-Jigoku/Hatchobaru and represented at the surface by the long lineament discerned above is supplying this entire part of the system (flowing both northward towards Kawarayu and westward toward Tanoharu) or whether two separate sources are involved is unclear.

The fluid source for the "high sulfur" hot springs is likewise somewhat ambiguous. The total discharge rate for this group of springs is low (30 kg/s or so) and discharge temperatures are uniformly low as well (50°C or less). We suspect that these springs are basically artesian; they lie at relatively low elevations (600 m ASL or so) and are immediately adjacent to Mount Waita (1500 m ASL). The basic notion is that meteoric water sinks downward near the summit of Mount Waita (where it is heated somewhat), then flows horizontally westward at depth through fissures under the influence of the prevailing pressure gradient to emerge at the hot springs. This model derives some support from the surface lineament map (Figure 8) which shows a series of east-west features in the area which could be the surface expressions of such a set of fluid conduits. Additional support is provided by the drilling records for the only deep wells in the area (DW-1 and DY-2); both exhibited noticeable circulation losses during drilling, but only in the upper part of each bore (above sea level). This likewise implies the existence of a shallow fracture system in the vicinity.

Much more definite statements can be made about the northern low-sulfur region. As discussed previously, magnetotelluric evidence suggests that a very deep source of upwelling hot fluid is oriented east-west underlying the Takenoyu/Hagenoyu area. This upflow probably occurs along an east-west set of subparallel faults associated with an abrupt change in basement depth. This upwelling fluid is presumably responsible for the high-temperature surface discharges at Takenoyu and Hagenoyu. Evidence is strong, however, that this upwelling fluid does not spread southward. First, as mentioned above, the natural discharges to the south (Yamakawa, Oguni-Kozan, Nuruyu and Teraono) are chemically very distinct from those at Takenoyu/Hagenoyu. Even more compelling, pressures measured in wells located just south of the fluid source (DB-9, DY-2) are some 15 bars higher than those to the north (TY-1, K-7, DY-1, DW-2, DB-4, DW-6, DW-7). Since fluid cannot flow against an adverse pressure gradient, the flow direction must be northward.

The similarity in water chemistry between the Takenoyu/Hagenoyu discharges and those several kilometers further north suggests that the upwelling fluid flows to the north at depth toward the low-elevation discharge points near the northern boundary of the study area. The excellent pressure correlation observed among the various wells in this northern area is strongly indicative of a highly permeable system of substantial horizontal extent. Presumably, heat is lost along the way due to mixing since discharge temperatures are substantially lower for the northernmost springs than for Takenoyu and Hagenoyu. The temperature maxima in the various northern wells between 0 m ASL and -500 m ASL and the high incidence of drilling fluid losses experienced in this same depth interval indicates that the primary channel for this northward current lies in this depth range.

It is instructive to attempt to estimate the permeability present in this vicinity in an approximate way. We assume that the discharges in the northern hot springs (Kabeyu, Ikiryu. Hosenji, Kushino and Kawazoko; total discharge 80 kg/s) are being supplied from a deep hot fluid source underlying Takenoyu/Hagenoyu, about 5 km to the south. The average elevation of these hot spring discharge points is 500 m ASL (pressure = 1 bar). Near Takenoyu/Hagenoyu, the pressure at 500 m ASL is estimated from the local downhole pressure measurements to be about 9.5 bars. Thus, the driving horizontal pressure gradient is 8.5 bars/5 km or 170 Pa/m. We next assume that the east-west width of this northward current is about 3 km, and that the mean temperature along the flow path is 125°C, midway between the 200°C source temperature and the 50 C discharge temperature. The associated fluid kinematic viscosity is 2.4 x 10^{-7} m^2/s; application of Darcy's law to obtain a permeability-thickness product then yields:

$$kH \approx 40 \text{ darcy-meters}$$

Most of the permeability is probably concentrated in the horizontal fracture zone in the upper part of the Pre-Kusu layer, although some permeability is present at greater depths as well (well DY-1 exhibits ~ 8 darcy-meters below -1100 m ASL as noted previously).

ONGOING ACTIVITIES

NEDO's exploratory drilling program in the Hohi area is now expanding eastward; two very deep wells are being completed northeast of Hatchobaru/Ohtake to investigate the origins and extent of the thermal anamoly supplying the power stations there. Reservoir engineering studies will soon be undertaken which will focus on this area to better characterize the southern thermal anamoly and its relationship with the local hot springs and other shallow thermal manifestations. Furthermore, geophysical survey studies in the area (particularly magnetotelluric measurements) are continuing.

In the northern reservoir, design work is presently in progress for a long-term (several month) drawdown/buildup test on well DY-1. Downhole pressures in DY-1 will be monitored continuously and, in addition, a number of the nearby shut-in wells will be instrumented to detect any induced pressure response. This large-scale pressure-transient test, planned for 1985 - 1986, should help quantitatively characterize the volume, transmissivity and structure of the northern thermal anamoly so that definite plans may be made for electrical power production.

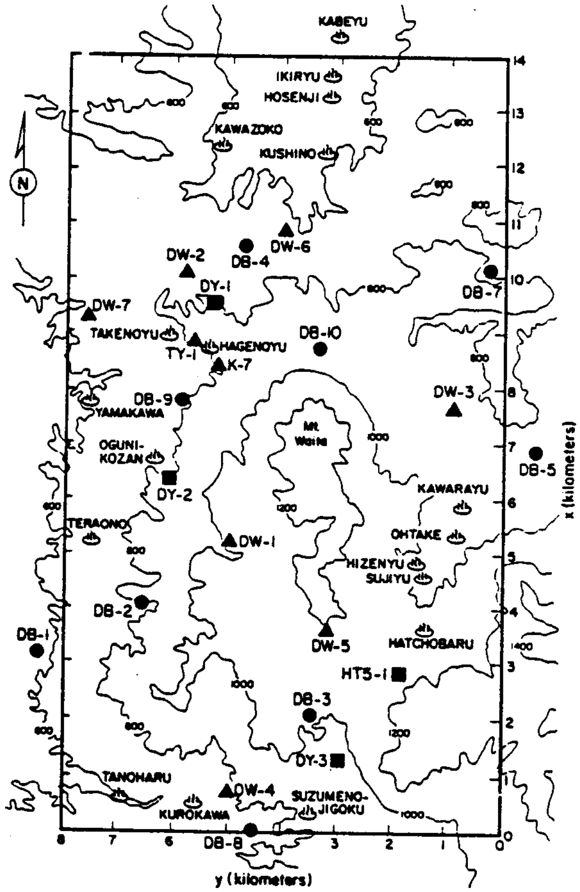


Figure 1. Outline of Hohi study area showing wells, hot springs and surface elevation contours (m ASLI.

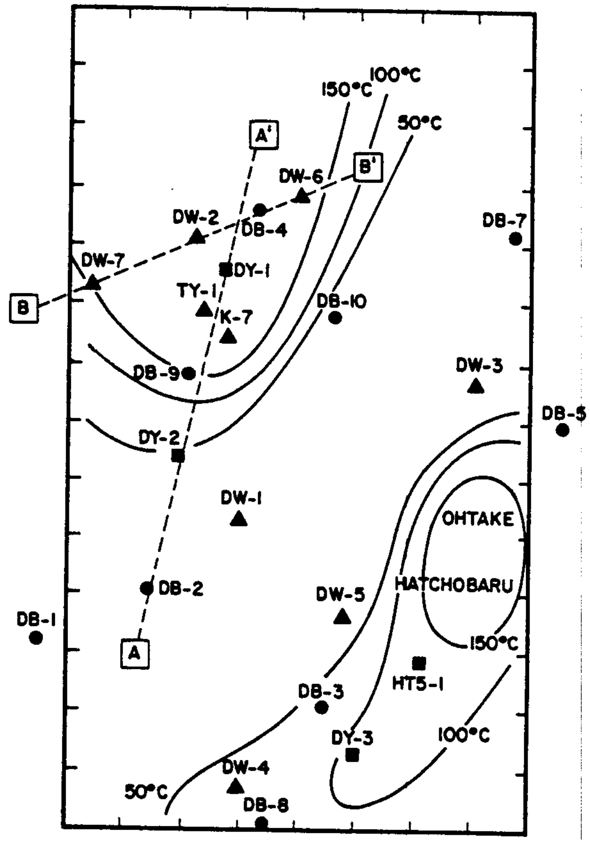


Figure 3. Estimated temperature at 500 m depth and location of A-A' and B-B' profiles.

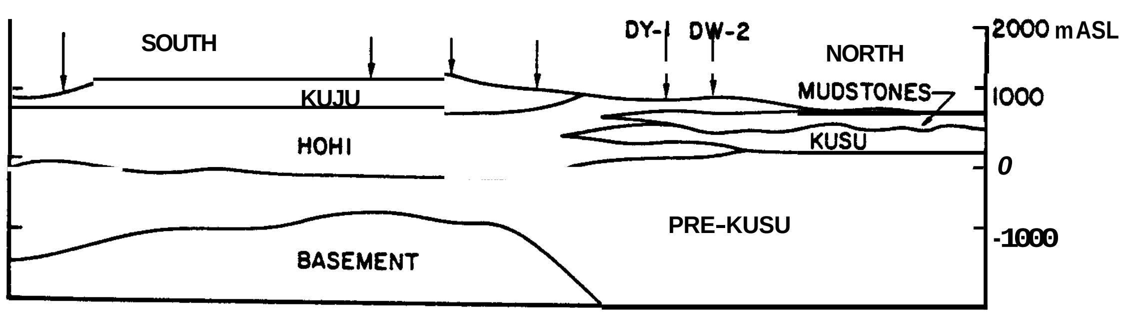


Figure 2. Stratigraphic sequence at Hohi.

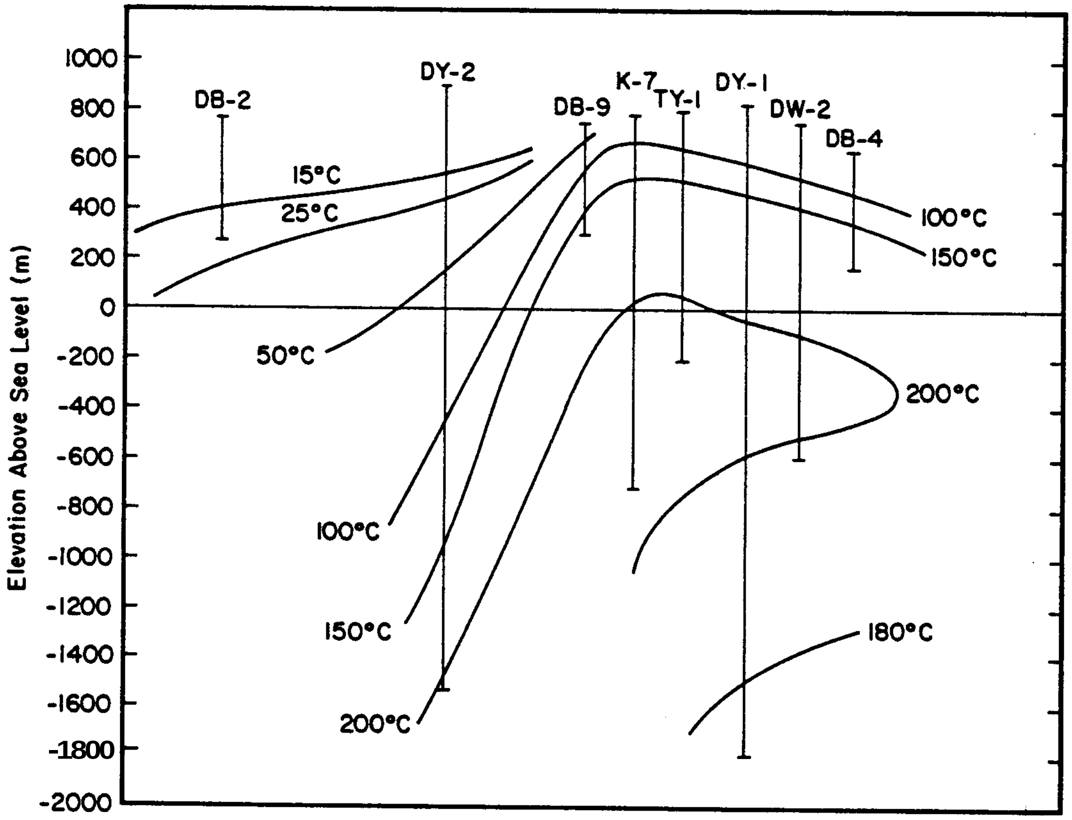


Figure 4. Vertical temperature distribution along south-north section A-A'.

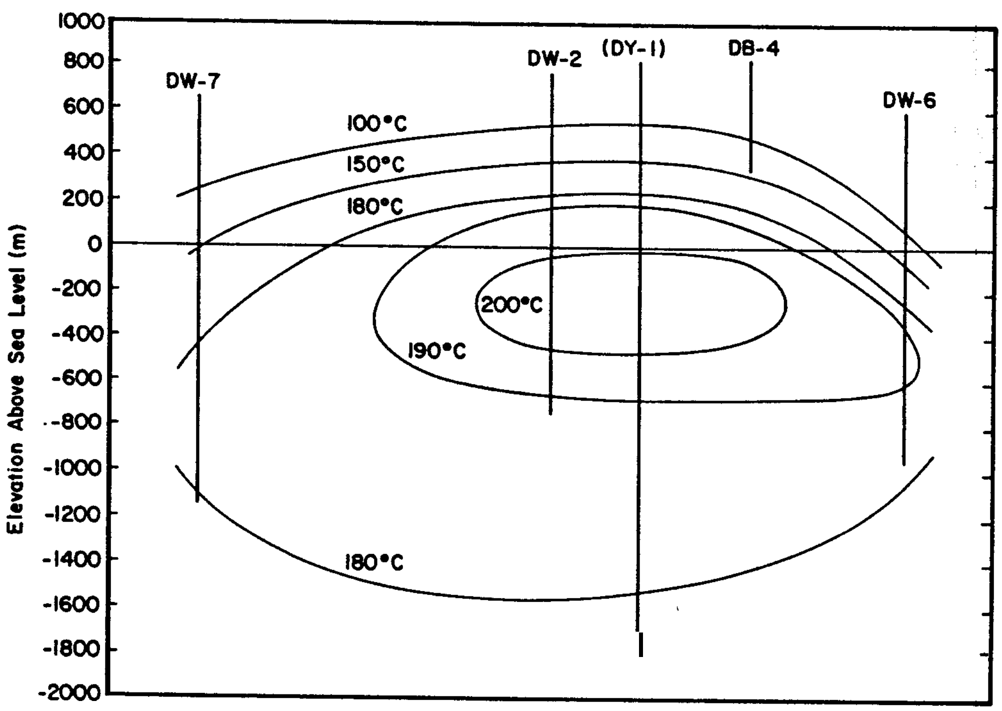
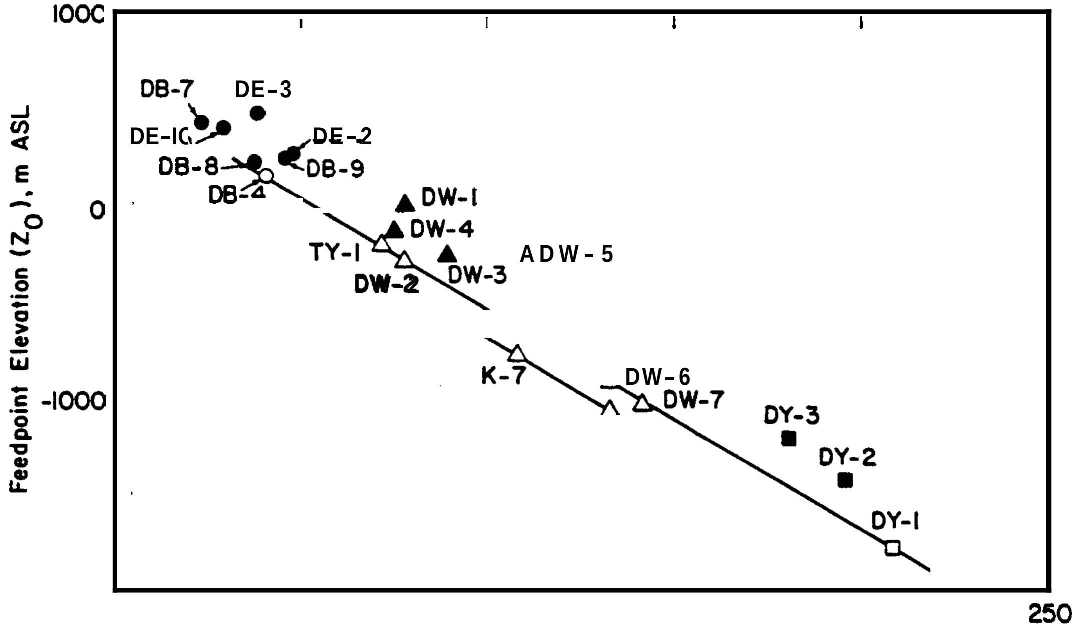


Figure 5. Vertical temperature distribution along west-east section B-B'.



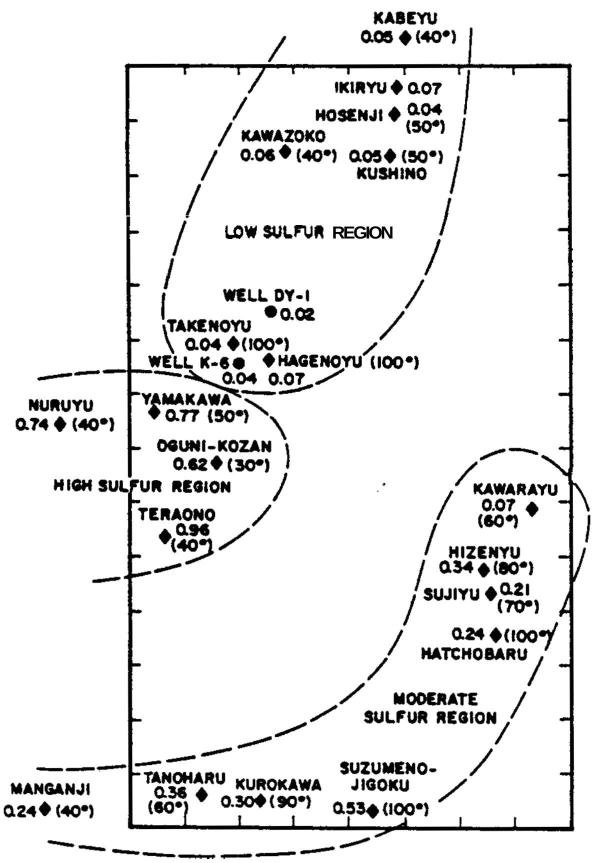


Figure 7. Temperatures and relative sulfur contents for hot springs and wells (sulfate/sulfate + carbonate + chloride).

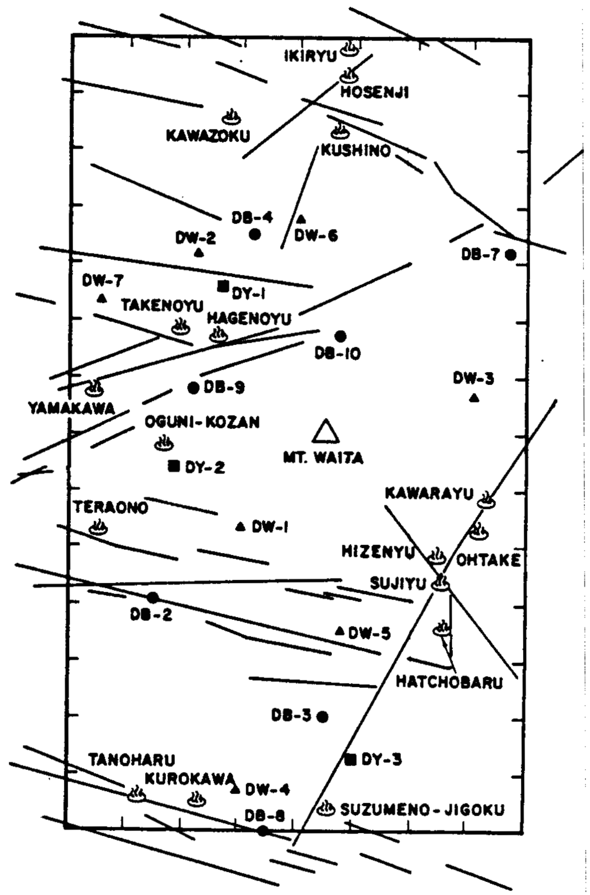


Figure 8. Major lineaments.