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Characterization of geothermal systems in volcano-tectonic depressions : Japan and New Zealand

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Abstract: Characterization of geothermal systems was investigated in two regional scale volcano-tectonic depressions, the Kuju-Beppu Graben (KBG), in Japan, and the young-Taupo Volcanic Zone (TVZ) in New Zealand. The distribution patterns of geothermal fields are different. In the KBG they are restricted to areas on and behind only the youngest volcanic front, but are evenly spaced throughout the whole of the young-TVZ. The youngest volcanism (<0.3 Ma) in the KBG comprises andesitic lava domes and stratovolcanoes, but is dominated by caldera-forming or dome-building rhyolite eruptions in the TVZ. The heat sources of the active geothermal fields are assumed to be andesitic magma chambers and consolidated magma plutons in the KBG, and are associated with high-level rhyolitic magma chambers in the TVZ. The different heat sources and heat flow regimes result in different geothermal field characteristics. In the TVZ shallow (500-1500 m depth), exploitable reservoirs contain boiling or near-boiling fluids (250-300^{o}C) stored in Quaternary permeable layered aquifers of volcano-sedimentary origin lying above a poorly permeable Mesozoic basement. In the KBG the reservoirs are deeper (1000-2000 m depth) and lower temperature (ca. 220^{o}C) because the Quaternary andesitic magma-ambient zone is believed to be deeper than that of the TVZ, and deep-penetrating groundwater extracts heat from fractured volcanics above a thicker conductive zone with lower geothermal gradient. Thus it is concluded that the heat discharged by geothermal fluids in the two volcano-tectonic depressions is greatly controlled both by the depth of the magma-ambient zones, and by the depth to which the cool groundwater convection cells can penetrate.

Key words: volcano-tectonic depression, geothermal system, Kuju-Beppu Graben, Taupo Volcanic Zone, heat source, geothermal reservoir.

1. Introduction

The structural location of geothermal fields is of considerable interest to geologists seeking to understand the connections between the shallow, exploitable horizons, and the deep, unexplored roots of hydrothermal systems. Some regions of intense geothermal activity are within a broad volcano-tectonic depression, a generic term first used by van Bemmelen (1949) to describe a large-scale depression, usually linear, that is controlled by both tectonic and volcanic processes (Bates and Jackson, 1987). The depressions are commonly associated with rifting on and behind island arcs generated by plate subduction, and are characterized by extensive pyroclastic flow deposits and structural features typically associated with grabens. This paper provides a comparative study of two such areas, the Kuju-Beppu Graben (KBG) in Kyushu Island, Japan, and the Taupo Volcanic Zone (TVZ) in the central part of North Island, New Zealand. Similar Quaternary volcano-tectonic depressions containing geothermal fields occur on other Western Pacific island arcs such as the Philippines and Indonesia. A preliminary comparison of the KBG and the TVZ was first presented by Tamanyu and Wood (1997), and a similar comparative study of the TVZ and the Philippines Mobile Belt, with special reference to arc- and rift-type geochemistry, was made by Reyes (1995). Hochstein (1995) made the comparison of crustal heat transfer in the TVZ with other volcanic arcs including Kyushu, Japan.

2. Volcano-tectonic setting

2.1 The Kuju-Beppu graben

The KBG is a volcano-tectonic depression about 50 km long and up to 40 km wide, located in the northern central part of Kyushu Island (Fig. 1). The KBG is regarded as the typical volcano-tectonic depression in Japan as well as the Kagoshima graben. It is characterized by a low gravity anomaly zone, and the mar-

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gins are delineated by three tectonic lines; the Matsuyama-Imari Tectonic Line to the north, the Oita-Kumamoto Tectonic Line (corresponding to the western extension of the Median Tectonic Line) to the south, and the southern extension of the Kokura-Tagawa Tectonic Line to the west (Sasada, 1984). The Kuju-Beppu Graben was first named by Matsumoto (1979), who considered it to be the eastern part of the larger Beppu-Shimabara Graben. It was also named as the Hohi volcanic zone by Kamata (1989). Tamanyu (1993) previously used the name Beppu-Kuju Graben, but here we revert to the KBG as having priority of nomenclature. The three tectonic lines delineating the KBG originated in the pre-Tertiary era, and were reactivated in Quaternary times. The KBG had formed during early-middle Pleistocene age, but includes earlier Pliocene depressions within it (Tamanyu, 1993). The debate continues whether the KBG is a continental rift with spreading south and north (Tada, 1993), or a right-lateral shear zone caused by oblique subduction of the Philippine plate beneath the Kyushu island of Japan (Fig. 1, Tsukuda, 1993). No evidence of crustal thinning has been demonstrated at the KBG (e.g. Yoshii, 1972; Zhao *et al.*, 1992). The KBG includes many geothermal fields, together known as "the Hohi geothermal area", and also includes the active volcanoes Yufu-Tsurumi, Kuju, and Aso (out of KGB), which lie on a NE-SW trend. The geothermal fields or high temperature hot spring areas occur only on and behind the active volcanic range except distant lateral flows.

2.2 The Taupo volcanic zone

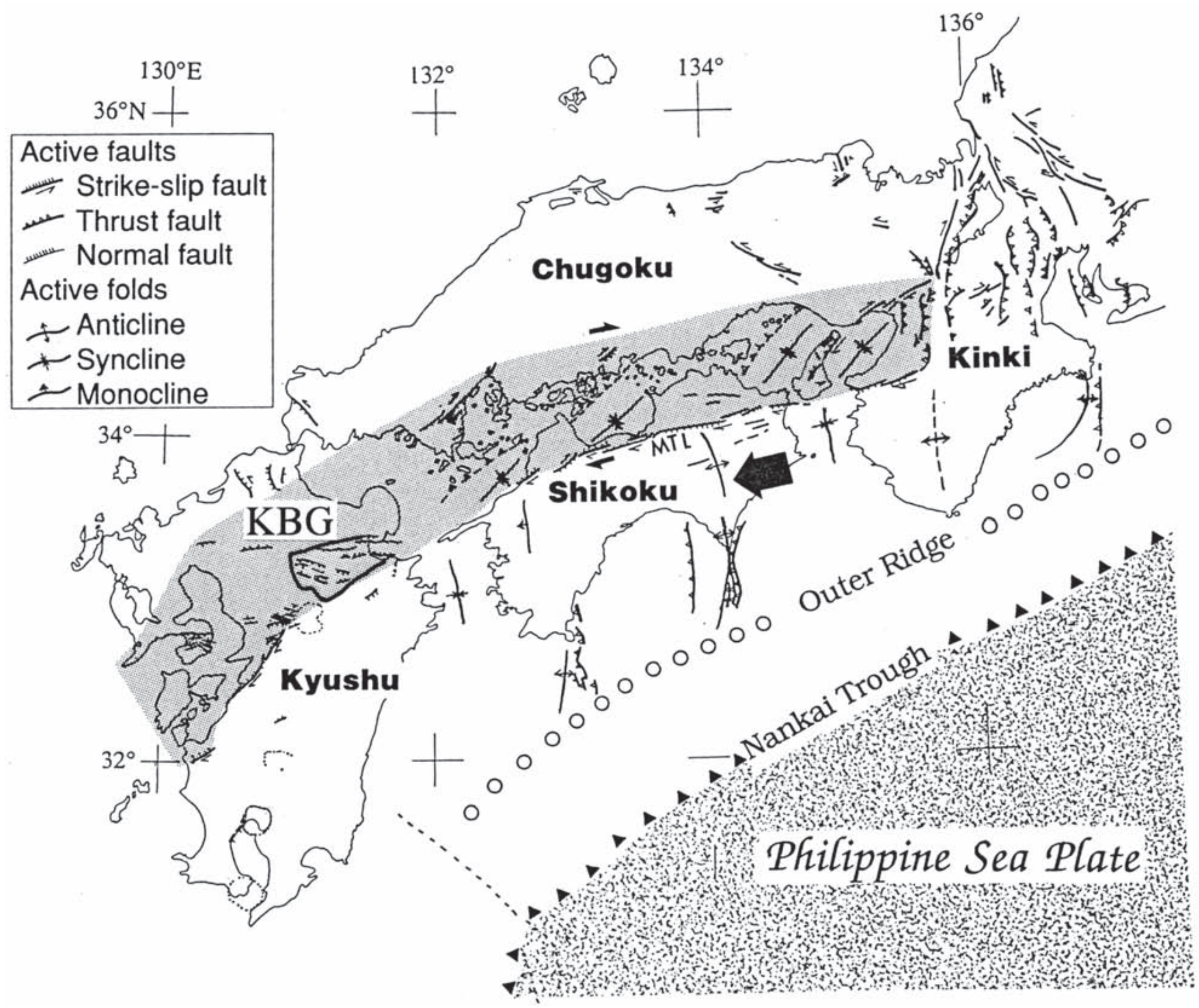

Fig. 1 Tectonic setting of the KBG in terms of oblique subduction of Philippine Sea Plate, after Tsukuda (1993). Solid arrow indicates the direction of the fore-arc translation. Shaded area indicates the right-lateral shear zone (Seto'uchi shear zone). MTL: Median Tectonic Line. The location of the KBG is added by the authors.

The TVZ is defined as the area enclosed by an envelope drawn around the late Pliocene to Quaternary caldera margins and individual vent sites associated with the NNE-SSW -oriented Kermadec subduction system. The TVZ is distinguished from other modern volcanic arcs by its anomalously high heat discharge, voluminous rhyolite volcanism and widespread geothermal activity, and regarded as the consequence of Pacific plate subduction beneath the North Island of New Zealand (Wilson *et al.*, 1984). The thin (ca. 15 km, Stern and Davey, 1987) continental crust spreads at rates possibly as high as 18 mm/year (Darby and Williams, 1991) resulting in active rifting and subsidence (Fig. 2a, 2b). Volcanic activity within the TVZ possibly commenced as early as 2 Ma. The central part has been dominated by voluminous rhyolite magma production since at least 1.6 Ma. Most TVZ geothermal fields are contained within the area of rhyolite volcanism, and to that part of it, which Wilson *et al.* (1995) have designated as the "young-TVZ" (Fig. 5). The young-TVZ includes all volcanic centres of the Whakamaru-group eruptions (0.34 Ma) as well as younger and presently active volcanoes. It excludes the older western sector of the TVZ where no post-Whakamaru-group volcanic centres are recognised. By contrast, the eastern margin has been the site of sporadic volcanism, probably for much of the life of the TVZ. Within the young-TVZ is the present day zone in which rifting and tilting occur, and is in effect, the graben and horst structure of the modern TVZ (Wilson *et al.*, 1995). The KBG and the young-TVZ have simi-

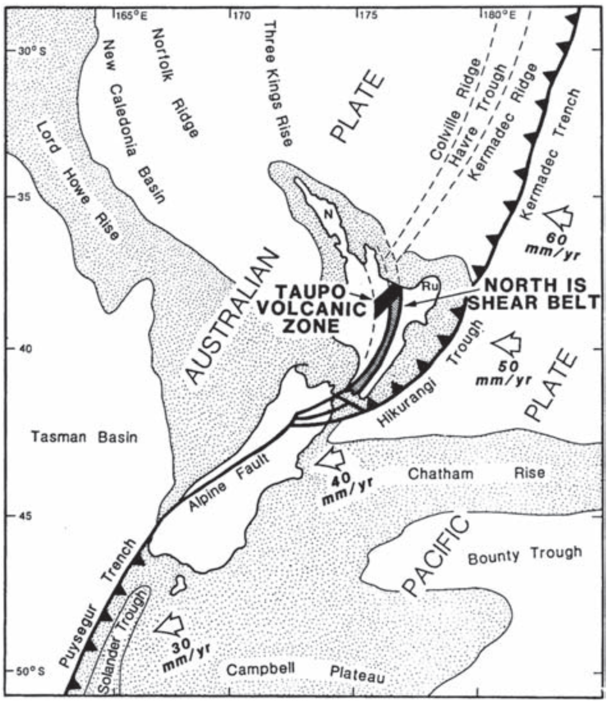

Fig. 2a Tectonic setting of TVZ in terms of Pacific Plate subduction (Cole, 1990). Stippled area represents continental crust. Arrows show motion of Pacific Plate relative to the Australian Plate. Rates are from Walcott (1987).

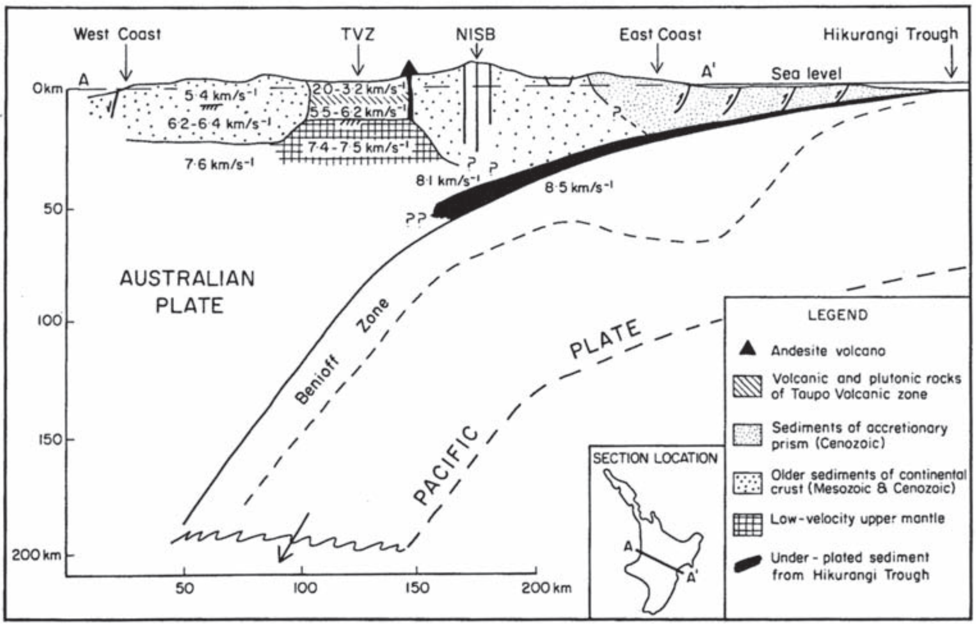

Fig. 2b Schematic cross section of the central North Island showing crustal and upper mantle structure as determined from seismology (Cole, 1990, after Smith *et al.* (1989) ; Walcott (1987))

lar width (20-40 km), though the latter has a much larger area of 3400 km^2 compared with 1500 km^2 of the KBG.

3. Geological framework

3.1 The KBG geological framework

The geological framework and evolutionary history of the KBG were investigated using stratigraphic evidence from drill hole correlations (e.g. Tamanyu, 1993). Four stages of volcanism and tectonism can be recognised in the Pliocene and Pleistocene epochs by Tamanyu (1993) based on stratigraphic correlation and dated ages (Fig. 3):

Pliocene depression stage (6?-1.1 Ma),
Early-middle Pleistocene depression stage (KBG, 1.1-0.5 Ma),
Late Pleistocene volcanic arcs stage (the older volcanic front and the youngest volcanic front)(<0.5 Ma),
Recent stage of active faulting (<0.01 Ma).

Five volcanic depressions, about 10 km in diameter, were formed as centers of volcanism in the Pliocene in and around the proto-KBG. Subsequently, the KBG was formed as a volcano-tectonic depression with extensive early Pleistocene andesitic volcanism. Thick volcanic piles accumulated within both Pliocene and Pleistocene depressions which have average subsidence rates of about 1 km/Ma (Tamanyu, 1993). The maximum subsidence rate of the KBG was calculated as 1.7 km/Ma in the Shishimuta subsidence zone. The last collapse associated with the Yabakei Pyroclastic Flows from this subsidence zone, was named as the Shishimuta Caldera by Kamata (1989). The late Pleistocene and Holocene volcanics are classified into an older dacite group and a younger andesite group. The latter forms the youngest volcanic front (<0.3 Ma) consisting of andesitic volcanoes : Tsurumi, Yufu, Kuju and Aso. This front crosses obliquely from southwest to northeast in and around the KBG.

3.2 TVZ geological framework

The geologic framework and evolutionary history of the TVZ have been investigated mainly by volcano-

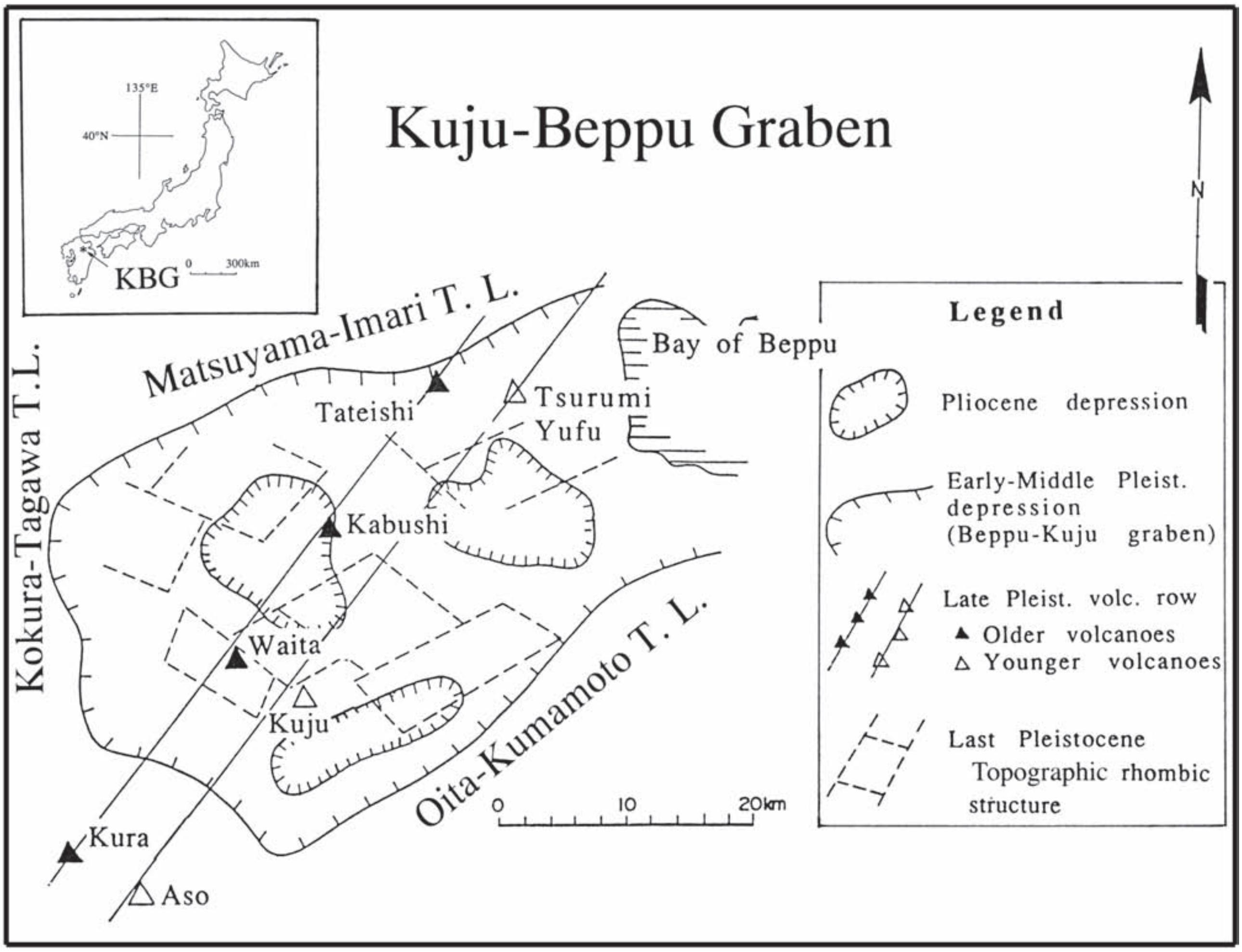

Fig. 3 Principal geologic structures in the KBG (Tamanyu, 1985)

stratigraphic correlation and radiometric dating. Three epochs have been identified (Wilson *et al.*, 1995):

The old TVZ (2.0-0.34 Ma),
The earlier young-TVZ (0.34 Ma to 65 ka),
The later young-TVZ (= The Modern TVZ) (<65 ka).

Geophysical and drilling data have also been used to reveal the subsurface stratigraphy and structures. The eastern margin of the TVZ corresponds to the Kaingaroa Fault Zone (Risk *et al.*, 1993) where deep resistivity structure and drillhole evidence confirm down-stepping of Mesozoic Torlesse Terrane basement to depths of 2 to 4 km over a lateral distance of about 10 km. Most of this faulting appear to have occurred prior to ca. 0.3 Ma, and there is no strong evidence to suggest that there has been any migration of volcanic or geothermal activity eastward since then. Hence, the relative position of the TVZ eastern boundary has remained within the active young-TVZ. Volcanic caldera collapse and regional tectonism have contributed to subsidence, while concomitant tilting and relative uplift has occurred in horst blocks bounded by major regional faults. Estimate of the amount of subsidence is made possible by drillhole data on the elevation of the top of the Whakamaru-group ignimbrites, which must have formed a flat surface across a wide area immediately after the ca. 0.33 Ma eruptive episode. At Ohaaki, near the eastern TVZ margin, the ignimbrite surface is covered by 800-1200 m of younger deposits, while at Mokai on the western edge of the graben of the modern active zone, the surface is around 1000 m deep. An average accumulation rate of 3 km/Ma is implied for the young-TVZ by the calculation of 1 km divided by 0.34 Ma.

4. Geothermal fields

4.1 The KBG Geothermal fields

There are eleven fields in the KBG with high-temperature (>75°C) hot springs (Fig. 4). All occur on or behind the youngest volcanic front, and there are no high-temperature hot springs in front of the youngest volcanic front, with the exception of Beppu North and South where the hot waters have migrated eastward from the active volcano Tsurumi (e.g. Allis and Yusa, 1989). Most of thermal fields are located in and around local high gravity anomaly zones. Four exceptions are the Yufuin and the Hosenji fields which originate from the edge of a high gravity anomaly zone and flow down into a low gravity anomaly zone, and the Tsuetate and the Amagase hot spring fields, which occur in isolation on the northwestern part of the KBG without relationship to any gravity anomalies. Four geothermal power plants are located at Otake, Hatchobaru, Takigami and Suginoi while another power plant is under planning at Oguni. It is worth noting that the Takigami geothermal power station is located at the boundary of high and low gravity anomalies, although no remarkable surface thermal manifestations occur there (Hayashi, *et al.*, 1988).

The convective heat flux from hot springs in the KBG is calculated as about 350 MW/1600 km^2 (0.22 MW/km^2), a value derived from the map of heat discharge by hot springs in Japan (Sumi, 1980), and from original data shown in Sumi (1977). This value is a minimum because it includes neither “natural steaming” nor thermal water discharging directly into steams and rivers. A larger value of about 700 MW/2400 km^2 (0.29 MW/km^2) includes hot springs and fumaroles, and was derived from the map showing average heat flow by mass transfer in central Kyushu (Ehara, 1989).

4.2 TVZ Geothermal fields

The natural geothermal output of the TVZ has been estimated at 4200±500 MW (Bibby *et al.*, 1995), and this is believed to account for 70% of the total heat transfer through the region (Hochstein *et al.*, 1993). About 90% of this geothermal heat output is channelled through 18 fields located within or on the margins of the modern zone of active faulting and rifting as shown on Fig. 5. The only field which lies well outside the young-TVZ is Mangakino, and the only field outside the rhyolite-dominant sector is the Tokaanu/Waihi field. The latter occurs to the south of Lake Taupo where the volcanic style is transitional from rhyolite to andesite-dominated.

The geothermal fields are more or less evenly spaced, though shallow hydrological effects have resulted in the surficial merging of some fields which appear to have independent deep heat sources. Examples are Wairakei-Tauhara, Orakeikorako-Ngatamariki, and Waimangu-Waiotapu-Reporoa. Other fields which appear separate at the surface may have deep hydrological connections, such as Mokai-Ongaroto (Bibby *et al.*, 1995).

The structural associations of TVZ geothermal fields were examined by Wood (1995) who concluded that the majority of the fields were located at the margins of major calderas. These calderas are believed to provide deep-rooted fracture systems which allows circulation of both cold and hot water into heat-source regions which may not be directly beneath the shallow parts of the fields, but more centrally located within the calderas. As a corollary to this, there are at least two examples of calderas filled with rhyolite domes and pyroclastic deposits (Haroharo and Maroa) which are singularly devoid of thermal activity in their elevated central parts (hence are possible areas of cold water downflow), but have major hot upflows at their margins (e.g. Waimangu and Mokai). Only one geothermal field, Taupo, is located convincingly within the central part of a caldera, where it is associated with the putative main eruptive vents (Caldwell & Bibby, 1992).

Three geothermal fields located within 10-15 km of the eastern TVZ margin are either clearly unrelated (Kawerau and Ohaaki), or only doubtfully related (Rotokawa) to a caldera. All three fields occur above the zone of faulting that drops the Mesozoic Torlesse Terrane basement progressively down from east to west into the TVZ depression (Wood, 1996). It is not certain if there is a cause-effect relationship between the east margin structure and the field locations. The fault zone appears to be continuous along the length of the TVZ, and may have been in this relative location for much of its lifetime. Hence it is unlikely that the fault zone is a continuous region of high permeability that allows groundwater to circulate down to a deep and continuous belt of hot rock/magma. Otherwise, there ought to be more, and evenly spaced hydrothermal systems of the Ohaaki type along the eastern margin. More likely, the fields have been generated above isolated volcanic-plutonic hot spots: the geological sequences at Ohaaki and Kawerau (drilled and cropping out at the periphery) include both rhyolite and andesite lava piles indicative of intermittent phases of magma generation and eruption throughout the time-frame of the young-TVZ. However, the major faults cutting the basement do appear to provide conduits for rising hot fluids (particularly where there are localized horst structures), though poor drilling results suggest the

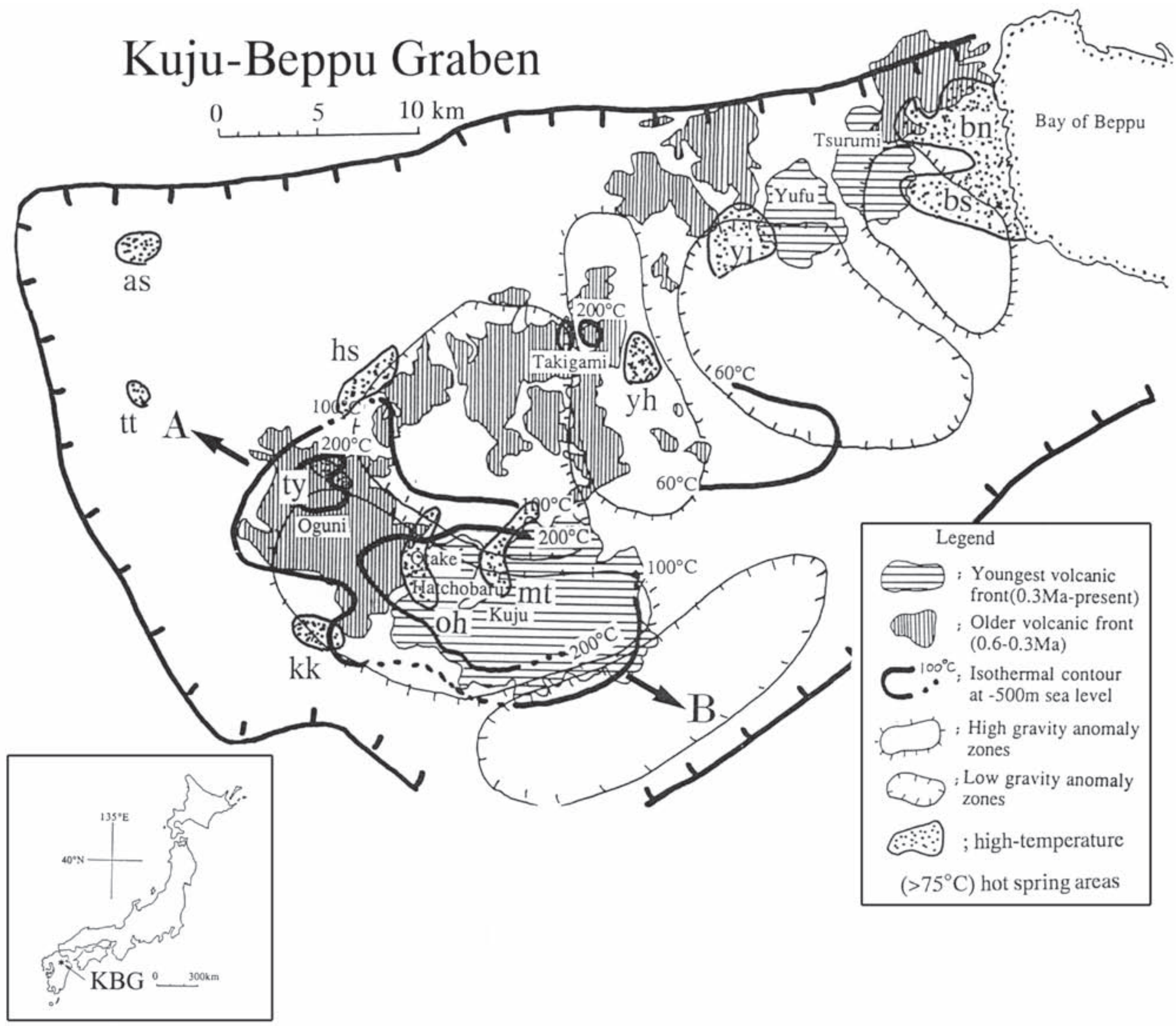

Fig. 4 Distribution map of the geothermal fields in the KBG (Tamanyu, 1994b, partly revised). Geothermal fields are referred from NEDO(1990), and stippled and labelled: bn=Beppu North, bs=Beppu South, yi=Yufuin, yh=Yunohira, mt=Makinoto-toge, oh=Otake-Hatchobaru, kk=Kurokawa, ty=Takenoyu, hs=Hosenji, tt=Tsuetate, as=Amagase

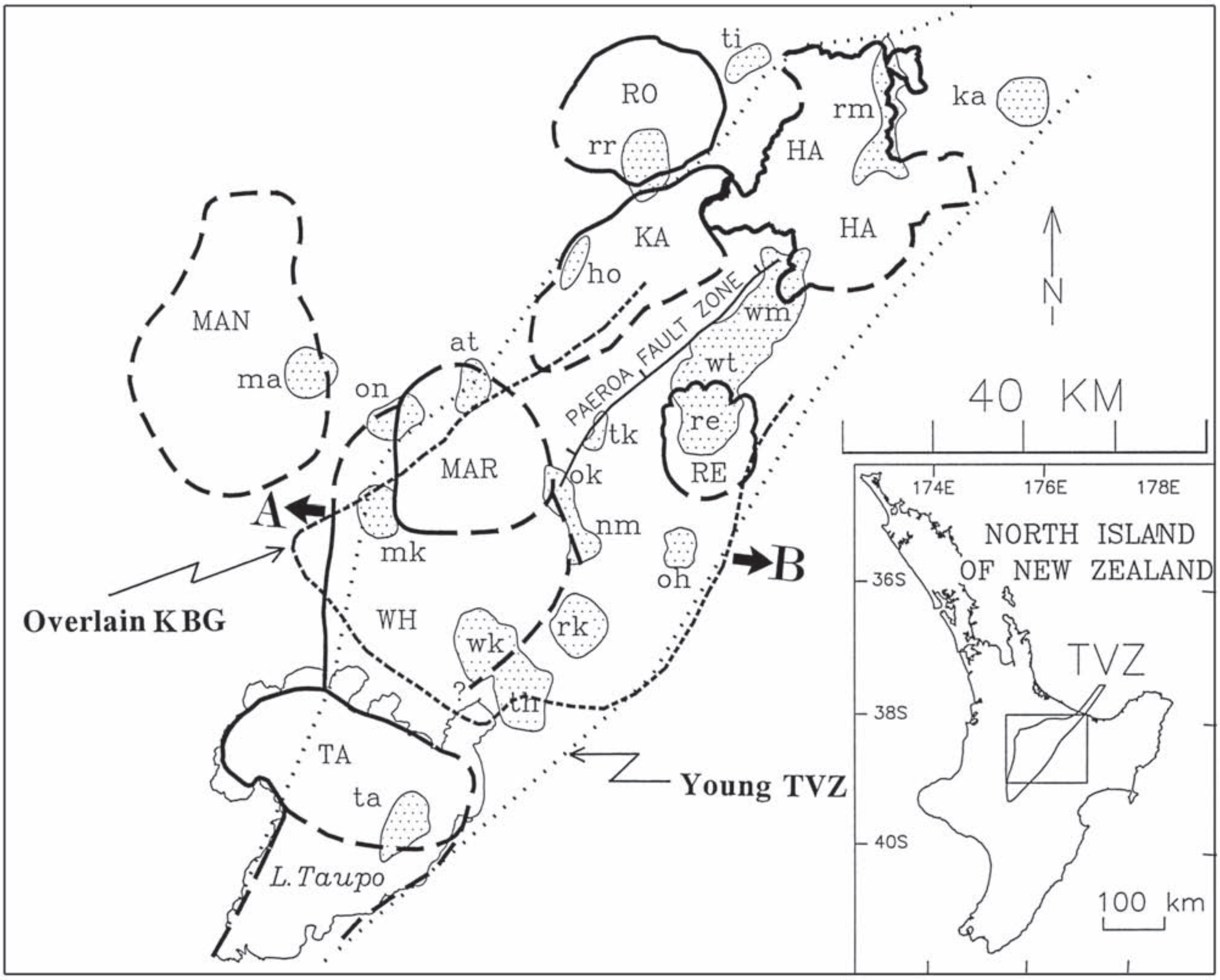

Fig. 5 Outline map of the central part of the Taupo Volcanic Zone (after Wood, 1995), showing geothermal fields (stippled areas) and calderas, and the position of the young-TVZ (dotted line). The outline of the KBG is overlain for comparison.
Geothermal fields: at=Atiamuri, ho=Horohoro, ka=Kawerau, ma=Mangakino, mk=Mokai, nm=Ngatamariki, oh=Ohaaki, ok=Orakeikorako, on=Ongaroto, re=Reporoa, rk=Rotokawa, rm=Rotoma, rr=Rotorua, ta=Taupo, th=Tauhara, ti=Tikitere, tk=Te Kopia, wk=Wairakei, wm=Waimangu, wt=Waiotapu.
Calderas: HA=Haroharo, KA=Kapenga, MAR=Maroa, MAN=Mangakino, RE=Reporoa, RO=Rotorua, TA=Taupo, WH=Whakamaru

permeable sectors of the faults have limited lateral extent (Wood, 1996).

Te Kopia geothermal field lies midway between the Maroa and Reporoa calderas, and is clearly associated with the Paeroa Fault Zone which controls the location of surface activity. However, the hydrothermal system may be linked at depth with Orakeikorako (Bignall and Browne, 1994), a field which occurs at the junction of the Maroa and Whakamaru caldera eastern margins (Wood, 1995).

5. Structural-geothermal cross sections

5.1 The KBG cross-section

Contours of shallow subsurface temperatures are usually concordant with surface geothermal manifestation such as fumaroles, alteration zones and hot springs. On the other hand, contours of deep subsurface temperatures are concordant with subsurface relief of the pre-Tertiary basement (Fig. 6). This thermal pattern indicates that hydrothermal convection is dominant in the Neogene formations, and conductive heat transfer is dominant in pre-Tertiary basement. The Neogene formations play the role of a permeable porous media for fluid flow, while the pre-Tertiary basement acts as an impermeable media, except where there is fracture permeability (Tamanyu, 1994a, 1994b). The top surface of pre-Tertiary formation can be estimated by analysis of Bouguer gravity anomaly data with reference to bore hole control points. The deep subsurface temperature pattern in pre-Tertiary basement reflects the underlying geothermal heat sources. The eastern high temperature zone is related to the younger (<0.3 Ma) andesitic volcanism, where we suggest that heat may be provided by relatively deep and restricted magma chambers. The western broad high temperature zone is related to the older (0.3-0.6 Ma) dacitic volcanism, and it may be that the heat sources are provided by high-level consolidated magma plutons (Fig. 6). This speculation implies that the magma-chambers related with the old volcanism still play an important role as the heat source for present geothermal systems as well as the younger volcanism-related magma chambers (Tamanyu, 1991).

5.2 TVZ cross-section

Most of the production, reinjection and exploration holes drilled into TVZ fields have terminated within the thick sequences of Quaternary volcanic and sedimentary rocks or at shallow depths into the underlying basement. Very few wells have been deliberately drilled to explore the production potential of the basement (Wood, 1996). In consequence, our knowledge of the deep structure is based largely on geophysical modelling, which combined with geological postulation about what the surface structures and borefield stratigraphies

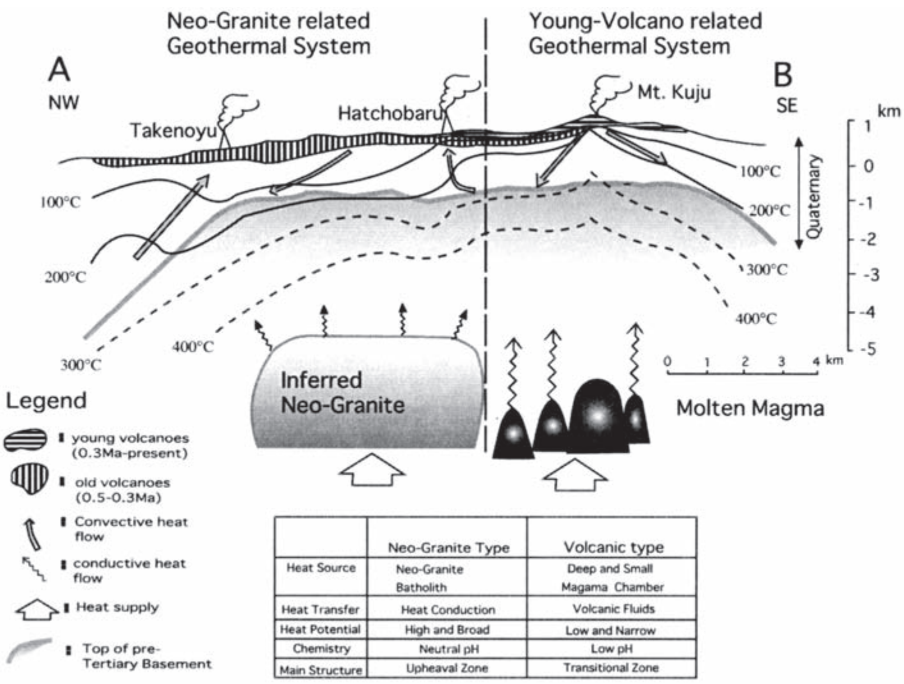

Fig. 6 Cross-section of geologic and thermal structures in the KBG (Tamanyu, 1994a)
Both ends of cross-section, A and B are shown in Fig. 4.

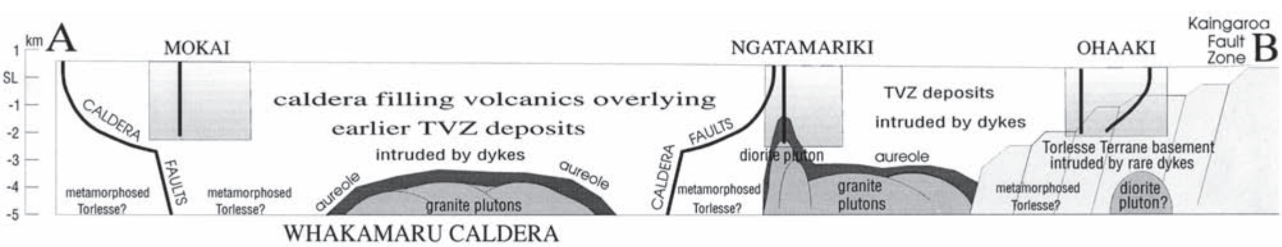

Fig. 7 Schematic cross-section of geologic and thermal structures in the young- TVZ (Wood, 1996). Mokai, Ngatamariki and Ohaaki geothermal systems are shown as shaded rectangular boxes in which the deepest drillholes marked as heavy lines.
Both ends of cross-section, A and B are shown in Fig. 5.

relate to at depth, allows reasoned speculation on what a transect across the TVZ may look like. Such a cross-section (Fig. 7) displaying most of the features expected within the young-TVZ down to the zone of plutonic magma accumulation was drawn through Ohaaki, Ngatamariki and Mokai geothermal fields by Wood (1996). The transect crosses the Kaingaroa Fault Zone where Torlesse Terrane basement is progressively thrown down to the west.

A postulated diorite pluton beneath eastern Ohaaki represents a speculative heat source that generates fluids with an "andesite signature" (Giggenbach, 1995), consistent with the presence of a buried, young (<0.3 Ma) andesitic volcano. Recent fluid and gas chemistry data also suggest that there is an actively degassing and relatively shallow-seated magmatic intrusion beneath eastern Ohaaki (Christenson *et al.*, 1998a). The western edge of the high-resistivity Torlesse Terrane corresponds to magnetic anomalies which Soengkono (1995) interpreted as hot plutons with tops at ca. -4000 m a.s.l. They are shown extending as far west as Ngatamariki where drilling proved a relatively shallow dioritic pluton surrounded by a metamorphic aureole (Christenson *et al.*, 1998b). West of Ngatamariki, the transect is dominated by the large, 0.33 Ma, Whakamaru caldera. Granite plutons are assumed to occupy the centre of the caldera. To the west, Mokai is a typical low-gas "rhyolitic" geothermal system (Giggenbach, 1995), possibly sustained by heat associated with plutonism related to the caldera-forming episodes, and located where caldera fractures provide deep access for groundwaters (Wood, 1995). Remnants of metamorphosed Torlesse Terrane may be present at depth in the western part of the transect, where multiple dyke intrusion is likely.

6. Comparison of structure, volcanism and geothermal activity

The KBG and the young-TVZ are compared in terms of their geological and geophysical aspects and summarized in Table 1. Both areas are Quaternary volcano-tectonic depressions filled with extensive volcanic products and accompanied by active geothermal manifestations. Major differences between them are the type of the youngest volcanism (<0.3 Ma), and the distribution patterns of the geothermal fields. The youngest volcanism in the young-TVZ is characterized by huge amount of rhyolitic pyroclastics with caldera formation and many rhyolite lava domes, whereas that in the KBG is characterized by andesite lava dome and stratovolcanoes with no large-scale caldera collapse. However, the older volcanism (0.3-0.6 Ma) of the KBG is similar to the youngest volcanism of the young-TVZ by huge amount of rhyolitic pyroclastics with caldera formation and many rhyolite lava domes.

	Kuju-Beppu Graben	young-Taupo Volc. Zone
1. Volcano-Tectonics		
setting	VTD*	VTD*
size	1,500 km^2	3,400 km^2
age	1.8 - 0.6 Ma	2 Ma - present
gravity anomaly	low	low
depression rate (max.)	<1.7 km/Ma (1.6 km)	<3.0 km/Ma (3 km)
boundary	pre-Tertiary TL**	Quaternary TL**
plate motion	oblique subduction	normal subduction
subduction rate	46 mm/yr	47 mm/yr
extension	lateral shear	rifting
active faultS	E-W normal faults	NNE-SSW normal faults
spreading rate	14 mm/yr (N-S)	18 mm/yr (E-W)
subsidence rate	2.5 mm/yr	3-4 mm/yr
crustal thickness	ca. 35 km	ca. 15 km
2. Geologic Framework		
evolutional history	4 stages in last 6Ma	3 stages in last 2 Ma
volcanic front	oblique to VTD*	parallel to VTD*
caldera	> 1 ?	> 6
dominant volcanism	andesite (< 0.3 Ma)	rhyolite (< 0.34 Ma)
ditto	dacite (0.6 - 0.3 Ma)	rhyolite (0.71-0.34 Ma)
arc volcanism	0.6 Ma - present	0.34 Ma - present
rift volcanism	> 0.6 Ma	2 Ma - present
gas signature (east)	andesite volc. features	andesite signature
(west)	dacite volc. features	rhyolite signature
subsurface features	subhorst and subgraben	caldera and step faults
3. Geothermal Fields		
geothermal areas	11 (>75 degree C)	20
geothermal activity	< 0.6 Ma	< 0.34 Ma
locations	on and behind VF***	margin of major calderas
ditto	on and around sub-horst	eastern margin (step fault)
hot water discharge	lateral flow	channeled plume
hydrothermal eruption	rare	common
shallow temperature	low	high
convective heat	400 -700 MW	4200 MW
conductive heat	ca. 700 MW	< 50 MW
heat source	andesitic magma	rhyolitic pluton
ditto	consolidated pluton	dyke swarm
resistivity anomaly	not consistent	consistent
magnetic anomaly	volcanic centres	inferred plutonic bodies

Table 1 Comparison of geological and geophysical features between the KBG and the young-TVZ.
VTD*: Volcano Tectonic Depression
TL**: Tectonic Line
VF***: Volcanic Front

Although the geothermal fields in the KBG and the TVZ are located in Quaternary volcano-tectonic depressions, there are major differences in the relative age of structures and volcanism, factors which appear to influence the nature of the respective geothermal systems. In the KBG, the major W-E oriented depression formed mainly in the 1.8 to 0.6 Ma period, and was followed from 0.6 Ma to the present by andesite-dacite volcanism along oblique NE-SW trends crossing the depression. The present KBG geothermal systems, and presumably their heat sources, are restricted to locations on or behind the volcanic arcs where there is high-level basement, and thus though they appear to be associated with arc magmatism, are not directly related to the graben formation. In contrast, the formation of the TVZ volcano-tectonic depression, its volcanism and geothermal fields are all concordantly located in time and space, and the fields are more or less evenly spaced. The apparently linear distribution of fields as seen on Fig. 5 is a consequence of the narrow, linear nature of the belt itself. The geothermally active central portion of the TVZ is dominated by rhyolite volcanism, but sporadic andesite-dacite eruptions have occurred in this area throughout the life of the TVZ, and both types of magmatism are believed to contribute to the total heat transfer.

The actual geothermal production reservoirs in the young-TVZ are located mainly in shallow-medium depth (500-1500 m) faulted, permeable stratigraphic aquifers where temperatures often reach boiling point (250-300°C). These aquifers are consequential on graben formation as they are the products of depression-infilling by primary lavas and pyroclastic deposits interbedded with detrital volcaniclastic sediments. By contrast, the potential geothermal reservoirs in the KBG have been identified in deep (1000-2000 m depth), volcanic horizons where permeability is fracture controlled, and temperatures are sub-boiling (around 220°C).

7. Discussion and conclusions

The rate of heat transfer is anomalously high in the TVZ in comparison to that of other active arcs including Kyushu Island (Hochstein, 1995, reported heat and mass transfer rates in the TVZ roughly 2 to 8 times those in some other Quaternary arcs). This anomalous heat appears to correlate with extrusions and presumed intrusions of rhyolitic melts, whose generation is not directly controlled by subduction processes (Hochstein, 1995). The convective heat discharge in the KBG is about 0.3 MW/km^2 (Sumi, 1980; Ehara, 1989) conductive heat discharge is similar at ca. 0.3 MW/km^2 (Ehara, 1989). By comparison, the data in Bibby *et al.* (1995) indicate the heat discharged through geothermal fields averaged across the area of the young-TVZ is ca. 1 MW/km^2. The rate is as high as 20-30 MW/km^2 in the largest fields, while conductive heat flow outside the fields is said to be negligible by comparison (Kissling, 1998 uses a figure of 90 mW/m^2). Based on the temperature profiles for deep drill holes, the thermal gradient is higher at the Hohi field in the KBG (ca. 100°C /km) than at the Wairakei field in the TVZ (ca. 60°C / km), although available data are restricted to major geothermal fields (Fig. 8). If thermal conductivity of host rocks is reasonably nearly equal in both areas, the average conductive heat discharge from deep to surface is calculated as higher in the KBG than in the TVZ. This means conductive heat is accumulating at the shallow parts as the shallow reservoir capped by shallow impermeable layers in the KBG, while less accumulating in the TVZ. In comparison, the convective heat discharge is much higher in the TVZ, but the conductive heat discharge is less than in the KBG. Various models to explain the phenomenon of anomalously high total heat transfer within the TVZ have been proposed (e.g. Hochstein *et al.*, 1993; Hochstein, 1995; Kissling, 1998; Weir, 1998), though none are entirely satisfactory. However, for this review the effect is of more concern than the origin.

The high heat transfer in the TVZ relative to the KBG is reflected in the differences seen in the characteristic thermal structure of geothermal fields in the respective areas. In the TVZ shallow plumes of boiling, or near-boiling groundwater rise and spread through the permeable depression-filling deposits. They are heated to some extent by conductive transfer through the poorly permeable basement, but mainly by fluids (deep-penetrating groundwater with a magmatic component) rising through elusive fractures and faults above a relatively shallow, essentially impermeable magma-ambient heat source zone (Wood, 1996; Christenson, *et al.*, 1998a). However, no drillholes have penetrated

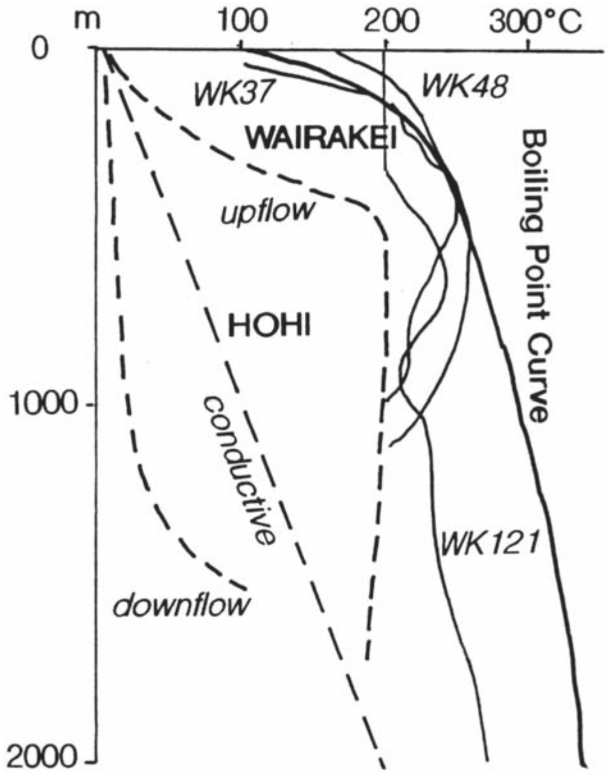

Fig. 8 Temperature profiles for representative boreholes from the Hohi field in the KBG and the Wairakei field in the TVZ. The profiles for the Hohi field are referred from Tamanyu (1994a), and those for the Wairakei field are from Healy (1984). Dashed lines are from the Hohi in the KBG and solid lines from the Wairakei in the TVZ. Bold line is the reference curve of water boiling point.

deep enough to confirm this possibility. By contrast, in the KBG where the deep thermal structure has been proven by many deep drill holes, the shallow levels of the fields are cooled below boiling by groundwater. It is possible that the KBG andesitic magma-ambient zone is much deeper than in the TVZ and the deep-penetrating groundwater is extracting heat from fractured volcanics above a conductive zone that is thicker but has a lower thermal gradient. Thus it is concluded that the heat discharged by geothermal fluids in the two volcano-tectonic depressions is greatly controlled both by the depth of the magma-ambient zones, and by the depth to which the cool groundwater convection cells can penetrate.

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火山性テクトニック陥没帯における地熱系の特徴：日本とニュージーランド

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要　旨

地熱系の分布における構造支配について研究するために，日本の九重-別府地溝帯(KBG)とニュージーランドのタウポ火山帯(TVZ)を比較検討した．その結果，その違いと類似性が明らかとなった．地熱地域の分布は，両者で大きく異なり，KBGでは中央部を斜交する若い火山フロントの直上ないしはその背後に限定されるのに対して，TVZでは地溝帯全体に広く分布している．最も若い火山活動に関しても両者で異なり，KBGでは安山岩質の成層火山を形成する火山活動であるのに対して，TVZではカルデラ形成を伴う流紋岩質火山活動である．従って，現在の地熱地域の熱源としては，KBGでは安山岩質マグマと固結したプルトンが想定されるのに対して，若いTVZでは浅所貫入した流紋岩質のプルトンと岩脈群が想定される．このような両者における熱源と地熱分布の違いは，異なる地熱地域特性を生じさせている．TVZ浅部(深度500-1500 m)では，沸騰温度およびそれに近い流体(250-300°C)が中生界の上位に重なる第四紀火山岩-堆積岩よりなる多孔質帯水層に賦存している．一方，KBGでは，より深い深度(1000-2000 m)に，より低い温度(220°C)の流体が賦存している．KBGでは第四紀安山岩質マグマ近傍域がTVZより深く位置し，天水は深くまで浸透して，地温勾配の低い熱伝導域の上位の破砕された火山岩類の中で熱せられている．このように，火山性テクトニック陥没帯で地熱流体から放出される熱は，マグマ近傍域の深度と天水の浸透する深度とに大きく規制されている．