主論文

Application of the fission-track dating method to evaluate the thermal history of three geothermal areas: North Kurikoma (Japan), Hijiori (Japan) and Valles caldera (USA)

Hisatoshi Ito*

*Central Research Institute of Electric Power Industry
(CRIEPI)
1646 Abiko, Abiko city, Chiba, Japan

ACKNOWLEDGMENTS

I greatly appreciate the encouragement and critical comments provided by Prof. Susumu Nishimura and Dr. Daiei Inoue during this study. I was able to perform the fission-track study as a member of Hot Dry Rock Project Team at Central Research Institute of Electric Power Industry (CRIEPI) under the supervision of Mr. Yoshinao Hori. CRIEPI allowed me to work at La Trobe University, Australia, from July 1993 to June 1994. Prof. Andrew J.W. Gleadow gave me the opportunity to study the fission-track method at La Trobe University and Dr. Barry P. Kohn, Dr. Paul B. O'Sullivan and Mr. Asaf Raza helped me in the laboratory there. Mr. Kenzo Kiho was helpful for the study of the North Kurikoma and the Hijiori geothermal areas. Dr. Kazuhiro Tanaka was helpful for the study of Valles caldera. New Energy and Industrial Technology Development Organization (NEDO) provided me with the HDR-1 bore-hole samples with the help of Mr. Masahiko Yagi. Mr. Isao Matsunaga showed me a sampling locality at Hijiori. Dr. Jamie N. Gardner provided me with the VC-2B bore-hole samples and important geological information on the Valles caldera. Dr. Fraser Goff reviewed the manuscript and provided me with important geological information on the Valles caldera study. Dr. A.W. Laughlin reviewed the manuscript of the Valles caldera study. Dr. Takahiro Tagami and Dr. Noriko Hasebe and Mr. Rhyji Yamada gave me important comments on the study and were helpful for the sample irradiation at the Kyoto University Research Reactor. Finally, Mrs. Andrea J. O'Sullivan and Dr. Paul B. O'Sullivan kindly corrected the English usage in this thesis with some important comments.

I sincerely thank all of them.

ABSTRACT

This study deals with the application of the fission-track method to constrain thermal history in three active geothermal areas: the North Kurikoma and the Hijiori geothermal areas, northeast Japan, and the Valles caldera, New Mexico, USA. In these areas an advanced technology to exploit geothermal energy, known as hot dry rock geothermal energy (HDR), has been engineered. One of many essential problems to establish HDR is to clarify the geological background, especially the thermal history of these geothermal areas.

It will be clarified in this study that, among many radiometric dating methods, the fission-track method can provide unique and essential information to constrain the thermal history of geothermal areas. This is because: 1) the fission-track method has unique closure temperatures in the range 100 - 250 ℃ using apatite and zircon; 2) temperature is by far the most dominant parameter that influences the dating system; 3) ages are determined on individual grains; and 4) it can provide not only the age information but also information on spontaneous track length, which constrains the interpretation of the thermal history.

This study consists of three parts. The first part deals with the North Kurikoma geothermal area, the second part deals with the Hijiori geothermal area and the third part deals with the Valles caldera.

For the first part, fission-track methods are applied to Neogene felsic volcanic rocks, a Neogene intrusive rock and pre-Tertiary granitic basement rocks, which are distributed in the North Kurikoma geothermal area. The Neogene felsic volcanic rocks were dated as ~2 Ma, which implies the caldera-forming volcanic activity occurred at ~2 Ma. The Neogene intrusive rock was dated as ~22 Ma. The concordant radiometric ages of ~22 Ma at three different localities indicate that a contemporaneous intrusion episode occurred at that time. The zircon fission-track age of mylonitized granodiorite ~0.5 - 1.0 km in depth was 31.2 ± 3.9 Ma, which is a thermally reduced age. The heat that influenced the fission-track system is assumed to have come laterally. Thermal history of some igneous rocks that are exposed in this area is also estimated.

For the second part, fission-track methods are applied to pre-Tertiary granitic basement rocks that are distributed beneath and outside of the Hijiori caldera. The zircon fission-track ages of the granodiorite ~1.5 - 2.2 km in depth were 48 - 35 Ma, which are thermally reduced ages. The heat that reduced the age of the sample ~1.5 km in depth is estimated to have come laterally. Cooling curves of the granodiorite beneath and outside of the Hijiori caldera are estimated. From the estimation, the granodiorite outside of the caldera cooled below ~100 ℃ at 4.3 ± 0.9 Ma, whereas the one ~1.5 - 2.2 km beneath the caldera has had almost constant temperature of ~240 - 270 ℃ since ~10,000 years ago.

For the third part, zircon fission-track methods are applied to samples whose present temperatures are 222 - 294 ℃, collected from a 1.76 km deep bore-hole in the Valles caldera. All of the ages obtained from Permian sandstone to Precambrian quartz monzonite indicate partially reduced ages of ~450 - 600 Ma. There is no correlation between zircon ages and sampling depth, probably due to hot fluid flow and/or hot vein emplacement associated with recent volcanic activity.

In addition to these results, it is inferred that 1) the K-Ar K-feldspar system seems more thermally resistant than the fission-track zircon system in the case of a secondary thermal effect, and 2) the closure temperature of zircon fission-track system seems to be higher than that previously determined from geological data.

CONTENTS

The outline of the study

1. Introduction

Our present fossil fuel resources are incapable of sustaining our needs for more than perhaps a few tens of decades unaided by new sources of energy and by drastic conservation measures (Armstead and Tester, 1987). With the exception of hydro-power, geothermal energy would at present seem to be capable of giving quicker relief than any of the other available resources (e.g. solar, tidal, wind and wave power) to the pressures on our reducing fuel supplies; we must lose no time in grasping the rewards it can offer (Armstead, 1983). In geothermal energy, hot dry rock (HDR) will be by far the most important resource partly because of its immensity and ubiquity and partly because its exploitation requires only the modest improvement of existing technology (Armstead and Tester, 1987). However, it has not yet been proved that a HDR system can produce energy at today's competitive price. One of many essential problems to establish HDR is to clarify the geological background, especially the thermal history, of a geothermal area where HDR will be operated.

In this thesis three active geothermal areas are studied: the North Kurikoma and the Hijiori geothermal areas, northeast Japan, and Valles caldera, New Mexico, USA (Fig. 1). Research-oriented HDR systems have been engineered at Ogachi site in the North Kurikoma geothermal area by Central Research Institute of Electric Power Industry (CRIEPI), at Hijiori site in the Hijiori geothermal area by New Energy and Industrial Technology Development Organization (NEDO) and at Fenton Hill site near the Valles caldera by Los Alamos National Laboratory.

This thesis consists of three parts. The first part, submitted to the Journal of Geophysical Research (Ito, H.), deals with the North Kurikoma geothermal area; the second part, submitted to Geology (Ito, H.), deals with the Hijiori geothermal area and the third part, published in the Journal of

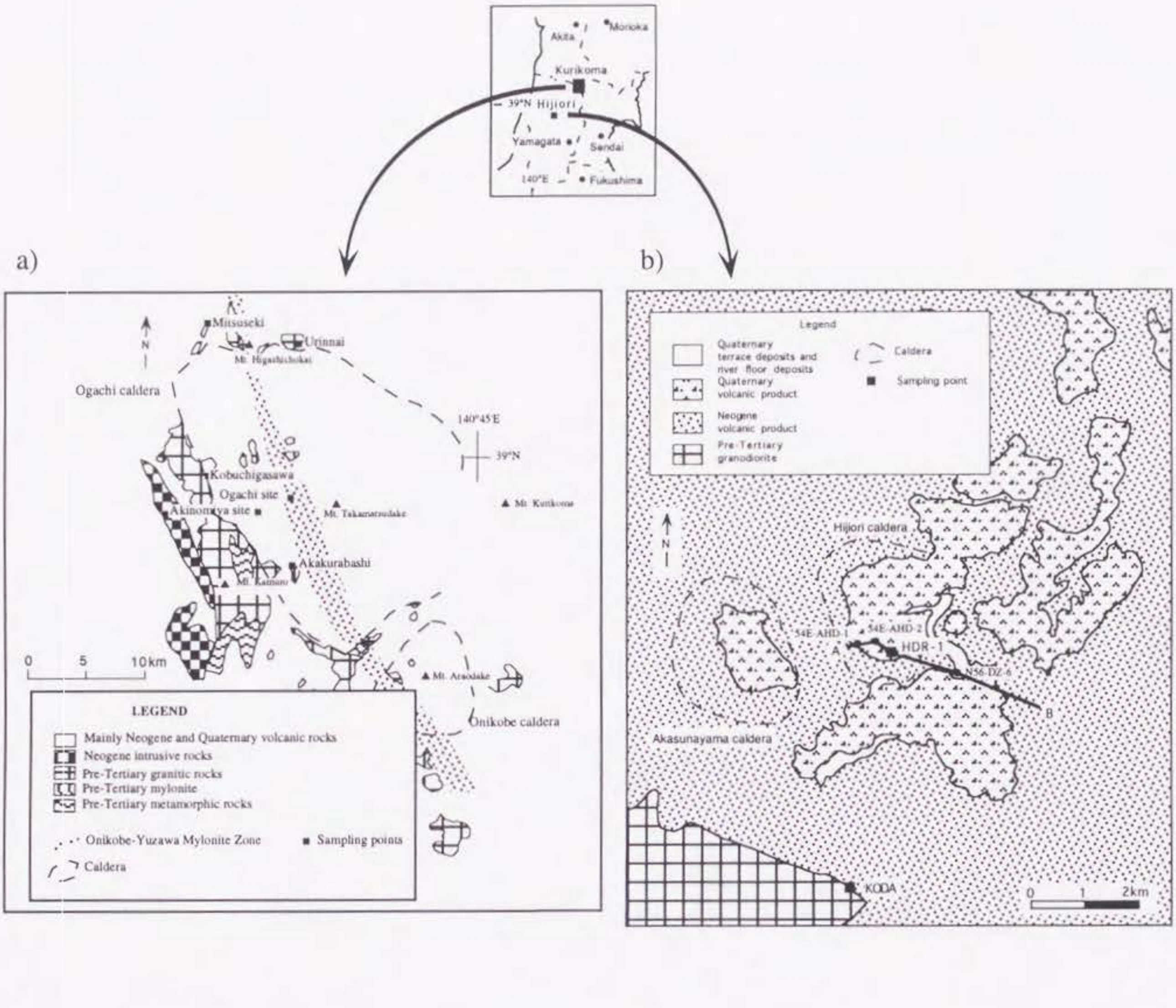

Fig. 1 The location maps and simplified geological maps of the study areas. a) North Kurikoma, b) Hijiori, c) Valles caldera.

Volcanology and Geothermal Research (Ito and Tanaka, 1995), deals with the Valles caldera.

2. Analytical method

The fission-track dating method is applied throughout this study. It was first developed as a new dating method based on the natural decay by spontaneous fission of the ^{238}U isotope (Price and Walker, 1963). It is distinct from the previously developed dating methods that involve the measurement of isotopic abundances by mass spectrometry, as ages are determined by counting fission tracks under a normal microscope.

The fission-track method has been utilized for dating igneous, sedimentary and metamorphic rocks. It has been applied to dating volcanic and metamorphic events, tectonic uplift, mineral deposits, stratigraphic correlation and so on (Wagner and Van den haute, 1992). The technique has previously been applied to geothermal regions, as reported by some researchers (e.g. Nishimura et al., 1976; Naeser and Forbes, 1976; Tamanyu and Kasuya, 1983; Gutierrez-Negrin et al., 1984), where it has helped to constrain the thermal history of some geothermal areas and has contributed to the understanding of thermal properties of the fission-track system.

It will be clarified in this study that, among many radiometric dating methods, the fission-track method can provide unique and essential information to constrain the thermal history of geothermal areas. There are several reasons for this. Firstly, the fission-track method has unique closure temperatures of 100 - 250 ℃, i.e., ~100 ℃ for apatite (Naeser and Faul, 1969; Gleadow and Duddy, 1981; Green et al., 1989) and ~240 ℃ for zircon (Hurford, 1986) over geologic time-scales. The temperature range is between that of the K-Ar dating system using biotite (Hurford, 1986) and that of the ESR dating system (Ikeya, 1983). Secondly, temperature is by far the most dominant parameter that influences the fission-track dating system (Fleisher et al., 1965). Thirdly, because individual grain ages are obtained, it is easier to discriminate essential grains, i.e., grains originally contained in the rock, from detrital and/or contaminated grains. Thus the fission-track dating method can be used for both boring-core and cuttings samples, which should contain contaminated grains. Fourthly, the fission-track method can provide information constraining not only the time of cooling of a sample, but also its thermal history using the length distribution of spontaneous confined tracks (Gleadow et al., 1986; Ito et al., 1989).

The technique to evaluate thermal history by the fission-track method

As mentioned above, the fission-track method has a unique characteristic to evaluate thermal history by the use of track length data. Here, the technique to evaluate thermal history by the fission-track length data is briefly outlined.

Fission tracks originally have almost constant length of ~ 11 μm in zircon (Yamada et al., 1995) and ~16 μm in apatite (Gleadow et al., 1986) when they are properly etched. They are thermally unstable above a certain temperature and the thermal property is recognized as in Fig. 2. In Fig. 2., fission tracks are 1) stable and length reduction does not occur in the track stability zone (TSZ), 2) unstable and length reduction occurs in the partial annealing zone (PAZ), and 3) unstable and tracks disappear after their formation in the total annealing zone (TAZ). It is apparent that the degree of track length reduction depends on the temperature and heating duration as shown in Fig. 2.

The track length distribution patterns should be classified as follows according to the following hypothetical thermal histories that will be closely associated in this paper (Fig. 3).

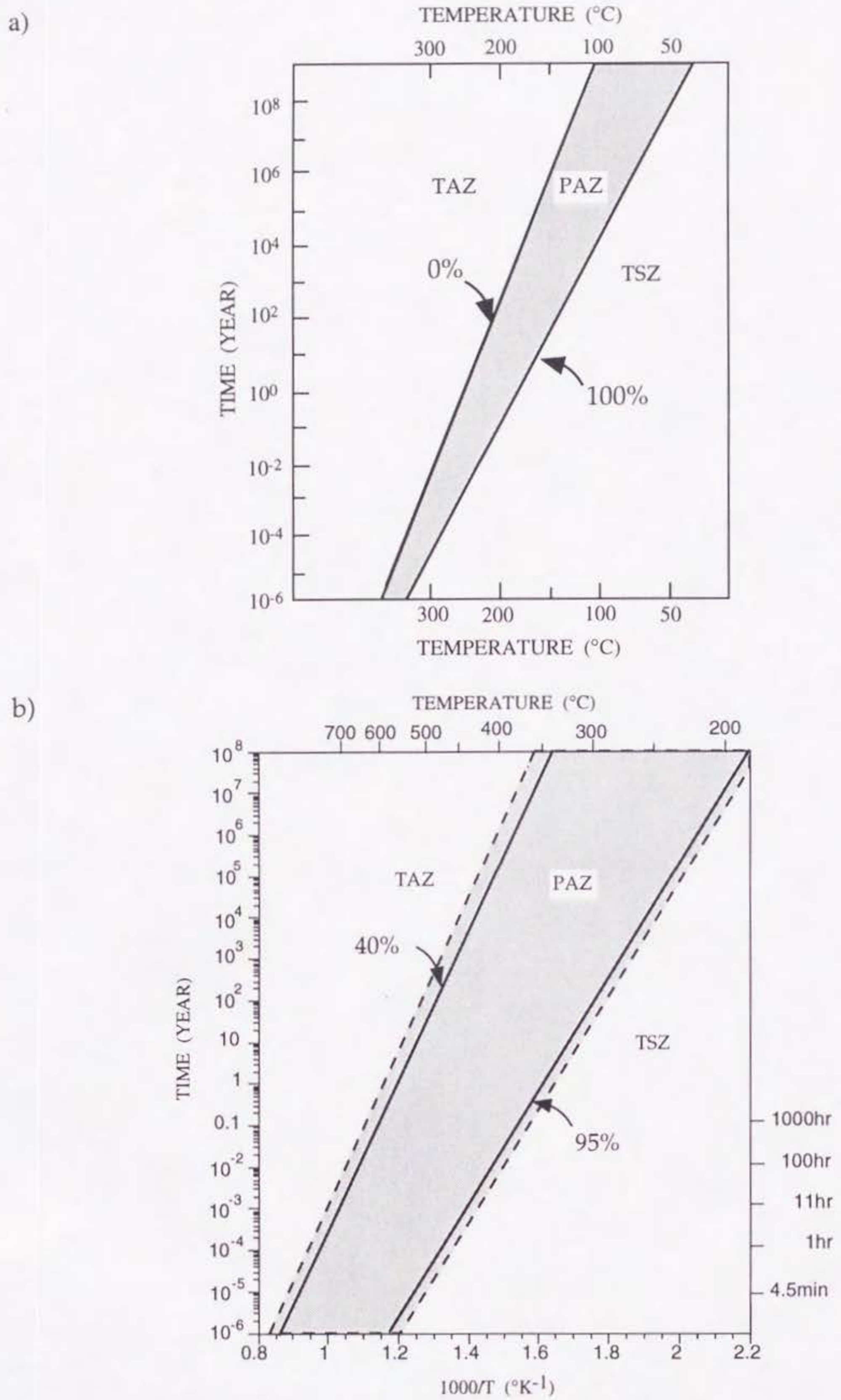

Fig. 2 Time-temperature relations for fission track reduction in a) apatite (modified from Gleadow and Duddy, 1981), and b) zircon (modified from Fig. 4. (b) in Yamada et al., 1995).

TAZ: total annealing zone, PAZ: partial annealing zone, TSZ: total stability zone. Track density reduction ratio in a) and track length reduction ratio in b) are shown in percentage, where 100 % means non-annealing and 0% means total annealing.

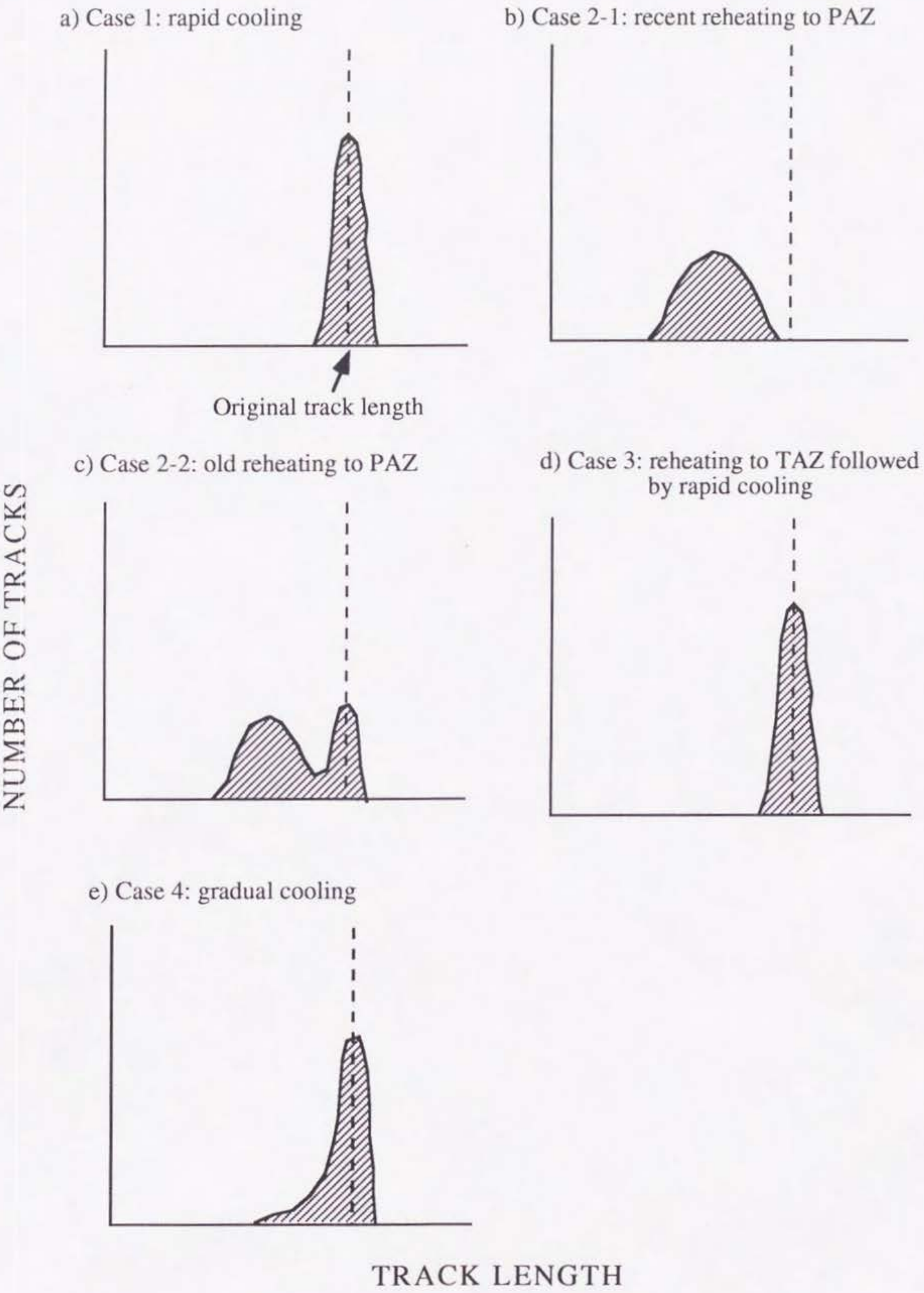

Fig. 3 Some schematic fission track length distribution patterns for different cooling histories.
PAZ: partial annealing zone, TAZ: total annealing zone

Case 1: if a rock cooled immediately after its formation and its temperature has been kept in the TSZ, the distribution of track length should be narrow with the mean track length which is essentially equal to the original track length (Fig. 3 a). This track length distribution pattern is observed in some volcanic rocks (Gleadow et al., 1986). The fission-track age should show the time when the rock was formed.

Case 2: if a rock that cooled immediately after its formation experienced a thermal event that raised its temperature to the PAZ should show the following two patterns: 1) all tracks are shorter than the original length and hence a broad unimodal distribution is observed when the thermal event was recent enough not to produce later unannealed tracks to a certain amount (Fig. 3 b), 2) some tracks are shorter than the original length and others are essentially the same with the original length and hence a bimodal distribution is observed when the thermal event was old enough to produce later unannealed tracks to a certain amount (Fig. 3 c). The fission-track age should show sometime between the time when the rock was formed and the time of the thermal event.

Case 3: if a rock that cooled immediately after its formation experienced a thermal event that raised its temperature to the TAZ and then followed by a rapid cooling should show a narrow distribution whose mean track length is essentially equal to the original track length (Fig. 3 d). In this case, although the track length distribution shows essentially the same pattern with that of case 1, its age should show the time of the thermal event.

Case 4: if a rock cooled gradually after its formation and has been kept in the TSZ, the distribution of track length should be negatively skewed, with a mean track length shorter than the original length (Fig. 3 e). This track length distribution pattern is observed in some granitic rocks (Gleadow et al., 1986). The fission-track age is regarded to be the time when the rock cooled below a certain temperature in the PAZ. This temperature corresponds with the closure temperature of the fission-track system and is usually assigned to the temperature at which 50 % of the fission track is retained (Dodson, 1979).

3. Constraints on the thermal history of three active geothermal areas by the fission-track analyses

In this thesis, the thermal history of three active geothermal areas, the North Kurikoma and the Hijiori geothermal areas and the Valles caldera, are examined using fission-track analyses.

In these geothermal areas, the following similar characteristics are observed: (1) hydrothermal manifestations, such as hot springs and fumaroles are observed; (2) the present geothermal gradient is abnormally high; (3) there is underlying granitic basement; (4) recent felsic volcanic activity formed a caldera; and (5) felsic volcanic activities have intermittently continued for at least a few million years.

The following differences are also observed: (1) the dimensions of the caldera are ~25 km for the assumed Ogachi caldera (Takeno, 1988) in the North Kurikoma geothermal area, ~2 km for the Hijiori caldera and ~20 km for the Valles caldera; (2) the caldera-forming volcanic activity occurred at ~2 Ma for the North Kurikoma as determined in this study, ~10,000 years ago for the Hijiori (Ui et al., 1973) and at ~1 Ma for the Valles caldera (Gardner et al., 1986; Self et al., 1986: Spell et al., 1990).

Through this study, the following constraints on the thermal history of each geothermal area are obtained.

The North Kurikoma geothermal area

(1) The zircon fission-track age of the Torageyama Formation was determined as ~2 Ma using dacite core samples of a 400 m deep bore-hole drilled at Akinomiya. Although this age was younger than most of the ages previously determined by K-Ar and fission-track dating methods, it was not an apparently young age caused by thermal annealing. This was ascertained by evaluating the thermal effect on detrital zircons involved in the dacite. Thus the caldera-forming felsic volcanic eruption was assumed to have occurred at ~2 Ma.

(2) Both zircon and apatite fission-track ages were determined on granitic rocks at four localities (Fig. 4). A weighted mean zircon fission-track age of 31.2 ± 3.9 Ma was obtained from mylonitized granodiorite ~500 - 1000 m in depth at Ogachi, where the present temperature is 142 - 225 ℃. This age is assumed to have been thermally reduced by the volcanic activity at ~2 Ma. The thermal effect on the zircon fission-track system was estimated almost equivalent within the depth of ~500 - 1000 m at Ogachi, which supposedly due to some lateral heat source, such as hot fluids and/or dykes.

(3) The zero age by the apatite fission-track method indicates that the temperature of the granodiorite ~580 m in depth at Ogachi has been kept at ~140 ℃ for ~2 million years unless the temperature exceeded ~140 ℃ at some time since ~2 Ma.

(4) The fission-track ages of the sporadically distributed Neogene intrusive rocks were determined as ~22 Ma at two different localities (Fig. 4). A K-Ar age previously determined at another locality is concordant with the fission-track ages (Fig. 4). Thus it was clarified that a contemporaneous intrusion episode occurred at ~22 Ma in this area.

(5) Granitic rocks east and west of the Onikobe-Yuzawa Mylonite Zone near the northern border of the Ogachi caldera were dated using zircon as 95.5 ± 6.6 Ma and 78.1 ± 5.2 Ma respectively, which are assumed little

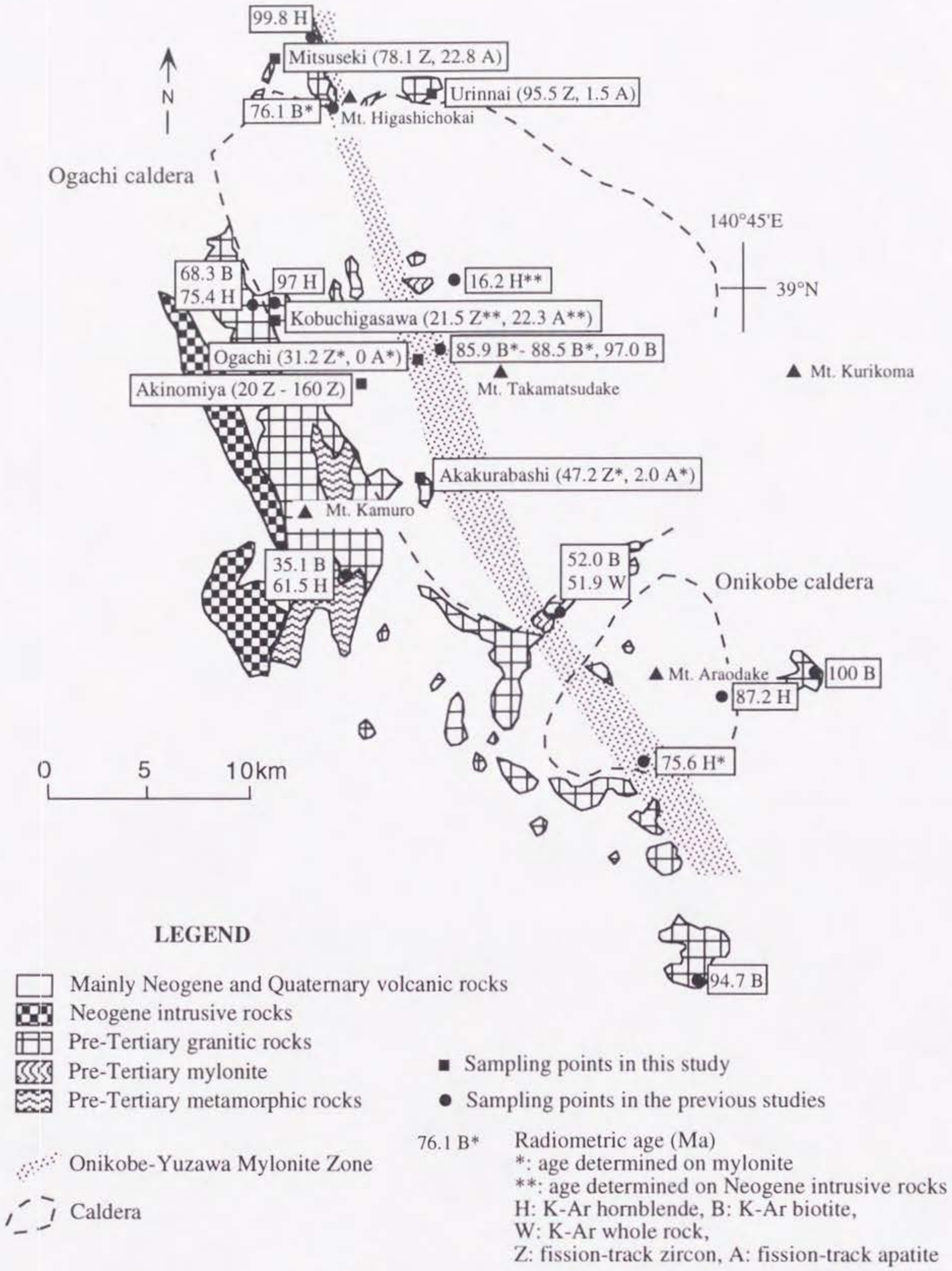

Fig. 4 Simplified geological map of the Kurikoma geothermal area (modified from Sasada, 1984, 1988) with the radiometric ages of mainly granitic rocks determined previously and in this study.

K-Ar ages are from Kawano and Ueda (1966), Sasada (1984, 1985, 1988) and Kuriyama (1985) and fission-track ages are from this study. The position of calderas is estimated from Takeno (1988) for the Ogachi caldera and Yamada (1988) for the Onikobe caldera.

thermally affected. The corresponding apatite ages were 1.5 ± 0.8 Ma and 22.8 ± 3.4 Ma respectively (Fig. 4). The former apatite age should reflect the felsic volcanic activity and the latter apatite age should reflect the intrusion episode.

(6) The thermal histories of some igneous rocks exposed in the region have been estimated by radiometric dating methods applied previously and in this study (Fig. 5).

The Hijiori geothermal area

(1) Samples obtained from granodiorite in the 2.2 km deep bore-hole HDR-1, which was drilled in the Hijiori caldera (Fig. 1b), yield three thermally reduced zircon fission-track ages of 48-35 Ma and track length data from two samples exhibit the reduced track length of 63-70 %. The present temperatures at the sampling depths are ~240-270 ℃ (Fig. 6).

(2) Apatite fission-track analyses of the bore-hole samples yielded zero ages, which are well explained by the previously reported annealing experiment (Gleadow and Duddy, 1981).

(3) The thermal effect on the zircon fission-track system was larger at 1500 m depth than at 2170 m depth, as the fission tracks in the former sample are more reduced than those in the latter sample. This is probably because the granodiorite at 1500 m depth is near the contact with the overlying Miocene deposits, and therefore should have been more susceptible to thermal fluids than the sample from 2170 m depth (Fig. 6).

(4) The small proportion of non-annealed fission tracks in the bore-hole sample zircons should indicate that the Holocene thermal effect was large enough to reduce fission tracks in zircon.

(5) A thermally reduced zircon fission-track age of 76.0 ± 2.6 Ma and track length data showing 63 % reduction were obtained from an outcrop

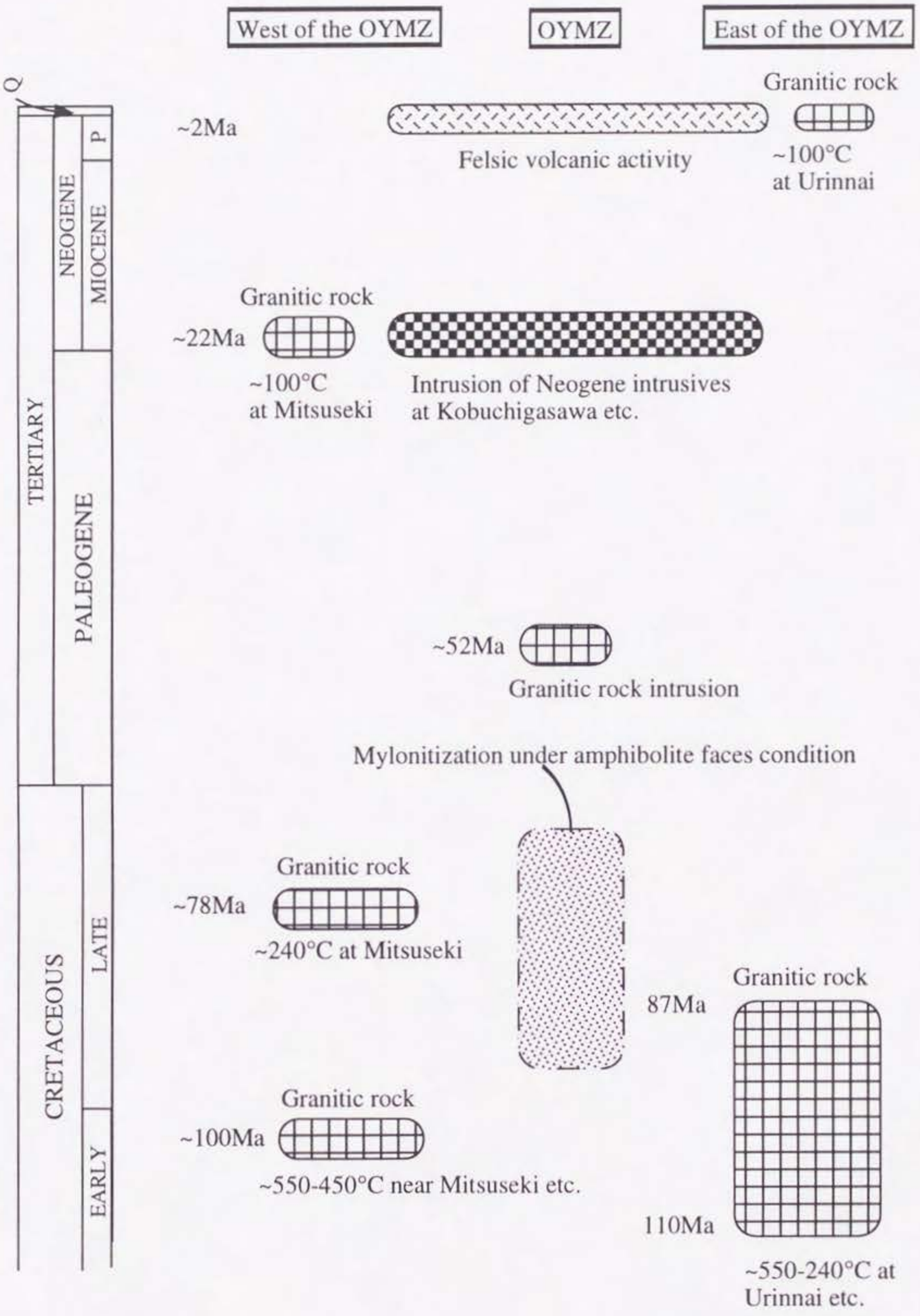

Fig. 5 Thermal history of some igneous rocks that are exposed in the North Kurikoma geothermal area.
OYMZ: Onikobe-Yuzawa Mylonite Zone, P: Pliocene, Q: Quaternary.

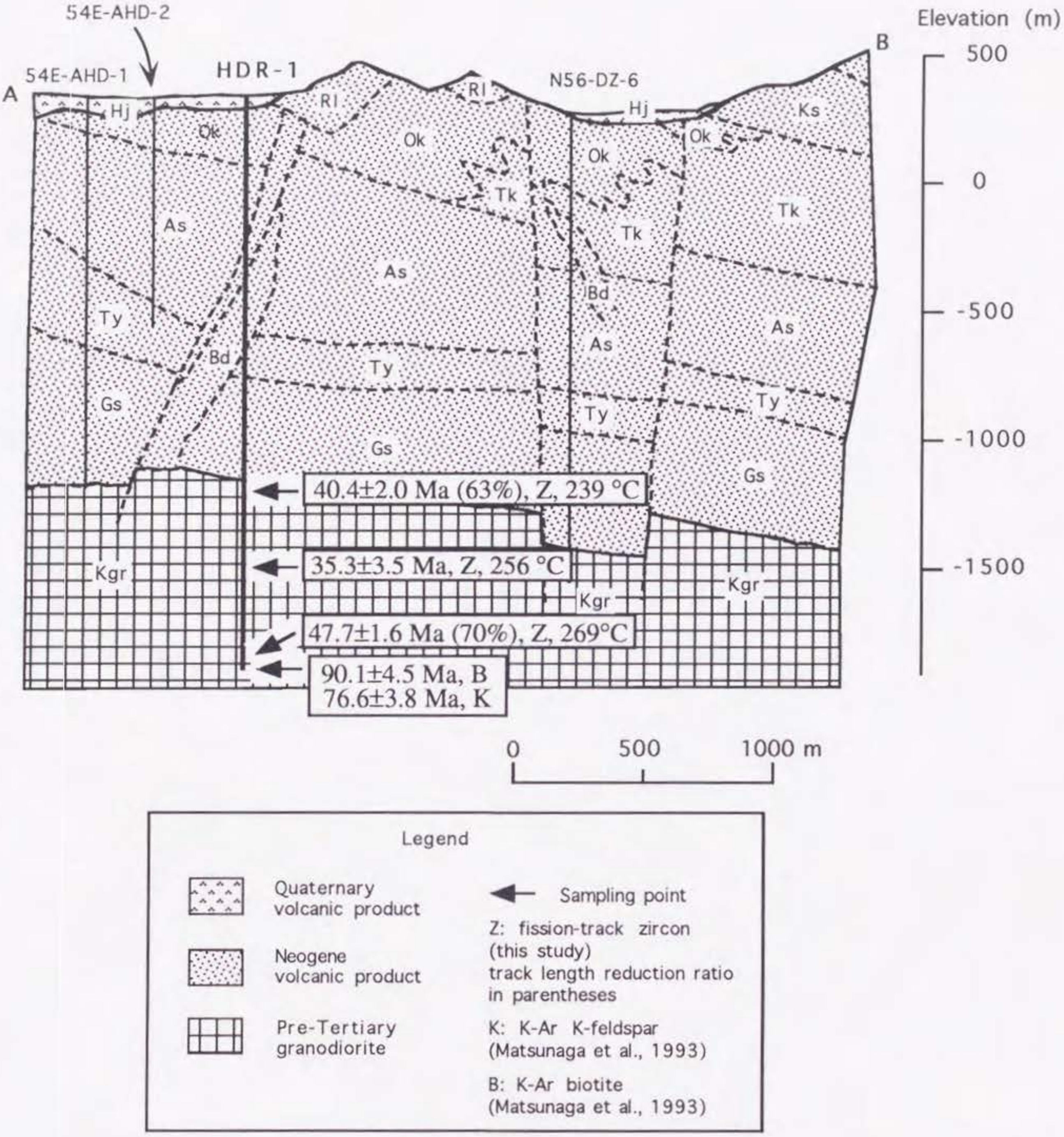

Fig. 6 A geological cross section of the Hijiori geothermal area (modified from NEDO, 1983) with the fission-track dating results (this study), the K-Ar dating results (Matsunaga et al., 1993) and the static temperature measurement results.
A-B line corresponds to that in Fig. 1b. Hj--Hijiori pyroclastic flow deposits (Holocene); Ks--Kusanagi Fm (Late Miocene); Ok--Okura silicious tuff Fm (Middle Miocene); Tk--Tsurookawa Fm (Middle Miocene); As--Aosawa Fm (Middle Miocene); Ty--Tachiyazawa Fm (Middle Miocene); Gs--Gassan Fm (Early Miocene); Kgr--Kodake granodiorite (Pre-Tertiary); Rl--Rhyolite and liparite; Bd--basalt and dolerite.

sample of the granodiorite which was collected outside of the Hijiori caldera.

(6) Cooling curves of the granodiorite beneath and outside of the Hijiori caldera were estimated using the radiometric ages determined previously (Matsunaga et al., 1993) and in this study (Fig. 7). It was concluded that the granodiorite outside of the caldera cooled below ~100 ℃ at 4.3 ± 0.9 Ma (cooling curve B in Fig. 7), whereas the one 1.5 - 2.2 km deep in the caldera has experienced almost constant temperature of ~240 - 270 ℃ since ~10,000 years ago (cooling curve A in Fig. 7).

The Valles caldera

Using the 1.76 km deep bore-hole VC-2B, which was drilled in the Valles caldera (Fig. 1c), the following are obtained:

(1) The zircon fission-track ages from the Permian Abo Formation to Precambrian quartz monzonite indicated partially annealed ages of about 450-600 Ma (Fig. 8). Although the zircons were obtained from Permian strata, they probably originated from Precambrian rocks.

(2) The fact that there is no correlation between zircon ages and sampling depth is probably due to hot fluid flow and/or hot vein emplacement associated with recent volcanic activity.

(3) The zircon fission-track ages from the Permian Yeso Formation indicate much younger ages than the Permian, the reason for which is unknown. These zircons seem to have come from different source areas because ages among zircon grains differ greatly (Fig. 8).

In addition to the results associated with regional geology, the following results associated with the thermal properties of the fission-track dating system are also obtained:

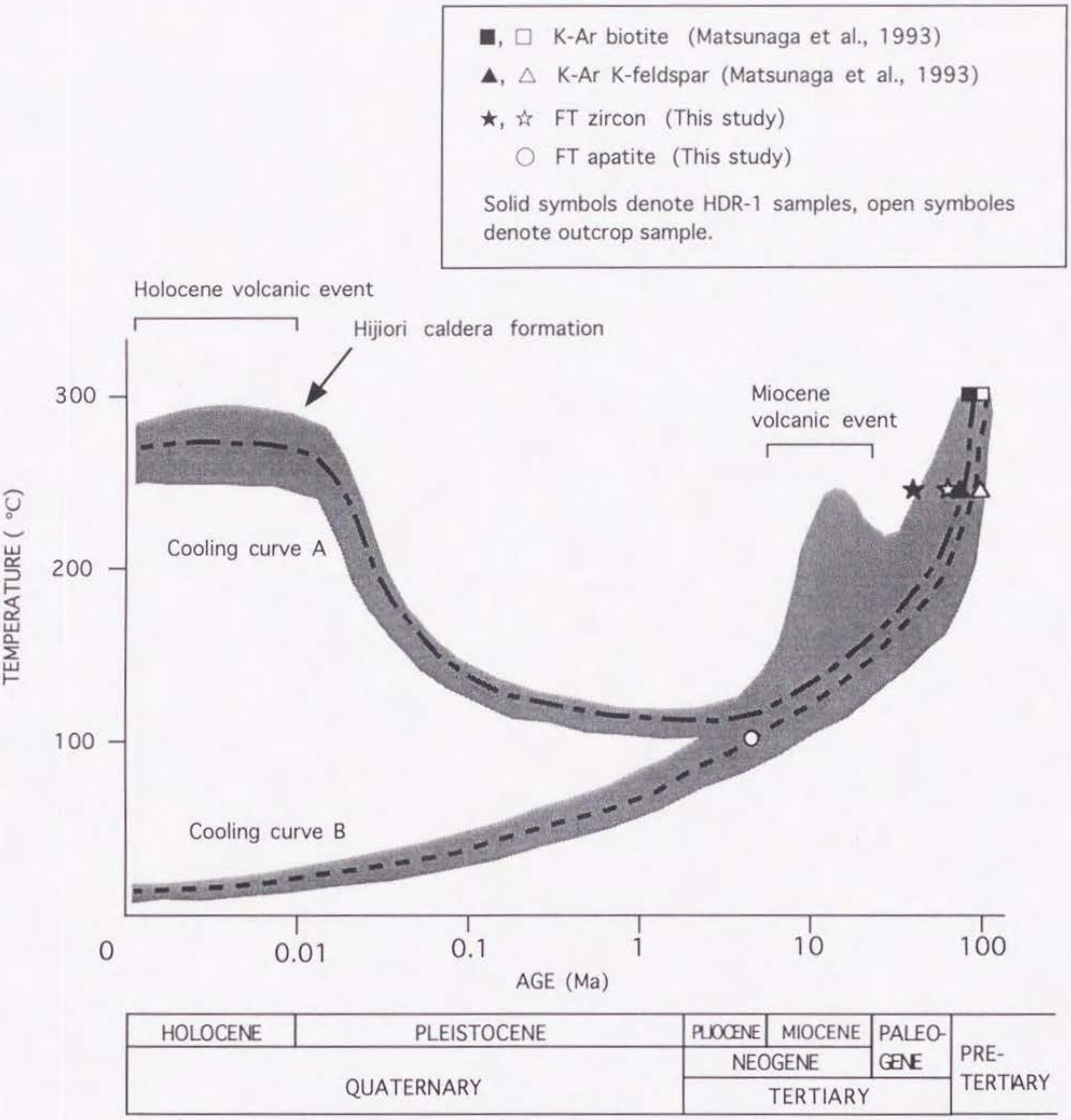

Fig. 7 Estimated cooling curves of the granodiorite beneath and outside of the Hijiori caldera.
The cooling curve A is that of the granodiorite which is 1.5 - 2.2 km in depth at the Hijiori caldera. The cooling curve B is that of the granodiorite which is exposed ~4 km south of the Hijiori caldera. The closure temperatures of K-Ar biotite, K-Ar K-feldspar, FT zircon and FT apatite are assumed to be ~300 °C, ~240 °C, ~240 °C and ~100 °C, respectively (Hurford, 1986; Green et al., 1989). FT zircon ages are reduced ages affected by the later thermal events. Shaded range denotes the uncertainty of the estimation.

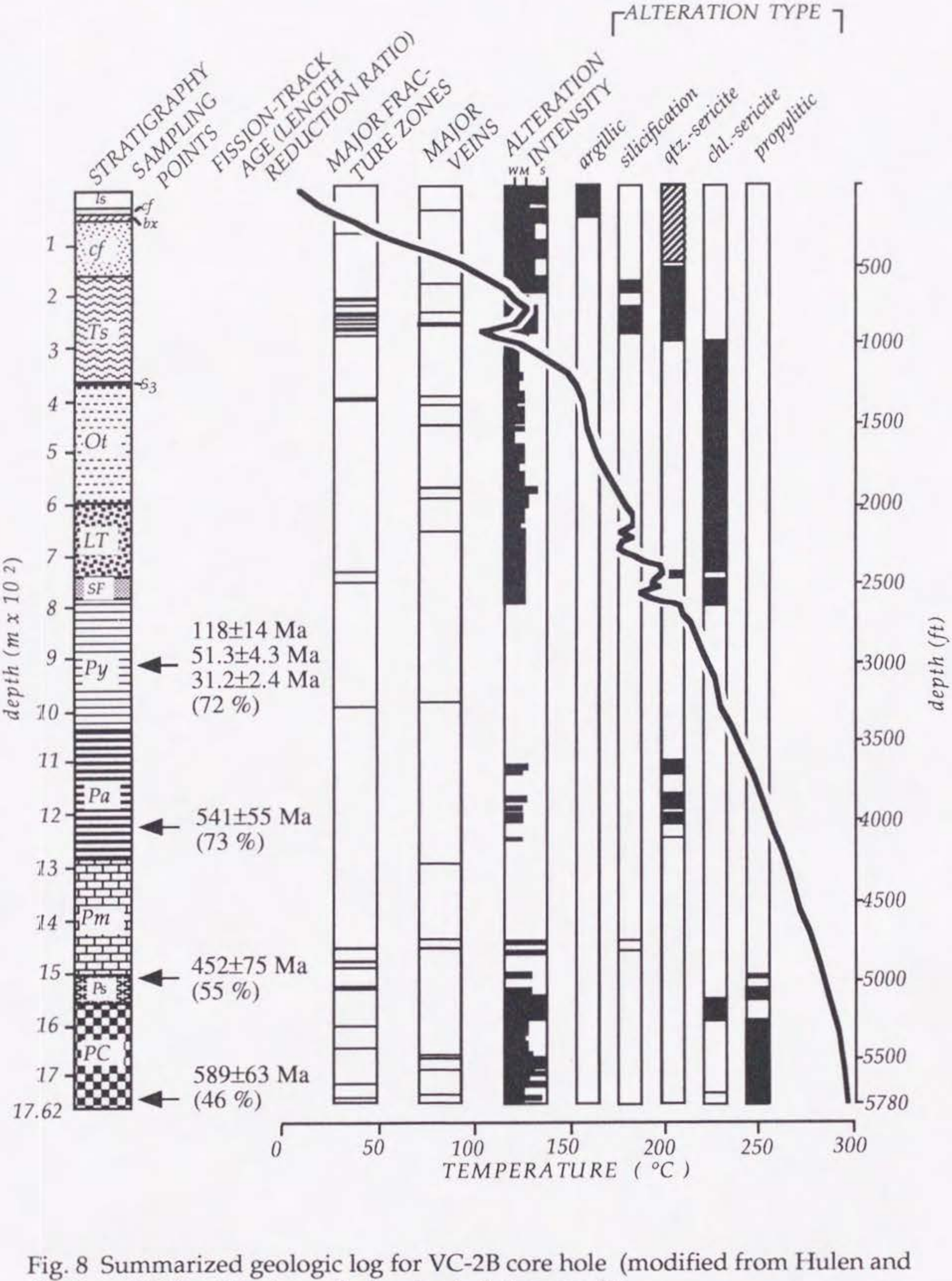

Fig. 8 Summarized geologic log for VC-2B core hole (modified from Hulen and Gardner, 1989) with zircon fission-track dating results.
ls--landslide debris; cf--caldera-fill clastic rocks; bx--hydrothermal breccia and dacite porphyry; Ts--Tshirege Member of Bandelier Tuff; S3--S3 clastic deposits; Ot--Otowi Member of Bandelier Tuff; LT--Lower Tuffs; SF--Santa Fe Group sandstone; Py--Permian Yeso Fm; Pa--Permian Abo Fm; Pm--Penn. Madera Limestone; Ps--Penn. Sandia Fm; PC--Precambrian quartz monzonite.

(1) Comparing the zircon fission-track dating results with the K-Ar dating ones of the HDR-1 bore-hole, the K-Ar K-feldspar system seems more thermally resistant than the fission-track zircon system where a secondary thermal effect is present.

(2) The closure temperature of the zircon fission-track system implied from the results of the VC-2B bore-hole, seems to be higher than that previously determined from geological data (Brandon and Vance, 1992).

Finally, it is noticeable that non-correlation between zircon ages and sampling depth is observed in all three geothermal areas. This indicates that some lateral heat flow, possibly by hot fluid flow and/or hot vein emplacements, played an important role in reducing the zircon fission-track ages although, at present, thermal conduction is predominant at the sampling depths in these areas.

REFERENCES

Armstead, H.C.H., 1983. Geothermal energy, 2nd. edn. E. & F.N. Spon, London, pp404.

Armstead, H.C.H. and Tester, J.W., 1987. Heat mining. E. & F.N. Spon, London, pp478.

Brandon, M.T. and Vance, J.A., 1992. Tectonic evolution of the Cenozoic Olympic subduction complex, Washington State, as deduced from fission track ages for detrital zircons. Amer. J. Sci., 292:565-636.

Dodson, M.H., 1979. Theory of cooling ages., in Lectures in Isotope Geology, ed. Jager, E. and Hunziker, J.C., Springer-verlag, Heiderberg.

Fleischer, R.L., Price, P.B. and Walker, R.M., 1965. Effects of temperature, pressure, and ionization of the formation and stability of fission tracks in minerals and glasses. J. Geophys. Res., 70:1497-1502.

Gardner, J. N., Goff, F., Garcia, S. and Hagan, R. C., 1986. Stratigraphic relations and lithologic variations in the Jamez volcanic field, New Mexico. J. Geophys. Res., 91: 1763-1778.

Gleadow, A.J.W. and Duddy, I.R., 1981. A natural long-term track annealing experiment for apatite. Nucl. Tracks, 5: 169-174.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. and Lovering, J.F., 1986. Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis. Contrib. Mineral. Petrol., 94:405-415.

Green, P.F., Duddy, I.R., Gleadow, A.J.W. and Lovering, J.F., 1989. Apatite fission-track analysis as a paleotemperature indicator for hydrocarbon exploration. In: N.D. Naeser and T.H. McCulloh (Editors), Thermal History of Sedimentary Basins, Springer-Verlag, New York, 181-195.

Gutierrez-Negrin, L., Lopez-Martinez, A. and Balcazar-Garcia, M., 1984. Application of dating for searching geothermic sources. Nucl. Tracks Radiat. Meas., 8: 385-389.

Hulen, J.B. and Gardner, J.N., 1989. Field geologic log for continental scientific drilling program corehole VC-2B Valles caldera, New Mexico. Earth Sci. Lab. Univ. Utah Research Inst., 92pp.

Hurford, A.J., 1986. Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol., 92:413-427.

Ikeya, M., 1983. ESR studies of geothermal boring cores at Hachobara power station. Jpn. J. Appl. Phys., 22: 763-765.

Ito, H. and Tanaka, K., 1995. Insights on the thermal history of the Valles caldera, New Mexico: evidence from zircon fission-track analysis. J. Volcanol. Geotherm. Res., 67: 153-160.

Ito, H., Sorkhabi R.B., Tagami, T. and Nishimura, S., 1989. Tectonic history of granitic bodies in the South Fossa Magna region, central Japan: new evidence from fission-track analysis of zircon. Tectonophysics, 166: 331-344.

Kawano, Y. and Ueda, Y., 1966. K-Ar dating on the igneous rocks in Japan (IV) -Granitic rocks in northeastern Japan-. Jpn. Assoc. Min. Pet. Ecno. Geol., J., 56: 41-55. *

Kuriyama, T., 1985. Geothermal system in the Yuzawa-Ogachi area, northern Honshu. J. Geotherm. Res. Soc. Jpn., 7: 311-328. *

Matsunaga, I., Kobayashi, H. and Yamaguchi, T., 1993. Granodiorite basement at the Hijiori Caldera - Thermal history estimated from data of K-Ar dating -. Resources and Environment, 2: 565-573. *

Naeser, C.W. and Faul, H., 1969. Fission track annealing in apatite and sphene. J. Geophys. Res., 74: 705-710.

Naeser, C.W. and Forbes, R.B., 1976. Variation of fission track ages with depth in two deep drill holes. Trans. Amer. Geophys. Union, 57: 353.

NEDO (New Energy Development Organization), 1983. Reports on an investigation of the geothermal development and promotion, the area of the lower reaches of Dozangawa River (Abstract), pp. 135. **

Nishimura, S., Taniguchi, M. and Sumi, K., 1976. Fission-track ages of the volcanic rocks in Oyasu-Doroyu geothermal field, Akita Prefecture - Fission-track age of the igneous rocks associated with geothermal activities in Japan (1)-. Geol. Surv. Jpn. Bull., 27: 713-717. *

Price, P.B. and Walker, R.M., 1963. Fossil tracks of charged particles in mica and the age of minerals., J. Geophys. Res., 68: 4847-4862.

Sasada, M., 1984. The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, northeastern Honshu, Japan -Part 1, Onikobe-Yuzawa Mylonite Zone-. J. Geol. Soc. Jpn., 90, 12: 865-874. *

Sasada, M., 1985. The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, Northeastern Honshu, Japan -Part 2, Boundary between the Abukuma and Kitakami Belts-. J. Geol. Soc. Jpn., 91: 1-17. *

Sasada, M., 1988. Onikobe-Yuzawa mylonite zone. Assoc. Geol. Collaboration Jpn., J., (Chikyu Kagaku), 42: 346-353. *

Self, S., Goff, F., Gardner, J. N., Wright, J. V. and Kite, W. M., 1986. Explosive rhyolitic volcanism in the James Mountains: Vent locations, caldera development and relation to regional structure. J. Geophys. Res., 91:1779-1798.

Spell, T. L., Harrison, T.M. and Wolff, J.A., 1990. ^{40}Ar/^{39}Ar dating of the Bandelier Tuff and San Diego Canyon Ignimbrites, Jamez Mountains, New Mexico; Temporal constraints on magmatic evolution. J. Volcanol. Geotherm. Res., 43: 175-193.

Takeno, N., 1988. Geology of the North Kurikoma geothermal area, Akita Prefecture, Northeast Japan. Rept. Geol. Surv. Jpn., 268: 191-210. *

Tamanyu, S. and Kasuya, M., 1983. Fission track ages of the boring core samples drilled in the Hohi geothermal aera. Part 1. Bull. Geol. Surv. Jpn., 34: 455-469.

Ui, T., Sugimura, A. and Shibahashi, K., 1973. ^{14}C age of the Hijiori pyroclastic flow deposit, northeastern Honshu, Japan. Bull. Volc. Soc. Jpn., 2nd ser., 18: 171-172. **

Yamada, E., 1988. Geologic development of the Onikobe caldera, Northeast Japan, with special reference to its hydrothermal system. Rept. Geol. Surv. Jpn., 268: 61-190.

Yamada, R., Tagami, T., Nishimura, S. and Ito, H., 1995. Annealing kinetics of fission tracks in zircon: an experimental study. Chem. Geol. (Isot. Geosci. Sect.), 122: 249-258.

Wagner, G.A. and Van den haute, P., 1992. Fission-track dating. Ferdinand Enke Verlag Stuttgart, pp285.

* in Japanese with English abstract

** in Japanese

Part 1

Constraints on the thermal history of the North Kurikoma geothermal area, northeast Japan: a fission-track study

ABSTRACT

Fission-track analyses were performed on granitic rocks and Neogene dacite rocks in order to constrain the thermal history of the North Kurikoma geothermal area. Zircon fission-track ages from four dacite samples were determined as ~2 Ma. This age was assumed to show the eruption age because the geothermal effect on detrital zircons included in the dacite was thought to be small. Thus the caldera-forming felsic volcanic activity is assumed to have occurred ~2 Ma.

Six zircon fission-track ages and three apatite fission-track ages were determined on the granitic rocks. Track length measurements were also carried out on zircon. The granodiorite ~500 - 1000 m beneath the Ogachi caldera, where the present temperatures are from 142 °C to 225 °C, yielded a weighted mean zircon fission-track age of 31.2 ± 3.9 Ma, which is assumed to have been thermally reduced by the volcanic activity of ~2 Ma. The almost equivalent thermal effect on the zircon fission-track system within the depth of ~500 - 1000 m of the granodiorite was supposedly due to some lateral heat source, such as hot fluids and/or dykes.

One of Neogene felsic intrusive rocks was dated as ~22 Ma by both zircon and apatite fission-track methods. Therefore the intrusion is assumed to have occurred at approximately 22 Ma in the North Kurikoma geothermal area.

Granitic rocks east and west of the Onikobe-Yuzawa Mylonite Zone near the northern border of the Ogachi caldera were dated by the zircon fission-track method as 95.5 ± 6.6 Ma and 78.1 ± 5.2 Ma respectively, which are thought to have experienced very little thermal overprinting. The corresponding apatite ages were 1.5 ± 0.8 Ma and 22.8 ± 3.4 Ma respectively. The former apatite age should reflect the felsic volcanic activity and the latter apatite age should reflect the intrusion episode.

1. Introduction

Geothermal energy is regarded as an important and promising alternative to fossil fuel energy. In order to utilize geothermal energy much more efficiently, a hot dry rock (HDR) geothermal energy concept was introduced. The HDR concept, which was proposed almost 20 years ago by researchers at the Los Alamos National Laboratory in the U.S.A. (Smith et al., 1973), involves extracting thermal energy from rock that is hot but does not contain sufficient natural fluids for conventional geothermal development. Research-oriented HDR systems have been engineered in the U.S.A. (Fenton Hill), Western Europe (Cornwall), and Japan (Hijiori, Ogachi, Iidate), but whether such systems can produce energy at competitive prices remains to be proven by further testing of these systems or their next generation (Stimac, 1993).

One of many essential requirements for establishing the HDR system is the need to elucidate the thermal history of the studied area. In order to accomplish this objective, radiometric age determinations can provide useful information (Takashima et al., 1987; WoldeGabriel and Goff, 1989, 1992; Ito, 1993).

Among many radiometric dating methods, the fission-track method can provide unique and essential information on the thermal history evaluation for the development of the HDR system. This is because the fission-track method has a unique closure temperature of 100 - 250 ℃, i.e., ~100 ℃ in apatite (Naeser and Faul, 1969; Gleadow and Duddy, 1981; Green et al, 1989) and ~240 ℃ (Hurford, 1986) for zircon, over geological time-scales. The temperature range is between that of the K-Ar dating system using biotite (Hurford, 1986) and that of ESR dating system (Ikeya, 1983).

Central Research Institute of Electric Power Industry (CRIEPI) initiated the HDR project in 1986. At first, the institute drilled two 400 m bore-holes at the Akinomiya site, northeast Japan (Fig. 1). The institute then drilled two 1000 m bore-holes at the Ogachi site (Fig. 1), ~3 km northeast of the Akinomiya site (Hori et al., 1994). Both Akinomiya and Ogachi sites are situated in the North Kurikoma geothermal area (Kimbara, 1988).

In order to make some contributions for the CRIEPI's HDR project, the fission-track method was applied. The main purposes are: 1) to date the Neogene volcanic rocks distributed at the North Kurikoma geothermal area; 2) to make some constraints on the thermal history of granitic rocks distributed at the North Kurikoma geothermal area; and finally 3) to make some constraints on the thermal history of the North Kurikoma geothermal area.

2. Geological setting

General

The North Kurikoma geothermal area, which is a part of the Kurikoma geothermal area (Fig. 1), is situated in the southern-most part of Akita prefecture, northeast Japan. This area has been regarded as a promising geothermal area because geothermal alteration zones are widely developed in and around hot springs (e.g. Oyasu, Doroyu and Akinomiya hot springs) and solfatara in this area (Kimbara, 1988).

According to Yamada et al. (1985), four almost independent geothermal areas are distributed in the Kurikoma geothermal region. Each of them is around Late Quaternary volcanoes, namely the Onikobe caldera, the Narugo volcano, the Takamatsudake volcano and the Kurikomayama volcano. The North Kurikoma geothermal area mentioned here corresponds to the geothermal area distributed around the Takamatsudake volcano. Most of this area is covered by mainly Neogene felsic volcanic rocks and partly

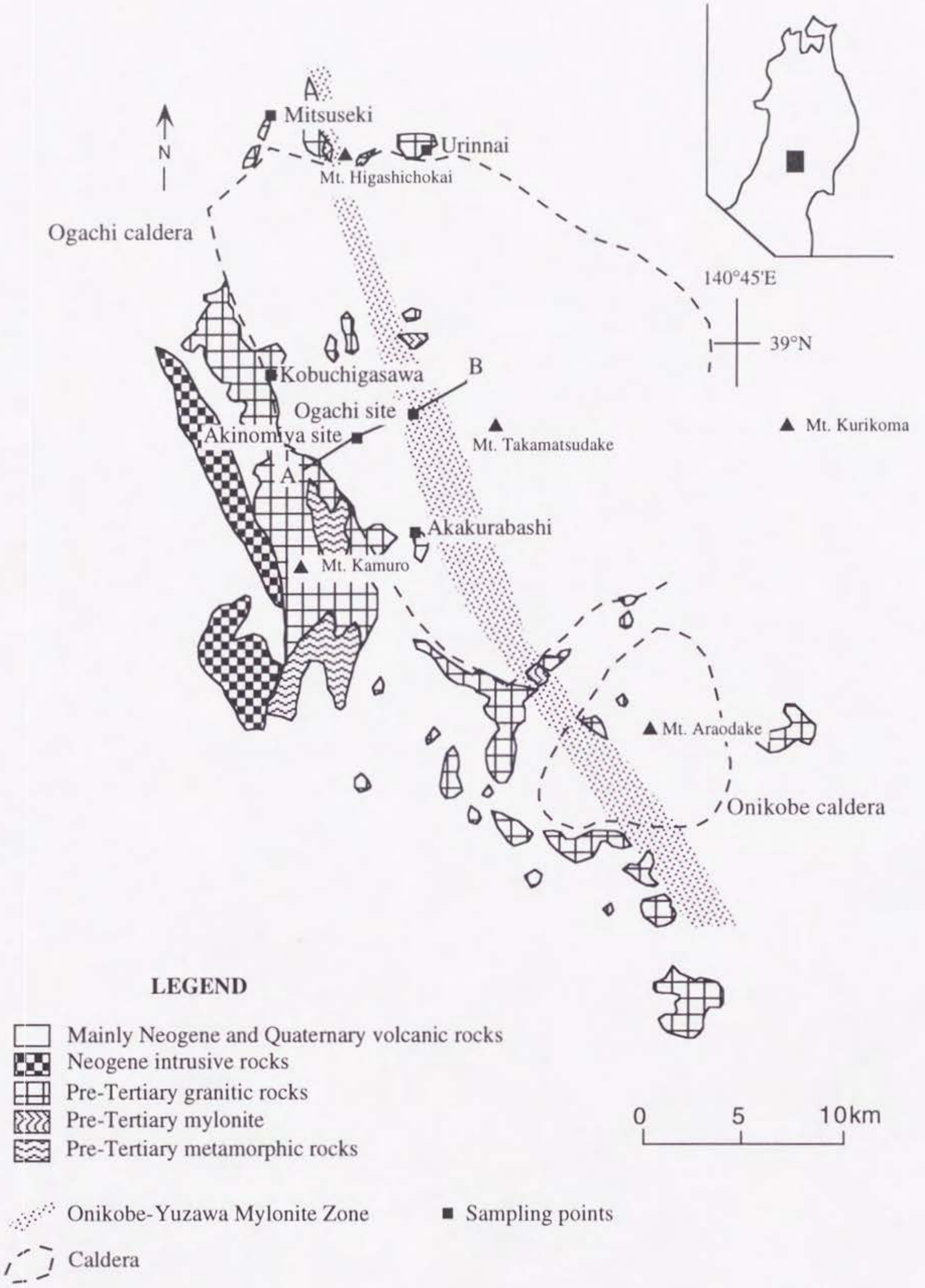

Fig. 1 Simplified geological map of the Kurikoma geothermal area (modified from Sasada, 1984, 1988).
The position of calderas is estimated from Takeno (1988) for the Ogachi caldera and Yamada (1988) for the Onikobe caldera.

Quaternary felsic volcanic rocks together with pre-Neogene basement rocks (Fig. 1).

There is a distinctive structural feature that shows NNW - SSE faults in this area. This structural feature corresponds to that of the "Matsushima-Honsho" tectonic zone (Oide and Onuma, 1960). Gravity anomaly data indicate that these NNW - SSE faults are boundaries of uplifted and subsided zones of basement rocks (Kuriyama, 1985). A mylonite zone, the "Onikobe-Yuzawa Mylonite Zone", is also distributed in the NNW trend (Sasada, 1984, 1985, 1988) in this area.

The geology of this area is briefly described as follows.

Basement rocks of Pre-Tertiary ages

The Onikobe-Yuzawa Mylonite Zone, ~45 km long and ~2 km wide, is situated in the middle of the North Kurikoma geothermal area (Sasada, 1988). It is assumed that the mylonitization occurred along the tectonic weak zone under the temperature and pressure conditions of amphibolite facies during the Late Cretaceous (Sasada, 1984, 1988).

Pre-Tertiary basement rocks are distributed on both sides of the Onikobe-Yuzawa Mylonite Zone (Fig. 1). The basement rocks show different characteristics on both sides of the mylonite zone (Sasada, 1985).

Granitic and metamorphic rocks are widely distributed west of the mylonite zone. The granitic rocks are quartz gabbro, quartz diorite, tonalite, granodiorite and granite. Some of them are well foliated. They yield K-Ar ages of 94 - 97 Ma, with the exception of some younger ages that seem to have been thermally affected (Sasada, 1988). Sasada (1985) assumed that a young age (35.1 Ma) obtained from the granitic rocks was caused by the thermal effect of Neogene intrusives. Sasada (1985) recognized these basement rocks as constituents of the Abukuma Belt.

Granitic rocks, pre-Tertiary sedimentary rocks, metamorphic rocks and serpentinite are sporadically distributed east of the mylonite zone. Most of the granitic rocks are tonalite. The granitic rocks yield K-Ar ages of 87 - 110 Ma (Sasada, 1988) except the one on the southern flank of Mt. Yakeishi-dake, which was dated as 244 Ma (Sasada, 1985). Sasada (1985) recognized these basement rocks as constituents of the Kitakami Belt.

Neogene intrusives

Intrusive bodies are exposed on both sides of the Onikobe-Yuzawa Mylonite Zone. A large intrusive body, called the Daiyama quartz diorite, is exposed west of the Pre-Tertiary granitic rocks of Mt. Kamuro (Fig. 1). The intrusive body clearly cuts the Nozoki Formation, which is the lowermost formation of the Neogene volcanic rocks and is assumed to have been deposited in the Early Miocene (Ozawa and Sumi, 1961). Many small intrusives are also recognized east of the mylonite zone (Sasada, 1985).

Volcanic rocks of Miocene to Quaternary ages

In the North Kurikoma geothermal area, thick felsic tuffs erupted during Neogene to Quaternary times and are widely distributed (Fig. 1, 2). The Neogene felsic tuffs are called the Torageyama Formation and the Sanzugawa Formation in ascending order (Takeno, 1988). They are distributed mainly along the NW-SE trend of a low gravity anomaly (Ohguchi, 1974), overlying Neogene pre-felsic volcanics and sediments. The Quaternary volcanic rocks are the Kabutoyama Formation and the Takamatsudake volcanic rocks in ascending order (Nishimura et al., 1976; Taniguchi et al., 1978; Kuriyama, 1985).

The Torageyama Formation is a thick (>1,100 m) pile of felsic volcanic rocks, comprising biotite dacite tuff which is partly welded. It is divided into three members: the Minasegawa Tuff Member, The Oyu Welded

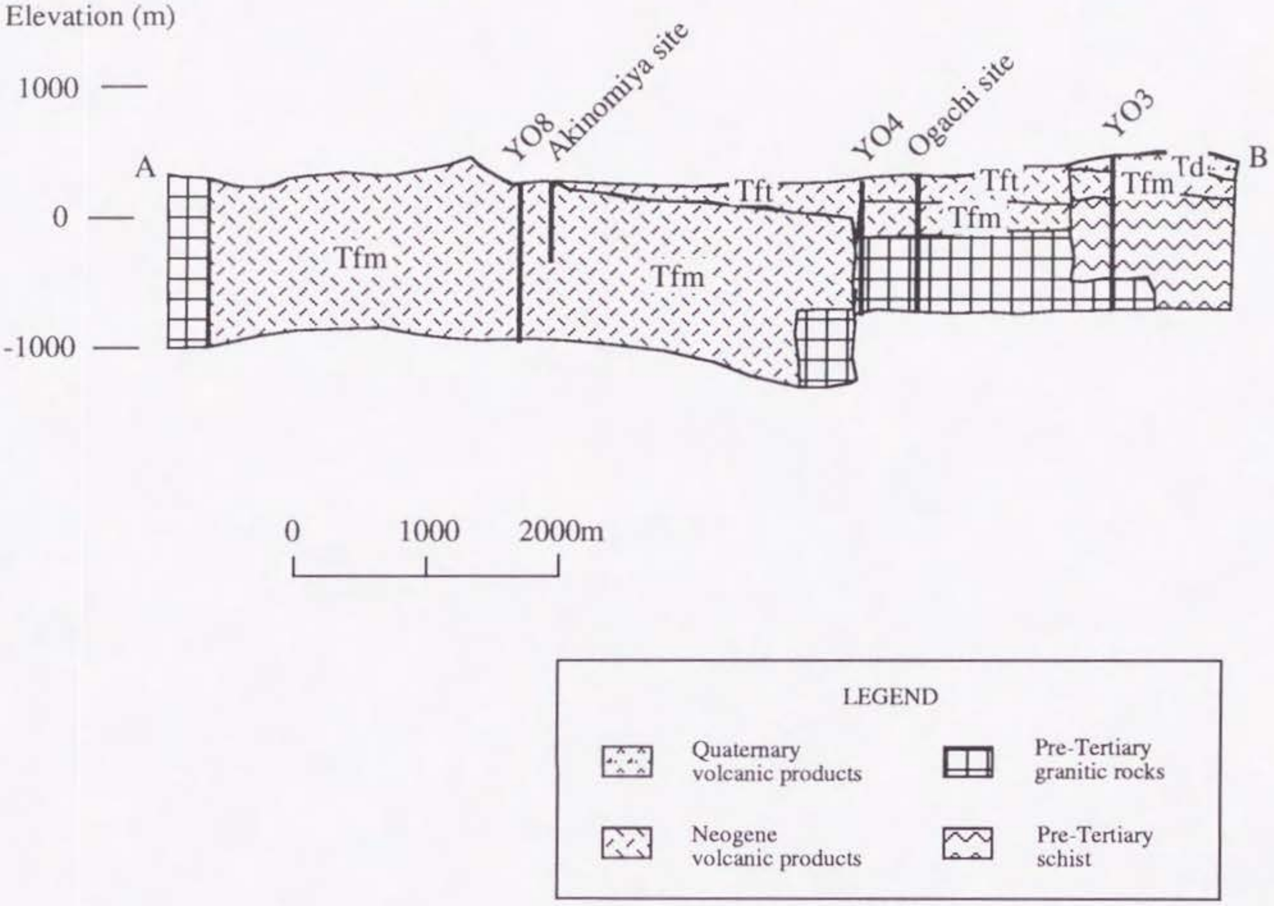

Fig. 2 Geological cross section of the North Kurikoma geothermal area (modified from Takeno, 1988).
A-B line corresponds to that in Fig. 1.Td--Takamatsudake Dacite (Quaternary); Tft--Torageyama Tuff Member of Torageyama Fm. (Neogene); Tfm--Minasegawa Tuff Member of Torageyama Fm. (Neogene).

Tuff Member and the Torageyama Tuff Member (Takeno, 1988). The Minasegawa Tuff Member is pumiceous dacite tuff with quartz, unconformably overlying Neogene pre-felsic volcanics and conformably underlying the Torageyama Formation. The Oyu Welded Tuff Member is dacite welded tuff that characteristically contains orthopyroxene. It is recognized regionally as being intercalated with the Minasegawa tuff Member. The Torageyama Tuff Member is pumiceous dacite tuff with quartz and biotite, which is partly welded.

The Sanzugawa Formation is a lake deposit with a thick pile of volcanic rocks (Takeno, 1988) and it fills a collapsed basin. This collapse structure is recognized as a caldera called the "Ogachi caldera" (Fig. 1) (Takeno, 1988). Takeno (1988) recognized that the caldera-forming volcanic activity produced most of the felsic tuff of the Torageyama Formation and was immediately followed by deposition of the Sanzugawa Formation in the caldera lake.

Many zircon fission-track and K-Ar dates have been reported for the Neogene volcanic rocks (Nishimura et al., 1976; Konda and Ueda, 1980; Yamada, 1981; Kuriyama, 1985; Takeno, 1988; Sakaguchi and Yamada, 1988). The previously determined radiometric ages are listed in Table 1. At present, those results are somewhat confusing, as mentioned below.

The Torageyama Formation was assumed to have been deposited during the Middle - Late Miocene because the lacustrine Sanzugawa Formation was thought to have been deposited in the Late Miocene based on fossil flora (Kato and Shimada, 1953; Muto, 1965). Kuriyama (1985) determined some zircon fission-track ages of 3.0 - 16.4 Ma for the Minasegawa Formation, which corresponds to the Torageyama Formation of Takeno (1988). He assumed the young age (3 - 6 Ma) of this formation was due to the annealing effect of the zircon fission-track system. On the other hand, Nishimura et al. (1976) dated the Oyu Welded Tuff Member as 2.1 Ma

Table 1. Previously determined ages of the Neogene and Quaternary volcanic rocks at the North Kurikoma geothermal area.

Stratigraphy	Dating method	Rock type	Age (Ma)	Reference
Minasegawa Fm.	FT(Zr)	dacite tuff	11.6±1.3	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite lapilli tuff	16.4±1.8	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite	3.3±0.6	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite	9.8±0.7	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite welded tuff	5.6±0.9	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite tuff	5.9±1.0	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite welded tuff	3.5±0.7	Kuriyama (1985)
Minasegawa Fm.	FT(Zr)	dacite tuff	3.0±0.7	Kuriyama (1985)
Torageyama Fm.	K-Ar(WR)	welded tuff	4.6±1.2	Yamada (1981)
Torageyama Fm.	K-Ar(WR)	welded tuff	4.8±0.2	Yamada (1981)
Torageyama Fm. Minasegawa Tuff M.	K-Ar(WR)	dacite tuff	6.0±0.8	Takeno (1988)
Torageyama Fm. Minasegawa Tuff M.	K-Ar(WR)	pumice tuff	5.7±1.4	Takeno (1988)
Torageyama Fm. Oyu Welded Tuff M.	FT(Zr)	dacite welded tuff	2.1	Nishimura et al. (1976)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	4.0±0.3	Takeno (1988)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	3.8±0.2	Takeno (1988)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	3.6±0.2	Takeno (1988)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	3.5±0.5	Takeno (1988)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	3.4±1.1	Takeno (1988)
Torageyama Fm. Torageyama Tuff M.	K-Ar(WR)	dacite tuff	2.8±0.5	Takeno (1988)
Sanzugawa Fm.	K-Ar(WR)	welded tuff	7.7	Konda and Ueda (1980)
Sanzugawa Fm.	FT(Zr)	sandy tuff	6.3±0.6	Kuriyama (1985)
Sanzugawa Fm.	FT(Zr)	sandy tuff	6.4±0.7	Kuriyama (1985)
Kabutoyama Fm.	FT(Zr)	dacite welded tuff	0.32	Nishimura et al. (1976)
Kabutoyama Fm.	FT(Zr)	dacite welded tuff	0.34	Nishimura et al. (1976)
Kabutoyama Fm.	K-Ar(WR)	dacite welded tuff	0.5±0.3	Sakaguchi and Yamada (1988)
Kabutoyama Fm.	K-Ar(WR)	dacite welded tuff	0.6±0.5	Sakaguchi and Yamada (1988)
Takamatsudake volcanic rocks	FT(Zr)	andesite lava	0.2	Nishimura et al. (1976)
Takamatsudake volcanic rocks	FT(Zr)	dacite	1.0±0.2	Kuriyama (1985)

FT(Zr): fission-track method using zircon, K-Ar(WR): K-Ar method using whole rock.

using the zircon fission-track method. They mentioned the contradiction of the fission-track age and the stratigraphy based on fossil flora. Takeno (1988) dated the Torageyama Formation using the K-Ar whole rock method as 5 - 6 Ma for the Minasegawa Tuff member and 3 - 4 Ma for the Torageyama Tuff Member. Yamada (1981) dated the Torageyama Formation as ~4.7 Ma using the K-Ar whole rock method.

Konda and Ueda (1980) determined a K-Ar whole rock age of 7.7 Ma for the Sanzugawa Formation and Kuriyama (1985) determined two zircon fission-track ages of 6.3 ± 0.6 Ma and 6.4 ± 0.7 Ma using sandy tuff. These ages contradict the young ages (2 - 5 Ma) of the Torageyama Formation determined by Nishimura et al. (1976), Yamada (1981) and Takeno (1988).

As for the Quaternary volcanic rocks, the dacitic Kabutoyama Formation was dated as ~0.33 Ma by the fission-track method (Nishimura et al., 1976) and 0.5 - 0.6 Ma by the K-Ar whole rock method (Sakaguchi and Yamada, 1988). The dacitic Takamatsudake volcanic rocks were dated as 0.2 - 1.0 Ma by the fission-track method (Nishimura et al., 1976; Kuriyama, 1985). Takashima and Honda (1988) determined some TL ages of altered rocks in this area and obtained some ages > 0.3 Ma, together with ages < 0.3 Ma, which they assumed to be the ages likely to be found in a geothermally hopeful area. Some ^{14}C ages of talus deposits confirmed that geothermal activity continued up to at least 7,350 ± 140 years ago in the North Kurikoma geothermal area. (Taniguchi et al., 1978).

3. Experimental methods

Sampling

Fission-track analyses were carried out mainly on Neogene volcanic rocks and pre-Tertiary granitic rocks.

The Neogene volcanic rocks were obtained from a 400 m deep bore-hole drilled by CRIEPI at the Akinomiya site (Fig. 1). The lithology and sampling points of the bore-hole are shown in Fig. 3. Dacite tuff samples at 217 m, 250 m, 300 m, 350 m and 387 m in depth were collected and named as AKI1, AKI2, AKI3, AKI4 and AKI5 respectively. Samples are all drilling core samples and the present temperatures of all the samples were measured as less than 50 ℃. Some thin sections of the samples were prepared and observed. All samples were similar in that they contain abundant quartz, plagioclase, various kinds of lithic fragments and opaque minerals. Plagioclase is mostly altered to carbonates. According to Takeno (1988), all of the samples correspond to the Minasegawa tuff Member of the Torageyama Formation.

The pre-Tertiary granodiorite was obtained from a 1000 m deep bore-hole drilled by CRIEPI at the Ogachi site, ~3 km northeast of the Akinomiya site (Fig. 1). The granodiorite of the bore-hole is situated in the Ogachi caldera (Takeno, 1988) and also in the Onikobe-Yuzawa Mylonite Zone of Sasada (1984, 1988). The lithology and sampling points of the bore-hole are shown in Fig. 4 with a static temperature measurement result. The bore-hole was drilled for an injection well of the HDR project, and reached ~230 ℃ at the bottom. The temperature increases linearly with depth and the geothermal gradient is ~21 ℃/100 m. Samples at 581 m, 781 m and 981 m in depth were collected and named as OG1, OG2 and OG3 respectively. All of the samples are drilling core samples. From the observation of the bore-hole core (500 - 1000 m in depth), the granodiorite shows a distinct foliation. From the microscopic observation of some thin sections, fine-grained and recrystallized aggregates of quartz (mortar structure) are observed. Plagioclase is partly sericitized. Mafic minerals are altered to chlorite. At greater depths, quartz gradually becomes more fine grained and shows

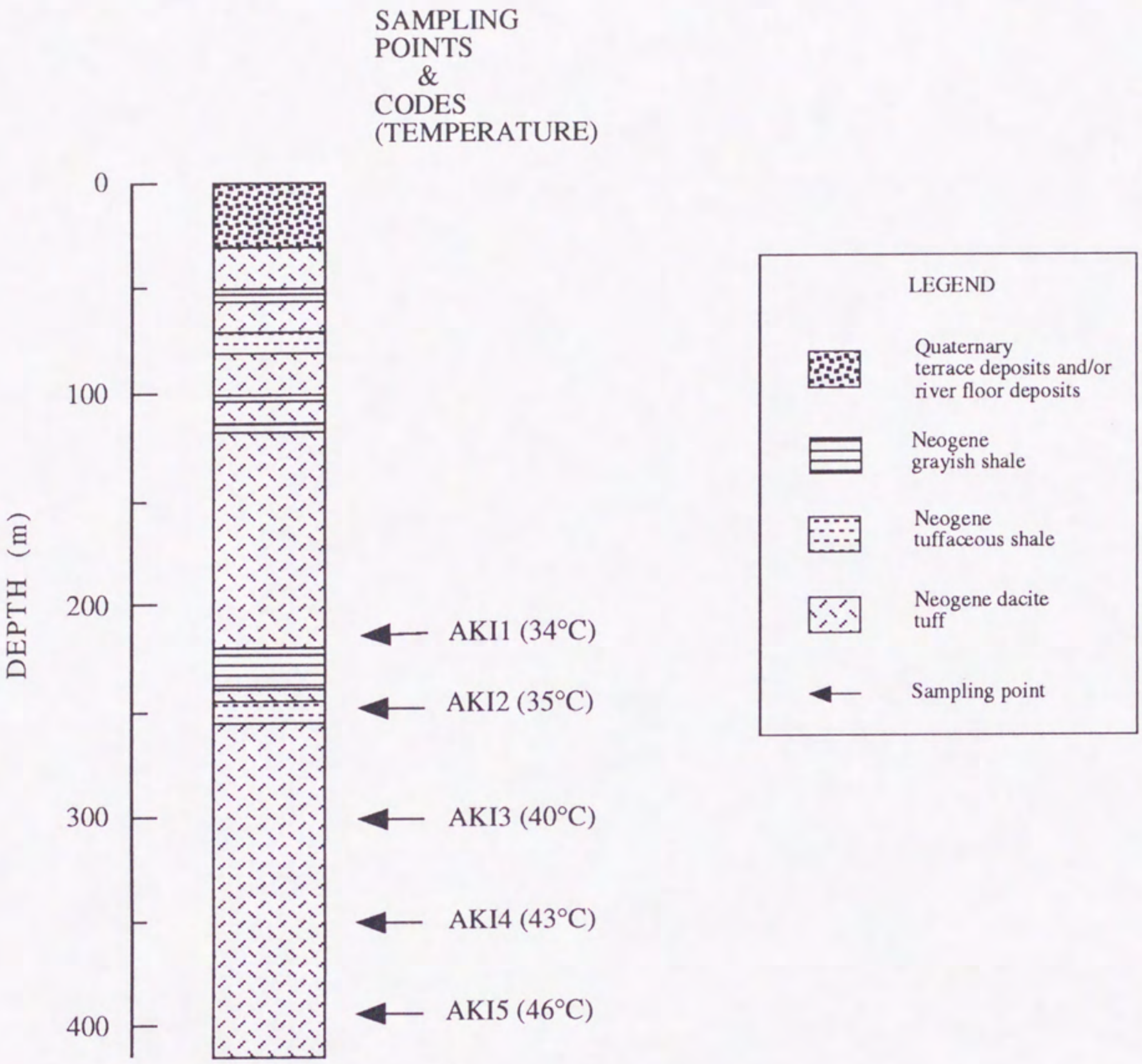

Fig. 3 Columnar section of the 400 m bore-hole drilled at the Akinomiya site and sampling points with static temperature measurements (in parentheses).

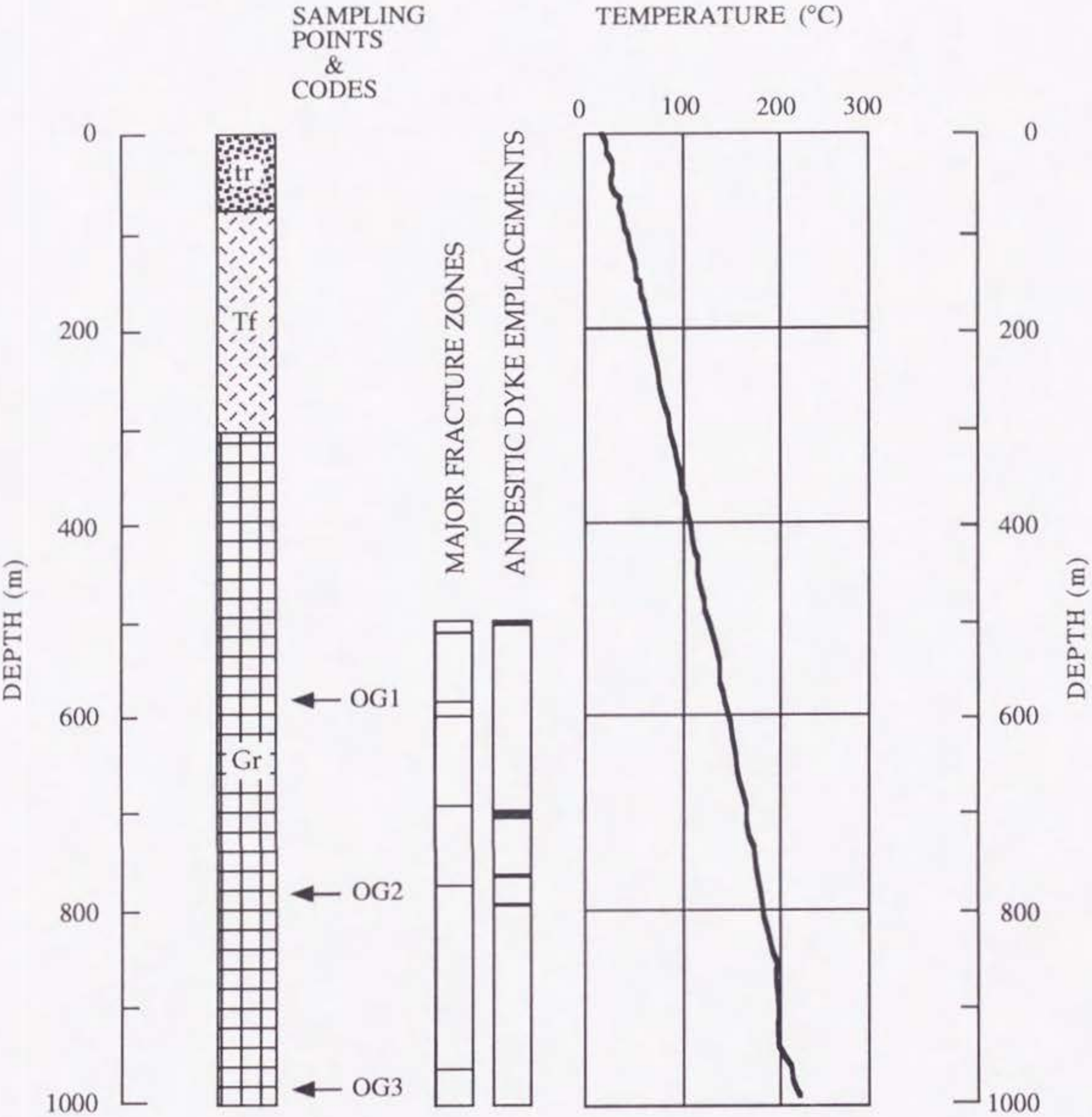

Fig. 4 Columnar section of the 1,000 m bore-hole drilled at the Ogachi site and sampling points with a static temperature measurement result (modified from Kondo, 1994).

Core samples were taken between 500 and 1000 m in depth, so data regarding fracture zones and dyke emplacements were obtained in this section.

tr--terrace deposits and/or river floor deposits (Quaternary); Tf--Torageyama Formation (Neogene); Gr--Pre-Tertiary granitic rocks.

porphyroclastic texture together with feldspar (Kondo, 1994). Thus it seems the mylonitization was more severe at greater depths (Kondo, 1994).

In order to compare the thermal history of the granodiorite that is underground and hot with that of the granitic rocks that are exposed and cool, four outcrop samples were collected. They were obtained at Akakurabashi, Kobuchigasawa, Mitsuseki and Urinnai (Fig. 1). Only the Urinnai sample is located east of the mylonite zone. The microscopic observation of these rocks are as follows. The granitic rock at Akakurabashi contains recrystallized quartz, partly sericitized plagioclase and chloritized mafic minerals. Fine-grained and elongated quartz aggregates are less common in this sample than those in the Ogachi sample. The Kobuchigasawa sample, which was severely weathered in outcrop, shows a porphyritic texture with quartz and unaltered plagioclase phenocrysts. Thus it was later recognized as a Neogene felsic intrusive rock. The granitic rock at Mitsuseki contains quartz, unaltered plagioclase and mafic minerals. The granitic rock at Urinnai contains quartz, unaltered plagioclase and biotite.

Laboratory procedures

Zircons and apatites were obtained through conventional mineral separation techniques including both magnetic and heavy liquid separations. In this study, some fission track analyses were carried out at CRIEPI, and the others were carried out at La Trobe University, Australia.

Laboratory procedures at CRIEPI

1. A sample (some pieces of rock with a total weight of 3 - 4 kg) is trimmed by a rock trimmer to fragments of ~3 cm in dimension and crushed into powder by a jaw crusher.

2. The sample is sieved through 60# (250 μm) mesh under water and grains smaller than 250 μm are collected .

3. Light minerals are washed away by panning.

4. The sample is sieved through 200# (74 μm) mesh under water and grains larger than 74 μm are collected.

5. After drying the sample at 60 ℃, ferromagnetic minerals are removed by a hand-magnet.

6. Magnetic minerals, such as biotite, hornblende and pyroxene etc., are removed by an isodynamic separator.

7. Heavy minerals are separated by bromoform (sp. gr. = 2.87 g/cm^3).

8. Heavier minerals (commonly zircons) are separated from lighter minerals (commonly apatite) by diiodomethane (sp. gr. = 3.33 g/cm^3).

9. If minerals other than zircons are included in the heavy fraction, they are bathed in HF (47%) overnight at room temperature, and when pyrites in particular are included, they are bathed in HNO_3 (60%) overnight at room temperature to dissolve those minerals.

10. Zircons are spread on a quartz glass slide, handpicked and arranged in an array of ~7x7 under a binocular microscope and then mounted in PFA teflon sheet. Apatites are spread on a teflon slide, handpicked and arranged in an array of ~10x10 under a binocular microscope and mounted using resin "PETROPOXY 154" at 120 ℃ for 5 min.

11. Both zircon and apatite mounts are ground to a depth that assures 4π geometry (~6 μm for zircon; ~8 μm for apatite) using 6 μm diamond paste and are then polished by 1 μm diamond paste.

12. Zircons are etched in NaOH:KOH (1:1) eutectic etchant (Gleadow et al., 1976) at 225 ℃ for sufficient time (usually 10-30 hours). The etching times are determined so that tracks parallel to the C axis of the grain are clearly observed. Apatites are etched in HNO_3 (0.6%) at 25 ℃ for 2-2.5 minutes. Age standard samples, which will be mentioned later in this section, are also treated the same way for the samples to be dated.

13. A uranium free muscovite sheet (as an external detector) is attached to each mount of zircon, apatite and standard glass. As a standard glass, which is a uranium-bearing glass used to monitor neutron dose, NBS-SRM 613 is used. The glass contains 37.4 ppm of uranium and a depleted $^{235}U/^{238}U$ ratio of 0.2392 atom % .

14. A bundle of samples to be dated, age standard samples and standard glasses for zircon dating are prepared and sent to Kyoto University Research Reactor (KUR) for neutron irradiation. Samples for apatite dating are also prepared the same way as for zircon dating and are sent to KUR for neutron irradiation. Samples for zircon dating are irradiated for 77 hours (or 190 hours) at the D_2O facility and samples for apatite dating are irradiated for 4 hours (or 90 min.) at the TcPn facility. The cadmium (Cd) ratio for Au of D_2O is > 5000 and that of TcPn is 12 - 15 (T. Tagami, personal communication, 1992).

15. Muscovites are etched in HF (47%) at 30 ℃ for 4.5 minutes.

16. Tracks are counted and track lengths are measured under x1000 magnification (x10 eye-pieces, x100 dry objective) on a Nikon® Optiphot-POL optical microscope. Only grain surfaces of high etching efficiency, which can be easily recognized by the existence of sharp polishing scratches (Gleadow, 1981), and those of optimal etching, which can be recognized by isotropic angular distribution of etched tracks (Sumii et al., 1987), were selected for counting.

17. Ages are determined using the external detector method (Gleadow, 1981) and the zeta calibration of Hurford and Green (1983) is adopted. More details of the age calculation and the zeta calibration will be mentioned later in this section.

18. Track lengths are measured through a micrometer scale fitted in one of the eye-pieces of the microscope. The precision of the measurement is ~0.2 μm. Only horizontally confined tracks (HCT's; Laslett et al., 1982),

including both track-in-tracks and track-in-cleavages (TINT's and TINCLE's respectively; Lal et al., 1969; Laslett et al., 1982) are selected.

Laboratory procedures at La Trobe University

Laboratory procedures at La Trobe University are essentially the same as those at CRIEPI, but some different techniques are adopted. Here only different points are mentioned (The number of each procedure corresponds with that at CRIEPI.)

1. Samples are crushed by a jaw crusher and pulverized by a disc mill.

7. Heavy minerals are separated by sodium polytungstate (SPT) (sp. gr. = 2.85 g/cm^3).

10. Zircons are placed on a quartz glass plate and then mounted in PFA teflon sheet at ~300 ℃ on a hotplate. Apatites are placed on petrographic (27 x 45 mm) glass slides and then mounted using resin "PETROPOXY 154" at 120 ℃ for 5 min. on a hotplate. Zircons and apatites are not arranged, because a computer-automated microscope system, Autoscan system (Smith and Leigh-Jones, 1985), is used.

11. Both zircon and apatite mounts are ground to a depth that assures 4 π geometry using carborundum paper (first 600# and then 1200#) on wet rotating laps and are then polished using 0.3 μm alumina on rotating laps.

12. Zircons are etched in NaOH:KOH (1:1) eutectic etchant at 220 - 240 ℃ for sufficient time (usually 10-30 hours). The etching times are determined so that tracks parallel to the C axis of the grain are clearly observed. Apatites are etched in 5 N HNO_3 at room temperature for 20 seconds. Age standard samples are also treated the same way for the samples to be dated.

13. As a standard glass, Corning 1 (CN1) glass is used for zircon dating and SRM612 glass is used for apatite dating. The CN1 glass contains

~39 ppm of uranium and a natural $^{235}U/^{238}U$ ratio of 0.7262 atom %. The SRM 612 glass has the same content as the SRM 613 glass.

14. A bundle of samples to be dated, age standard samples and standard glasses for zircon dating are prepared and irradiated in the X-7 position of the Australian Atomic Energy Commission's HIFAR reactor at Lucas Heights, N.S.W., Australia. This thermal neutron irradiation position has a cadmium ratio for gold activation of 125. Samples for apatite dating are also prepared and irradiated in the same way as for zircon dating. A neutron dose of ~1 x 10^{15} n cm^{-2} is used for zircon samples and ~1 x 10^{16} n cm^{-2} is used for apatite samples.

15. Muscovites are etched in HF (47%) at room temperature for 20 - 25 minutes.

16. Tracks are counted and track lengths are measured under x1250 magnification on a Zeiss® optical microscope.

18. Track lengths are measured using a digitizing tablet interfaced with the Autoscan system. The precision of measured track length is ~0.2 µm.

Age calculation

The fission-track age (T) is calculated by means of zeta calibration as follows (Hurford and Green, 1983):

$$T=1/\lambda_D \ln[1+\lambda_D(\rho_s/\rho_i)\rho_d g\zeta]$$

where,

λ_D = the total decay constant for ^{238}U (1.551×10^{-10} yr^{-1}),

ρ_s = spontaneous track density of ^{238}U (tracks/cm^2) for the sample to be dated,

ρ_i = induced track density of ^{235}U (tracks/cm^2) for the sample to be dated,

ρ_d = induced track density of ^{235}U (tracks/cm^2) for the standard glass,
g = a geometric factor (0.5 for internal surface grain, 1 for external surface grain),
ζ = zeta calibration factor.

The error of the fission-track age (σT) is calculated as follows:

$$\sigma T = T[1/N_s + 1/N_i + 1/N_D + (\sigma\zeta/\zeta)^2]^{1/2}$$

where,
N_s = spontaneous track number of ^{238}U (tracks/cm^2) for the sample to be dated,
N_i = induced track number of ^{235}U (tracks/cm^2) for the sample to be dated,
N_D = induced track number of ^{235}U (tracks/cm^2) for the standard glass,
$\sigma\zeta$ = error of the zeta value.

Zeta calculation

The zeta value is calculated as follows (Hurford and Green, 1983):

$$\zeta = [\exp(\lambda_D T_{STD}) - 1]/[\lambda_D g(\rho_{sSTD}/\rho_{iSTD})\rho_d]$$

where,
T_{STD} = the age of the age standard sample,
ρ_{sSTD} = spontaneous track density of ^{238}U (tracks/cm^2) for the age standard,
ρ_{iSTD} = induced track density of ^{235}U (tracks/cm^2) for the age standard.

The error of the zeta value is calculated as follows:

$$\sigma\zeta = \zeta[1/N_{sSTD}+1/N_{iSTD}+1/N_D+(\sigma T_{STD}/T_{STD})^2]^{1/2}$$

where,

N_{sSTD} = spontaneous track number of ^{238}U (tracks/cm^2) for the age standard,

N_{iSTD} = induced track number of ^{235}U (tracks/cm^2) for the age standard,

σT_{STD} = age error of the age standard.

Zeta values at CRIEPI

The zeta value of zircon was determined using three age standards. They are Fish Canyon Tuff, Buluk Member 4 Tuff and Tardree Rhyolite, whose ages are 27.8±0.1 Ma, 16.2±0.1 Ma and 58.7±0.6 Ma respectively (Hurford and Green, 1983; Hurford and Watkins, 1987).

Zircons of Fish Canyon Tuff were obtained from the rock sample using the same laboratory procedures mentioned above (1 - 9 of the "Laboratory procedures at CRIEPI"). Zircons of Buluk Member 4 Tuff and Tardree Rhyolite were provided through the Fission Track Research Group of Japan.

The zircons for the zeta value determination were prepared using the same procedures adopted for unknown-age samples (10 - 16 of the "Laboratory procedures at CRIEPI"). The zeta obtained for zircon was 374.0 ± 6.5 (1σ error) for dosimeter glass SRM613 (Table 2).

The zeta value of apatite was determined using the Fish Canyon Tuff age standard. The apatites for the zeta value determination were prepared using the same procedures adopted for unknown-age samples (1 - 16 of the "Laboratory procedures at CRIEPI"). The zeta obtained for apatite was 265.2 ± 10.3 (1σ error) for dosimeter glass SRM613 (Table 3).

Table 2 Zeta (ζ) values of zircon age standards determined at CRIEPI.

Age standard	Sample code	Irradiated month/year	Number of grains	Dosimeter		Spontaneous		Induced		$P(\chi^2)$ (%)	$\zeta \pm 1\sigma$
				number	density ($x10^5cm^{-2}$)	number	density ($x10^6cm^{-2}$)	number	density ($x10^6cm^{-2}$)		
Fish Canyon Tuff	FCTZ -1	07/90	10	1029	1.07	1434	4.72	1001	3.29	3	362.3±18.7
Fish Canyon Tuff	FCTZ-2	07/90	9	1020	1.06	1467	6.33	873	3.76	2	311.6±16.5
Buluk Member 4 Tuff	BM-1	07/90	6	1012	1.06	402	1.36	366	1.24	60	279.7±22.0
Tardree Rhyolite	TR-1	07/90	11	1004	1.05	1717	6.92	474	1.91	15	312.4±19.0
Fish Canyon Tuff	FCTZ-1	12/90	12	1924	1.154	1668	4.62	1391	3.85	30	402.8±17.3
Fish Canyon Tuff	FCTZ-2	12/90	11	1924	1.154	1762	6.13	1358	4.72	3	372.2±15.9
Fish Canyon Tuff	FCTZ-4	12/90	7	1924	1.154	1098	5.82	943	4.99	60	414.8±20.7
Buluk Member 4 Tuff	BM-1	12/90	8	1924	1.154	483	1.24	559	1.44	15	325.4±21.5
Tardree Rhyolite	TR-1	12/90	11	1924	1.154	1717	6.92	686	2.76	50	410.5±20.8
Fish Canyon Tuff	FCTZ-1	11/91	12	2687	2.50	1668	4.62	3391	9.39	<0.1	452.5±16.1
Fish Canyon Tuff	FCTZ-2	11/91	11	2687	2.50	1762	6.13	2961	10.3	0.5	374.1±13.4
Fish Canyon Tuff	FCTZ-4	11/91	6	2687	2.50	882	5.35	1696	10.29	20	428.0±19.6
Buluk Member 4 Tuff	BM-1	11/91	7	2687	2.50	454	1.32	1184	3.45	20	338.0±19.8
Tardree Rhyolite	TR-1	11/91	11	2687	2.50	1717	6.92	1476	5.95	<0.1	407.1±16.4
Fish Canyon Tuff	FCTZ-5	01/95	13	1864	1.00	1653	5.63	1101	3.75	2	370.2±16.8
											374.0 ± 6.5

Zeta value underlined, which is the weighted mean, is adopted. The ages of the age standard samples are 27.8 ± 0.1 Ma for Fish Canyon Tuff, 16.2 ± 0.1 Ma for Buluk Member 4 Tuff and 58.7 ± 0.6 Ma for Tardree Rhyolite (Hurford and Green, 1983; Hurford and Watkins, 1987). Dosimeter glass SRM 613 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

Table 3 Zeta (ζ) values of apatite age standards determined at CRIEPI.

Age standard	Sample code	Irradiated month/year	Number of grains	Dosimeter number density ($\times10^5$cm^{-2})		Spontaneous number density ($\times10^5$cm^{-2})		Induced number density ($\times10^5$cm^{-2})		P(χ^2) (%)	ζ ± 1σ
Fish Canyon Tuff	FCTA-2	07/90	18	1445	2.51	306	2.30	375	2.81	80	271.7±22.1
Fish Canyon Tuff	FCTA-2	12/90	19	1195	6.93	314	2.29	1051	7.65	80	269.2±19.0
Fish Canyon Tuff	FCTA-3	12/90	12	1213	7.03	218	2.61	709	8.47	20	257.7±21.3
Fish Canyon Tuff	FCTA-3	01/95	13	2901	7.21	234	2.62	793	8.87	40	262.0±20.1
											265.2±10.3

Zeta value underlined, which is the weighted mean, is adopted. The age of Fish Canyon Tuff is 27.8±0.1 Ma (Hurford and Green, 1983). Dosimeter glass SRM 613 used. P(χ^2): Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

Zeta values at La Trobe University

The zeta value of zircon was determined using Fish Canyon Tuff and Tardree Rhyolite. It was determined by counting spontaneous and induced fission tracks of the age standard samples that had already been prepared by the same procedures adopted for unknown-age samples at La Trobe University. The zeta obtained for zircon was 135.1 ± 3.2 (1σ error) for dosimeter glass CN1 (Table 4).

The zeta value of apatite was determined using Fish Canyon Tuff, Mt. Dromedary and Durango samples. The ages of Mt. Dromedary and Durango samples are 98.7±0.3 Ma and 31.4±0.3 Ma respectively (Hurford and Green, 1983; Green, 1985). The zeta value was determined by counting spontaneous and induced fission tracks of the age standard samples that had been already prepared by the same procedures adopted for unknown-age samples at La Trobe University. The zeta obtained for apatite was 329.1 ± 16.0 (1σ error) for dosimeter glass SRM612 (Table 5).

4. Results

Small amounts of zircons and apatites were obtained from the Neogene volcanic rocks (sample code: AKI2 - AKI5). Sample AKI1 did not yield sufficient zircon or apatite for fission-track analysis. From microscopic observation, two types of zircons were recognized. One type was more transparent and more angular than the other. The former type was later confirmed to be essential zircons and the latter was confirmed to be detrital zircons through the dating procedure. A large amount of pyrite was recognized during the mineral separation of the Neogene volcanic rocks.

Large amounts of zircons and apatites were obtained from the granitic and intrusive rocks. There was less pyrite than in the Neogene volcanic

Table 4 Zeta (ζ) values of zircon age standards determined at La Trobe Univ..

Age standard	Sample code	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	$\zeta \pm 1\sigma$
Fish Canyon Tuff	FCT931(LU273)	8	1165	5.17	1645	5.37	2209	7.21	42.6	144.7±6.4
Fish Canyon Tuff	FCT932(LU273)	6	1178	5.23	951	3.98	1281	5.37	74.7	143.6±7.5
Fish Canyon Tuff	FCT934(LU279)	8	1166	5.17	698	5.23	982	7.36	97.3	151.5±8.7
Fish Canyon Tuff	FCT936(LU296)	6	2002	4.65	595	4.82	636	5.15	96.1	128.1±7.9
Fish Canyon Tuff	FCT937(LU296)	5	2002	4.65	435	5.49	459	5.79	32.7	126.4±8.9
Fish Canyon Tuff	FCT1(PT538-7)	6	1052	4.88	546	5.42	635	6.30	0.4	132.7±8.8
Fish Canyon Tuff	FCT2(PT538-10)	5	1052	4.88	517	5.36	556	5.76	2.8	122.7±8.4
Tardree Rhyolite	TD1(PT538-6)	10	1052	4.88	809	6.47	443	3.55	2	132.3±8.9
Tardree Rhyolite	TD2(PT538-9)	6	1052	4.88	495	6.11	274	3.38	93.6	133.7±11.0
										135.1±3.2

Zeta value underlined, which is the weighted mean, is adopted. The ages of the age standard samples are 27.8±0.1 Ma for Fish Canyon Tuff and 58.7±0.6 Ma for Tardree Rhyolite (Hurford and Green, 1983; Hurford and Watkins, 1987). Dosimeter glass CN-1 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

Table 5 Zeta (ζ) values of apatite age standards determined at La Trobe Univ..

Age standard	Sample code	Number of grains	Dosimeter number density ($\times 10^5 cm^{-2}$)		Spontaneous number density ($\times 10^5 cm^{-2}$)		Induced number density ($\times 10^5 cm^{-2}$)		$P(\chi^2)$ (%)	$\zeta \pm 1\sigma$
Fish Canyon Tuff	FCT93-2(LU267)	20	1686	1.497	297	2.20	2525	1.87	73	315.3±24.3
Fish Canyon Tuff	72N824(PT544)	15	3139	1.457	146	1.84	1176	1.48	51	308±27.6
Fish Canyon Tuff	FCT1(LU266)	13	3426	1.590	70	2.24	512	1.64	73	256.3±33.0
Fish Canyon Tuff	72N81(PT545)	15	3053	1.417	226	2.02	1807	1.61	93	314.4±22.9
Mt.Dromedary	MTD1(LU253)	18	1353	1.256	304	8.67	774	2.21	23	403.2±29.6
Mt.Dromedary	MTD2(LU253)	16	1377	1.277	289	7.60	800	2.11	66	431.2±31.9
Mt.Dromedary	MTD3(LU253)	15	1400	1.299	239	8.06	683	2.30	95	437.6±35.0
Mt.Dromedary	8322-42(PT544)	13	3139	1.457	421	5.25	1225	1.53	41	397.3±23.7
Mt.Dromedary	MTD4(LU266)	11	3241	1.504	124	7.99	314	2.02	46	334.9±36.1
Mt.Dromedary	8322-41(PT545)	15	3053	1.417	456	5.48	1375	1.65	69	423.3±24.3
Durango	DUR1(LU253)	16	1635	1.517	250	1.81	1474	1.07	32	244.7±17.9
Durango	DUR2(LU253)	9	1659	1.539	137	1.89	952	1.32	99	284.2±27.0
Durango	DUR3(LU253)	10	1682	1.560	153	1.78	1019	1.18	47	268.8±24.3
Durango	8122-3(PT544)	13	3139	1.457	186	1.76	1382	1.30	95	321.0±25.9
Durango	DUR4(LU266)	13	3117	1.447	98	1.81	706	1.30	81	313.4±34.4
Durango	81223(PT545)	15	3053	1.417	212	1.67	1707	1.35	100	357.7±27.1
										329.1±16.0

Zeta value underlined, which is the weighted mean, is adopted. The ages of the age standard samples are 27.8±0.1 Ma for Fish Canyon Tuff, 98.7±0.3 Ma for Mt. Dromedary and 31.4±0.3 Ma for Durango (Hurford and Green, 1983; Green, 1985). Dosimeter glass SRM612 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

samples. Zircons of the Kobuchigasawa sample, which is the felsic intrusive rock, are distinct from those of the granitic rocks. They are mostly transparent, euhedral, elongated and large (300 - 1000 μm) crystals, while zircons from the granitic rock samples are generally less transparent and 200 - 400 μm in dimension.

The zircon and apatite fission-track ages are listed in Table 6 and Table 7 respectively. Each set of data in Table 6 and Table 7 has been subjected to the χ^2-test (Galbraith, 1981) to detect the presence of additional uncertainty, beyond that allowed by Poisson variation in track counts. Those data for which the χ^2 value is acceptable at the 5% level have been subjected to the "conventional analysis" (Green, 1981). For those data which fail the χ^2-test, the conventional analysis is not applicable (Galbraith, 1981) and for these data the mean of the individual crystal track density ratio ($\rho s/\rho i$) and the error on the mean ratio were used for age calculation (Green, 1981).

All of the Neogene volcanic rock samples (AKI2 - AKI5) were dated as ~2 Ma by the zircon fission-track method. Some zircons had much higher spontaneous track densities than other zircons. These fission-track ages were calculated as 20 - 160 Ma, which obviously demonstrates that they are detrital zircons. The detrital zircons were excluded for the dating of the Neogene volcanic rocks in Table 6. The apatite fission-track dating was discarded because of the very low spontaneous track density.

The granodiorite from the bore-hole (sample code: OG1 - OG3) was dated as ~25 - 35 Ma by the zircon fission-track method. Some apatite pilot samples were etched and most apatite grains were observed to have no tracks (except for some grains which have some track-like pits). Thus the apatite fission-track ages were regarded as being zero.

The granitic and intrusive rocks from the outcrop localities were dated by both zircon and apatite fission-track methods. The granitic rock at Akakurabashi was dated as 47.2 ± 3.0 Ma and 2.0 ± 1.3 Ma by zircon and

Table 6 Zircon fission track analytical data of the North Kurikoma geothermal area.

Locality	Sample code	Laboratory	Bore-hole depth (m)	Temp. (°C)	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	Age ± 1σ (Ma)
Akinomiya	AKI2	CRIEPI	250	35	11	956	0.997	110	0.32	783	2.30	0.1	3.0±0.7
Akinomiya	AKI3	CRIEPI	301	40	12	948	0.989	80	0.23	620	1.79	25	2.4±0.3
Akinomiya	AKI4	CRIEPI	350	43	15	940	0.981	49	0.08	742	1.22	68	1.2±0.2
Akinomiya	AKI5	CRIEPI	388	46	15	932	0.972	110	0.21	1009	1.94	0.4	2.0±0.4
Ogachi	OG1-1	CRIEPI	581	142	4	1337	2.41	247	2.63	358	3.81	15.8	31.0±2.8
Ogachi	OG1-2	CRIEPI	581	142	7	1363	2.45	540	4.11	598	4.55	0.1	40.3±4.8
Ogachi	OG1	CRIEPI	581	142	11	----		----		----		----	33.4±4.0
Ogachi	OG2	CRIEPI	781	183	12	1345	2.42	1013	3.72	1192	4.38	0	37.2±3.3
Ogachi	OG3-1	CRIEPI	981	225	7	1354	2.44	454	3.06	768	5.17	0	30.1±4.6
Ogachi	OG3-2	CRIEPI	981	225	8	1371	2.47	277	1.72	577	3.58	4.3	23.3±2.7
Ogachi	OG3	CRIEPI	981	225	15	----		----		----		----	25.0±3.0
Akakurabashi	KAMU1	La Trobe	-----	~10	8	1190	5.28	851	5.11	641	3.85	18	47.2±3.0
Kobuchigasawa	KAMU2	La Trobe	-----	~10	13	1202	5.34	631	0.90	1058	1.51	40	21.5±1.3
Mitsuseki	940815	CRIEPI	-----	~10	11	1864	1.00	1307	4.52	312	1.07	30	78.1±5.2
Urinnai	940816	CRIEPI	-----	~10	12	1864	1.00	1437	5.53	280	1.08	30	95.5±6.6

Samples at Akinomiya are dacite tuff. Sample at Kobuchigasawa is intrusive rock. Other samples are granitic rocks. Ages are determined on individual grain-mounted sheet. Age of OG1 is weighted mean of OG1-1 and OG1-2. Age of OG3 is weighted mean of OG3-1 and OG3-2. Ages underlined are adopted. Samples analysed at CRIEPI are calculated using ζ=374.0±6.5 (1σ error). Dosimeter glass SRM 613 is used. Samples analysed at La Trobe Univ. are calculated using ζ=135.1±3.2 (1σ error). Dosimeter glass CN1 is used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981). Mean ρs/ρi ratio used to calculate age and uncertainty where $P(\chi^2) < 5\%$ (ρs: spontaneous track density, ρi: induced track density). Mean ρs/ρi ratios of AKI2, AKI5, OG1-2, OG2, OG3-1 and OG3-2 are 0.158 ± 0.038, 0.107 ± 0.021, 0.881 ± 0.101, 0.824 ± 0.068, 0.661 ± 0.100 and 0.506 ± 0.057, respectively.

Table 7 Apatite fission track analytical data of the North Kurikoma geothermal area.

Locality	Sample code	Laboratory	Temp. (°C)	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)	Spontaneous number density ($x10^5cm^{-2}$)	Induced number density ($x10^5cm^{-2}$)	$P(\chi^2)$ (%)	Age ± 1σ (Ma)
Akakurabashi	KAMU1A	La Trobe	~10	17	1627 14.4	6 0.039	655 4.28	2	2.0±1.3
Kobuchigasawa	KAMU2A-1	La Trobe	~10	12	1627 14.4	31 0.357	351 4.04	82	20.9±4.1
Kobuchigasawa	KAMU2A-2	CRIEPI	~10	10	2901 7.21	30 0.402	118 1.58	30	24.3±5.0
Kobuchigasawa	KAMU2A	—	~10	22	—	—	—	—	22.3±1.7
Mitsuseki	940815A	CRIEPI	~10	9	2901 7.21	56 0.927	234 3.88	80	22.8±3.4
Urinnai	940816A	CRIEPI	~10	12	2901 7.21	4 0.054	257 3.48	75	1.5±0.8

Sample at Kobuchigasawa is intrusive rock. Other samples are granitic rocks. Ages are determined on individual grain-mounted sheet. Age of KAMU2A is weighted mean of KAMU2A-1 and KAMU2A-2. Ages underlined are adopted. Samples analysed at CRIEPI are calculated using $\zeta=265.2 \pm 10.3$ (1σ error). Dosimeter glass SRM 613 is used. Samples analysed at La Trobe Univ. are calculated using $\zeta=329.1 \pm 16.0$ (1σ error). Dosimeter glass SRM 612 is used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981). Mean ρs/ρi ratio used to calculate age and uncertainty where $P(\chi^2) < 5\%$ (ρs: spontaneous track density, ρi: induced track density). Mean ρs/ρi ratios of KAMU1A is 0.009 ± 0.004.

apatite fission-track methods respectively. The felsic intrusive rock at Kobuchigasawa was dated as 21.5 ± 1.3 Ma and 22.3 ± 1.7 Ma by zircon and apatite fission-track methods respectively. The granitic rock at Mitsuseki was dated as 78.1 ± 5.2 Ma and 22.8 ± 3.4 Ma by zircon and apatite fission-track methods respectively. The granitic rock at Urinnai was dated as 95.5 ± 6.6 Ma and 1.5 ± 0.8 Ma by zircon and apatite fission-track methods respectively.

Radiometric ages of granitic and intrusive rocks determined previously and in this study are shown in Fig. 5.

Track length measurements were performed on zircons of all the samples (Fig. 6).

In Fig. 6, the reduced track length ratio (%), which is defined as l/l_0, where l is the measured track length and l_0 is the non-annealed track length, is included. Moreover, the proportion of non-annealed tracks ($r_{>10}$) is presented by assuming that tracks longer than 10 μm are non-annealed. The proportion of tracks whose length is 5 - 10 μm and shorter than 5 μm are also shown as r_{5-10} and $r_{<5}$ respectively.

In Fig. 6, data for sample AKI are those from detrital zircons contained in samples AKI2, AKI3 and AKI5. Track length measurement of essential grains of the Neogene volcanic rocks was discarded because of the very low track density.

5. Discussion

The activity of Neogene volcanic rocks

As shown in Table 6, four zircon fission-track ages of the Torageyama Formation at Akinomiya site were determined. The ages were 1.2 - 3.0 Ma. Of these, the ages of AKI3 and AKI4 passed the χ^2-test and were determined with a small uncertainty. They were 2.4 ± 0.3 Ma and 1.2 ± 0.2 Ma

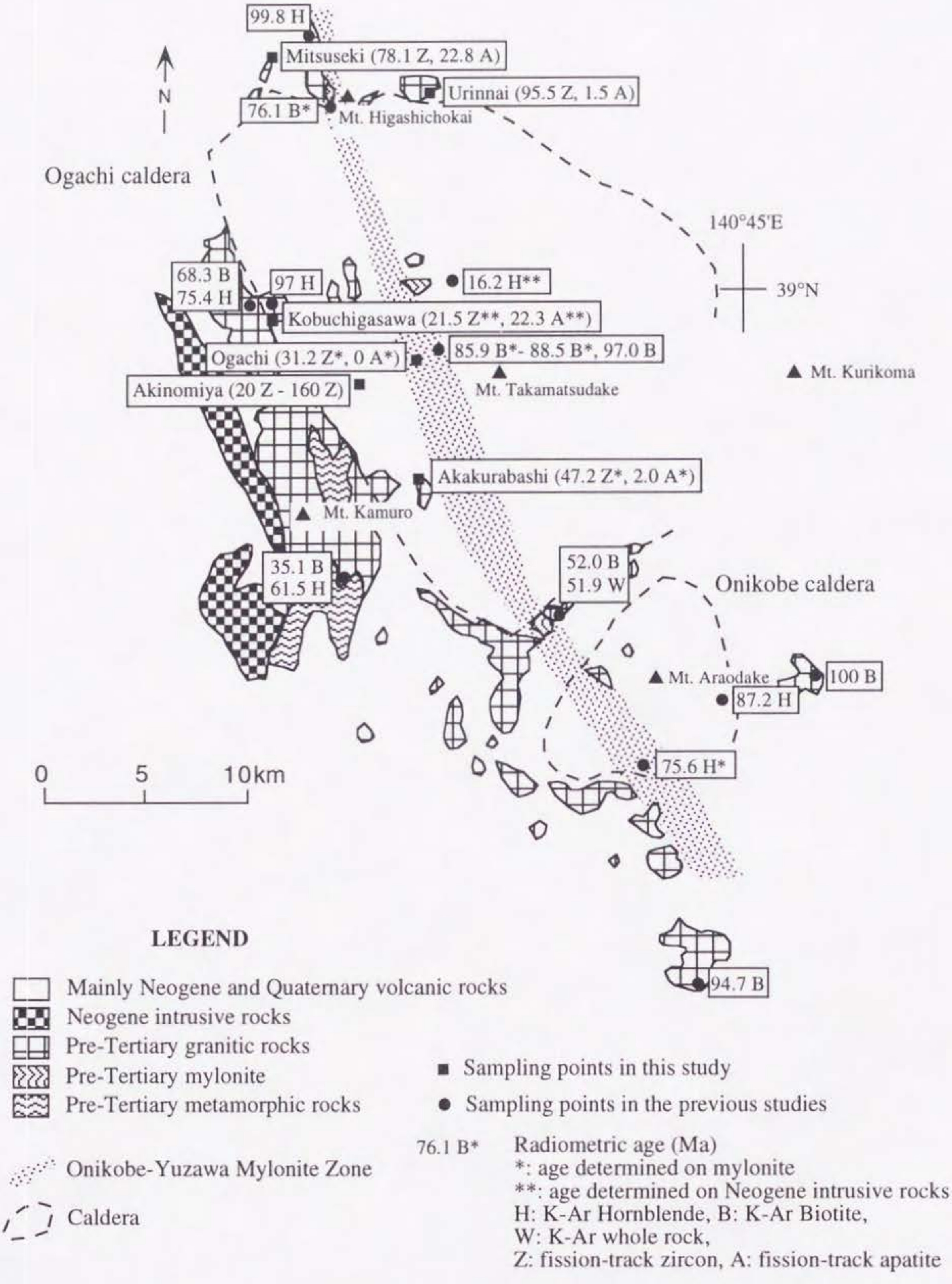

Fig. 5 Simplified geological map of the Kurikoma geothermal area (modified from Sasada, 1984, 1988) with the radiometric ages of mainly granitic rocks determined previously and in this study.
K-Ar ages are from Kawano and Ueda (1966), Sasada (1984, 1985, 1988) and Kuriyama (1985) and fission-track ages are from this study. The position of calderas is estimated from Takeno (1988) for the Ogachi caldera and Yamada (1988) for the Onikobe caldera.

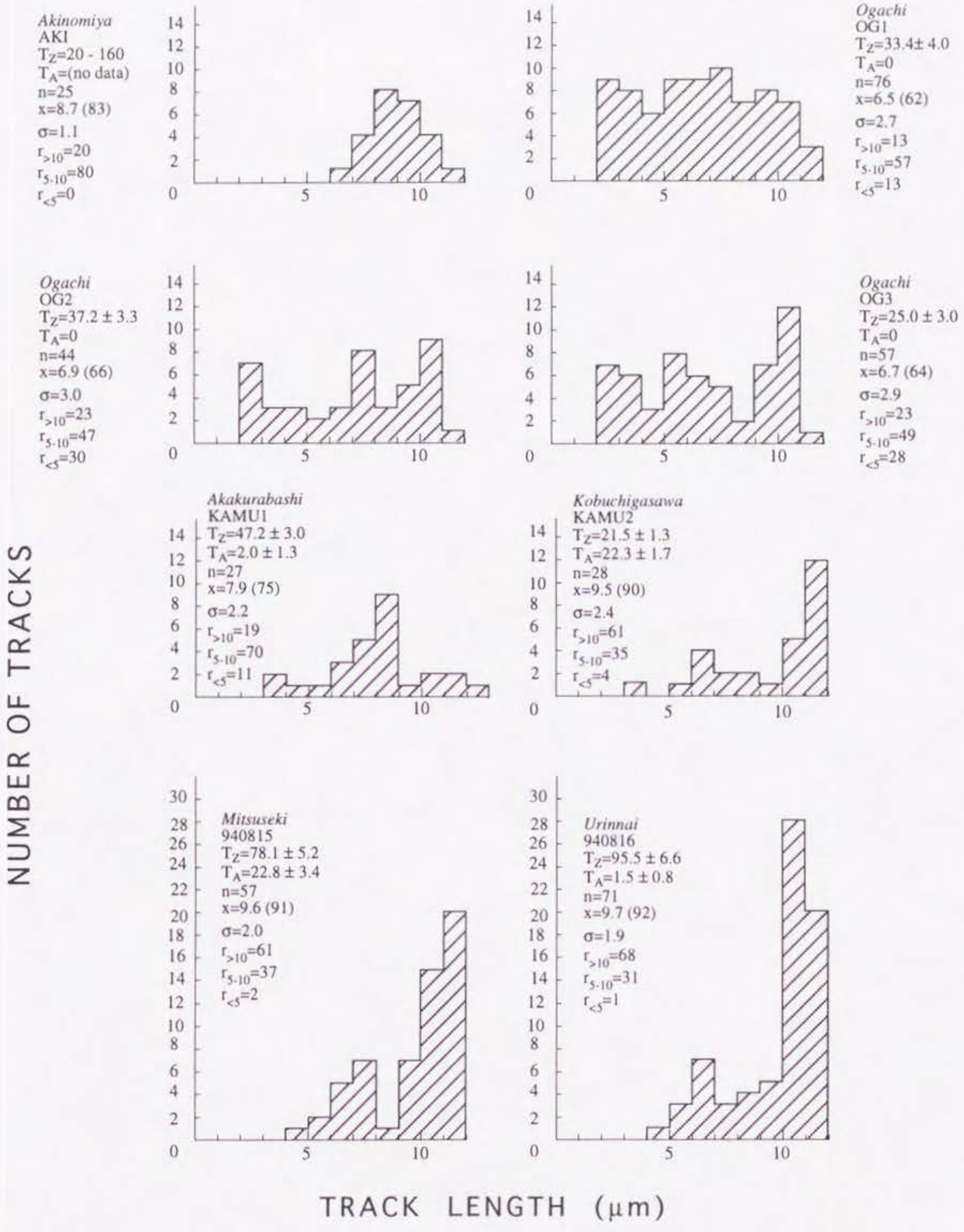

Fig. 6 Confined spontaneous track length distributions observed in zircons from the North Kurikoma geothermal area.
The first column : sampling locality, the second column: sample code, T_Z: zircon fission-track age (Ma), T_A: apatite fission-track age (Ma), n: number of tracks measured, x: mean track length and reduced track length ratio (%) in parentheses (non-annealed track length is assumed to be 10.5 μm), σ: standard deviation of track length distributions, $r_{>10}$: proportion (%) of tracks > 10 μm, $r_{5\text{-}10}$: proportion (%) of tracks of 5-10 μm, $r_{<5}$: proportion (%) of tracks < 5 μm. Data of "AKI" sample are those from detrital zircons contained in AKI2, AKI3 and AKI5 samples.

respectively. These ages do not overlap, even with 2 σ error bars, so it follows that sample AKI3 is older than AKI4. However, this contradicts the stratigraphy. The single grain ages of AKI3 have a broader distribution than those of AKI4, as shown in Fig. 7. This implies that the age of AKI3 may still include some detrital grain ages. On the other hand, the data of AKI3 pass the χ^2-test, which indicates that no detrital zircons are included in the AKI3 sample. Thus, statistically, there is no reason to exclude some grain ages from the AKI3 data. The ages of AKI2 and AKI5 failed the χ^2-test; therefore some detrital grains may be included in the age determination. In order for these samples to pass the χ^2-test, if some grains that contribute most to the failure of the χ^2-test are excluded in the age determination, the recalculated ages become 2.4 ± 0.3 Ma for AKI2 and 1.9 ± 0.2 Ma for AKI5 (Fig. 7), which are not so different from the original data of Table 6. Hence, it is better to regard the ages of AKI2 - AKI5 more broadly as ~2 Ma or 1 - 3 Ma.

As mentioned in the previous section, there were some detrital zircons in the Akinomiya samples. The range of individual grain ages for these detrital zircons is ~20 - 160 Ma. Track length measurements of these samples are shown as compiled data for "AKI" in Fig. 6. The reduced track length ratio of AKI is 83 percent, which means that the thermal effect on the detrital zircon was small. It is evident that the detrital zircons have experienced more thermal annealing than the essential zircons, as the former are much older than the latter and have experienced at least the same annealing episodes as the latter since they were trapped as detrital grains. Thus, it is concluded that the fission-track ages of the Torageyama Formation, which were determined using the essential zircons, are the ones that have experienced little thermal annealing.

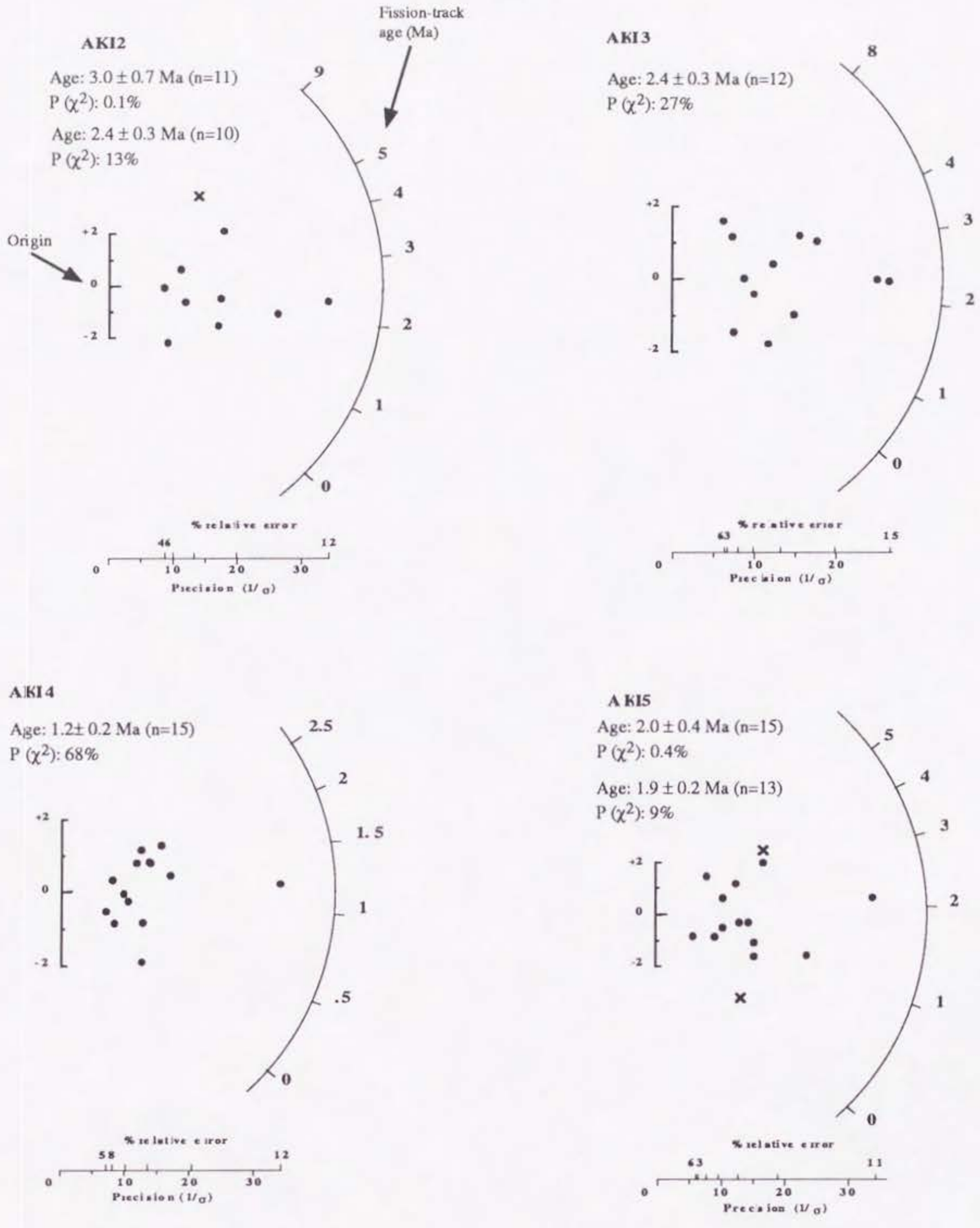

Fig. 7 Radial plots (Galbraith, 1990) of single-grain fission-track ages of the Neogene volcanic rocks at the Akinomiya site.
In radial plots, grain ages are read by projecting radius from origin through data point onto radial scale. Key features of these plots are that all grains have error bars of equal length and grains with more precise ages plot further to the right. If single-grain ages are statistically concordant, grain ages cluster within ±2 σ wide swath (Dumitru et al., 1994). n: number of grains for age calculation. "x" in the plot: grain age that contributes most to the failure of χ^2 test.

According to Takeno (1988), all of the samples correspond to the Minasegawa tuff Member of the Torageyama Formation, which were dated as 6.0 ± 0.8 Ma and 5.7 ± 1.4 Ma by the K-Ar whole rock method (Table 1). Those ages are older than the fission-track ages obtained in this study. The older ages of the K-Ar whole rock method should be due to detrital grains (mostly biotite), because the dacite tuff contains lithic fragments to some extent. Kuriyama (1985) determined eight zircon fission-track ages of 3.0 - 16.4 Ma for the Minasegawa Formation, which corresponds to the Torageyama Formation of Takeno (1988). He proposed that the young ages (3 - 6 Ma) of this formation were due to the effect of annealing on the zircon fission-track system. However, in this study, the annealing effect on the zircon fission-track ages of the Torageyama Formation was very small, which should also be true of the samples analyzed by Kuriyama (1985). Thus, it seems the old ages (> ~4 Ma) determined by Kuriyama (1985) were also due to the presence of detrital grains. Nishimura et al. (1976) determined the Oyu Welded Tuff Member as 2.1 Ma using the zircon fission-track method, which is concordant with the results in this study.

Based on the K-Ar dating results, Takeno (1988) proposed that there were two volcanic stages that formed the Torageyama Formation. The earlier stage, at 5-6 Ma, formed the Minasegawa Tuff Member and the later stage, at 3-4 Ma, formed the Torageyama Tuff Member. The fission-track dating results, in this study at least, deny the earlier stage of Takeno (1988), because the Minasegawa Tuff Member has been dated as ~2 Ma in this study. Thus there seems to have been no age gap between the volcanic activities that formed the Minasegawa and Torageyama Tuff Members. Therefore, it is implied that the volcanic activity that formed the Ogachi caldera occurred at ~2 Ma.

Thermal history of the granodiorite beneath the Ogachi site

The zircon fission-track dating results from the granodiorite beneath the Ogachi site were 33.4 ± 4.0 Ma for OG1 (581 m in depth), 37.2 ± 3.3 Ma for OG2 (781m in depth) and 25.0 ± 3.0 Ma for OG3 (981 m in depth) (Table 6). They are concordant within 2 σ error bars. The weighted mean age of these three samples becomes 31.2 ± 3.9 Ma, which can be regarded as the age of the granodiorite ~500 - 1000 m in depth beneath the Ogachi site. The reduced track length ratios were 62 percent for OG1, 66 percent for OG2 and 64 percent for OG3 (Fig. 6). As the track lengths in zircons are reduced, the fission-track age does not show the age of the cooling below its closure temperature (~240 ℃ from Hurford, 1986) after emplacement, but shows sometime younger than the cooling age.

The fission-track ages and the reduced track length ratios are similar for these sampling points. This means that the annealing effect on the zircon fission-track system of the granodiorite ~500 - 1000 m in depth is almost the same, although the present temperature differs by 83 ℃ between OG1 and OG3 samples. As will also be mentioned in Parts 2 and 3, if the thermal effect on the granodiorite has been dominantly by thermal conduction from a deeper heat source, the thermal effect should have been larger at greater depths. The almost equivalent thermal effect should indicate that lateral heat flow played an important role. The lateral heat source is probably some convectional heat such as thermal fluid and/or dyke emplacement.

It is possible to know qualitatively the timing and intensity of the thermal effect from the track length distribution data (Ito et al., 1989). The track length distribution data of the Ogachi bore-hole samples are similar in that: 1) the reduced track length ratios are smaller than those of the other samples; 2) tracks < 5 μm comprise a larger proportion than those of the other samples; and 3) tracks > 10 μm are small in proportion (Fig. 6). The first and second points indicate that the thermal effect on the granodiorite beneath the Ogachi site was stronger than at the other sites. The main reason should be that the granodiorite beneath the Ogachi site is situated in the active geothermal area and the samples were obtained from underground, where it is still hot. The granodiorite is mylonitized, so another possible heat source was the mylonitization. However, the mylonitization occurred during the Late Cretaceous (Sasada, 1988), which is much older than the fission-track ages. Thus, it seems that no record of the mylonitization remains in the zircon fission-track system, which makes it difficult to evaluate its thermal effect. The third point indicates that the thermal effect on the granodiorite occurred recently compared with the zircon fission-track age of ~30 Ma. The recent thermal event that affected the zircon fission-track system of the granodiorite should be the felsic volcanic activity that occurred at ~2 Ma.

The apatite fission-track ages of the Ogachi samples were regarded as almost zero, as mentioned in the previous section. Some bore-hole studies of apatite fission-track dating indicated that fission tracks in apatites were completely erased (annealed) if placed at ~140 ℃ for $\sim 2 \times 10^6$ years (Gleadow and Duddy, 1981) (Fig. 8). The present temperature of the OG1 sample is ~140 ℃. Thus, the apatite fission-track data indicate that the present temperature of the OG1 sample has been kept almost constant since the eruption of the felsic volcanic rocks, i.e. ~2 Ma, unless the temperature exceeded ~140 ℃ at some time since ~2 Ma.

Thermal history of the granitic rocks at the outcrops

The Akakurabashi sample

The sample of granitic rock obtained from Akakurabashi was collected near the Onikobe-Yuzawa Mylonite zone (Sasada, 1988) (Fig. 5). Microscopic observation reveals a mylonitic texture. The zircon fission-track age is 47.2 ± 3.0 Ma and is evidently an apparent age because the mean zircon fission track length is reduced (Fig. 6). The thermal effect recorded

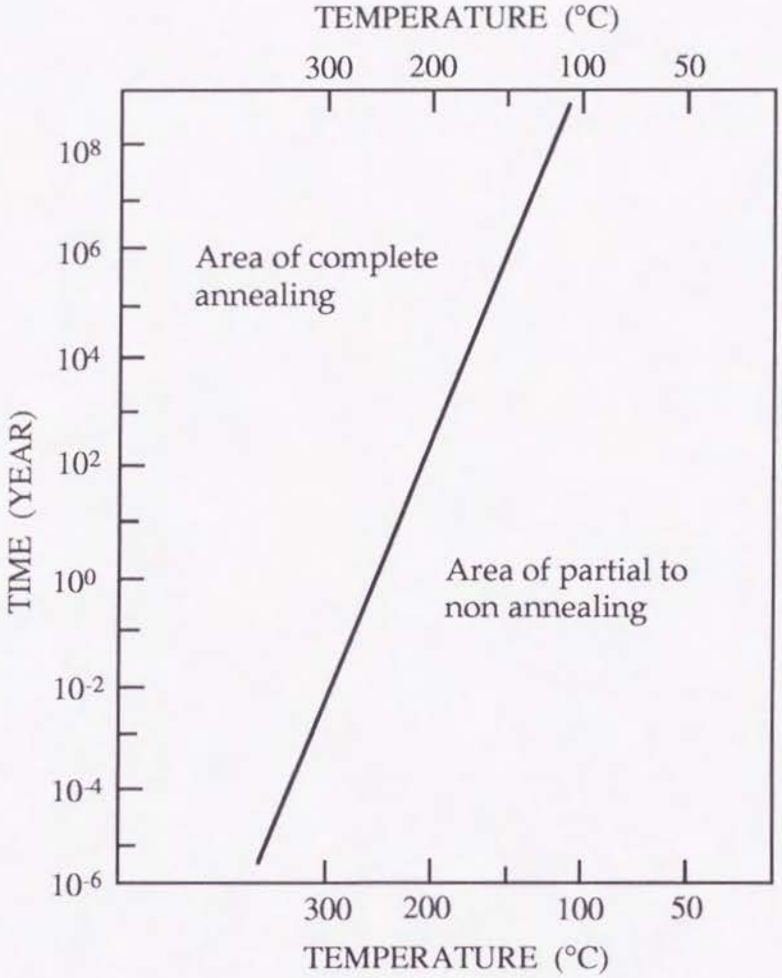

Fig. 8 Time-temperature relation to completely anneal (reset) the apatite fission-track system (modified from Gleadow and Duddy, 1981).

by the zircon fission tracks is evidently that of the recent (~2 Ma) felsic volcanic activity because of the same reasons mentioned above in the Ogachi samples.

The apatite fission-track age is 2.0 ± 1.3 Ma, which is concordant with the eruption age of the felsic volcanic rocks. This indicates that the heat from the recent Neogene volcanic eruption raised the temperature of the granitic rock more than a certain temperature (Tx). Tx depends on the heating time, and can be delineated using Fig. 8, provided that the heating duration is determined.

The Kobuchigasawa sample

The intrusive rock sample at Kobuchigasawa was obtained from the western border of the Ogachi caldera (Fig. 5). The zircon and apatite fission-track ages are 21.5 ± 1.3 Ma and 22.3 ± 1.7 Ma respectively, which show essentially the same age. This indicates that the intrusive rock cooled from the zircon closure temperature (~240 °C from Hurford, 1986) to less than the apatite closure temperature (~100 °C from Naeser and Faul, 1969 etc.) at ~22 Ma and since then has not experienced enough heat to influence even the apatite fission-track dating system. The zircon track length distribution data are characterized by the large proportion of non-annealed tracks (Fig. 6). This supports the thermal history estimated by the fission-track ages. As the Neogene intrusives are sporadically distributed in this area (Sasada, 1985), the intrusive rock at Kobuchigasawa should be one of the Neogene intrusives and the fission-track data should indicate the age of intrusion.

A K-Ar hornblende age of 97 Ma was determined using diorite near Kobuchigasawa (Kawano and Ueda, 1964) and K-Ar hornblende and biotite ages of 75.4 ± 3.8 Ma and 68.3 ± 3.4 Ma respectively were presented by Sasada (1985), using quartz gabbro near Kobuchigasawa (Fig. 5). These ages differ greatly from the fission-track ages obtained for the Kobuchigasawa sample, and are equal with or close to the original K-Ar ages of the granitic rocks in this area. Thus, the Neogene intrusive rock at Kobuchigasawa seems to have had very little thermal influence on the K-Ar dating systems of the nearby granitic rocks.

The Mitsuseki sample

The granitic rock sample obtained from Mitsuseki was collected near the northern border of the Ogachi caldera, to the west of the Onikobe-Yuzawa Mylonite Zone (Fig. 5). It yielded a zircon fission-track age of 78.1 ± 5.2 Ma. The track length distribution data are characterized by the large proportion of non-annealed tracks, although there are some short tracks (Fig. 6). These zircon fission-track data indicate that the granitic rock at Mitsuseki cooled below the zircon closure temperature at 78.1 ± 5.2 Ma and the zircon fission-track system has not been thermally influenced since (Yamada et al., 1995). Although the zircon fission-track age obtained belongs to the estimated mylonitization age of Late Cretaceous (Sasada, 1984, 1988), it should not reflect the effect of the mylonitization, since the sample does not show any mylonitic texture.

A K-Ar hornblende age of 99.8 ± 5.0 Ma (Sasada, 1985) was determined using tonalite near Mitsuseki. Hurrison et al. (1979) regarded the discrepancy of the K-Ar hornblende and the fission-track zircon ages of the Quottoon Pluton, Canada, to be due to the slow cooling of the pluton, assuming the closure temperature of K-Ar hornblende is ~450 - 550 ℃. The age discrepancy of the K-Ar hornblende and the fission-track zircon in this case should also be due to the slow cooling of the granitic rock.

An apatite fission-track age was determined as 22.8 ± 3.4 Ma. This age is significantly younger than those obtained using the other dating methods and is concordant with the age of the Neogene intrusives. Thus the thermal effect of the Neogene intrusives seems to have been great enough to reset the apatite fission-track system but to influence the zircon fission-track system.

The Urinnai sample

The granitic rock sample at Urinnai was obtained near the northern border of the Ogachi caldera, to the east of the Onikobe-Yuzawa Mylonite Zone (Fig. 5). It yielded a zircon fission-track age of 95.5 ± 6.6 Ma. The track length distribution data are characterized by the large proportion of non-annealed tracks, although there are some short tracks (Fig. 6). These zircon fission-track data indicate that the granitic rock at Urinnai cooled below the zircon closure temperature at 95.5 ± 6.6 Ma and since then has experienced insufficient heating to influence the zircon fission-track system. This zircon fission-track age is in the range of previously determined K-Ar ages of 87 - 110 Ma, which were obtained from the granitic rocks distributed east of the mylonite zone (Sasada, 1988).

An apatite fission-track age was determined as 1.5 ± 0.8 Ma. This age is significantly younger than the zircon fission-track age and is concordant with the eruption age of the Neogene felsic volcanic rocks as determined in this study. Thus, the thermal effect of the recent Neogene volcanic eruption raised the temperature of the granitic rock to the "area of complete annealing", as shown in Fig. 8.

Constraints on the thermal history of the North Kurikoma geothermal area

It is possible to constrain the thermal history of the North Kurikoma geothermal area based on the radiometric ages determined previously and in this study (Fig. 9).

The K-Ar hornblende and biotite ages (Sasada, 1988) and the zircon fission-track age (this study) of the granitic rocks east of the Onikobe-

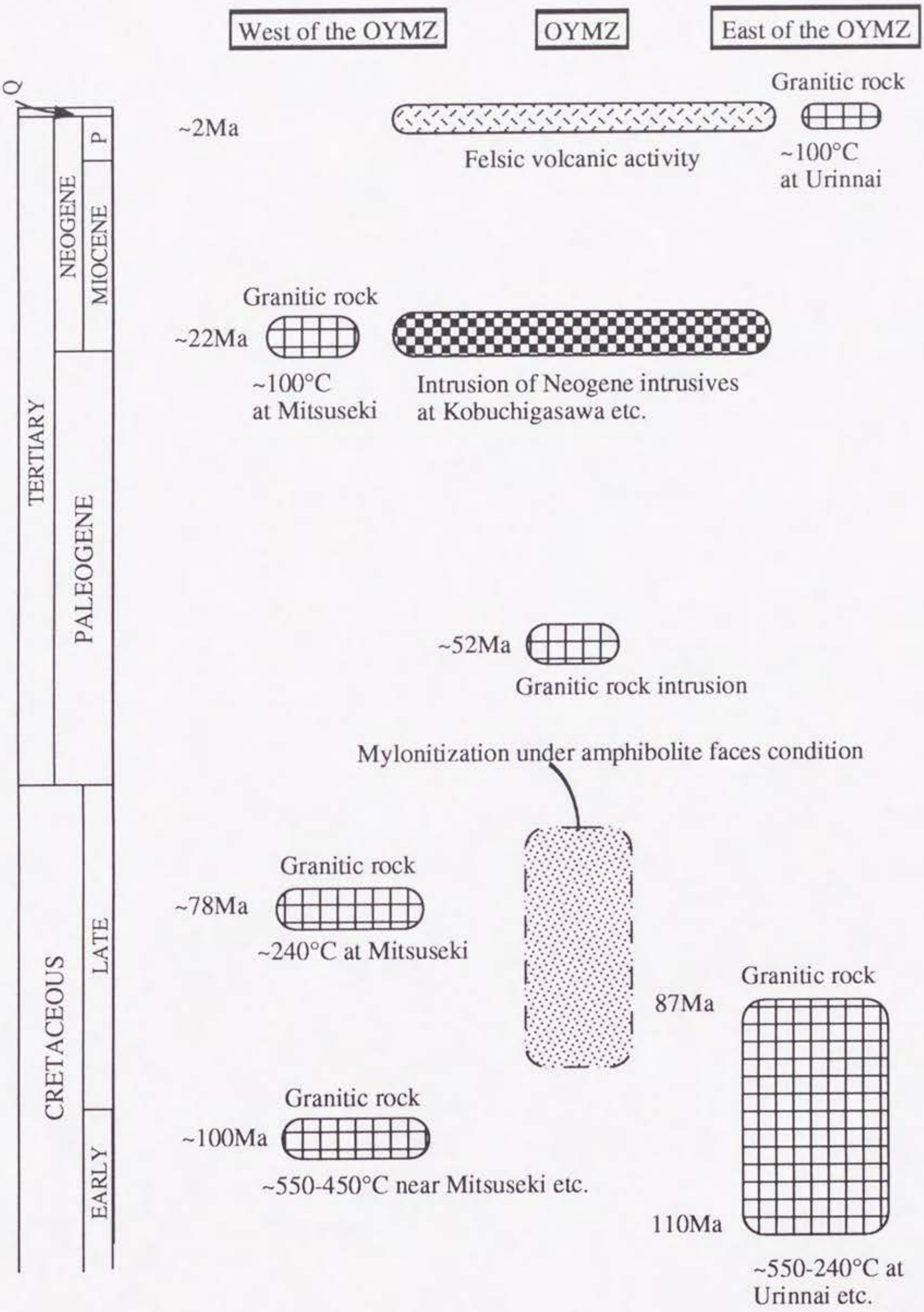

Fig. 9 Thermal history of some igneous rocks that are exposed in the North Kurikoma geothermal area.
OYMZ: Onikobe-Yuzawa Mylonite Zone, P: Pliocene, Q: Quaternary.

Yuzawa Mylonite Zone were determined as 87 - 110 Ma, which should be little thermally affected, so the temperature of these granitic rocks was ~550 - 240 ℃ during the period 110 - 87 Ma.

As for the granitic rocks west of the mylonite zone, since the K-Ar hornblende ages were 99.8 ± 5.0 Ma near Mitsuseki (Sasada, 1985) and 97 Ma (Kawano and Ueda, 1966) near Kobuchigasawa, the temperature of these granitic rocks was ~550 - 450 ℃ at ~100 Ma. Because the zircon fission-track age at Mitsuseki was 78.1 ± 5.2 Ma, which is little thermally affected, the granitic rock around this locality cooled to ~240 ℃ at ~78 Ma.

A mylonitization event that formed the Onikobe-Yuzawa Mylonite Zone occurred under the temperature and pressure conditions of amphibolite facies during the Late Cretaceous (Sasada, 1984, 1988).

Some granitic rocks intruded at ~52 Ma, because a granitic rock that intrudes the Onikobe Yuzawa Mylonite Zone was dated as 52.0 ± 3.6 Ma by K-Ar biotite and 51.9 ± 2.6 Ma by K-Ar whole rock methods respectively (Sasada, 1984) (Fig. 5).

During the Miocene there were some felsic intrusions, which are largely exposed west of the mylonite zone. The time of intrusion of these rocks was assumed to be ~22 Ma at Kobuchigasawa, based on the fission-track data in this study. A K-Ar hornblende age of 16.2 ± 9.1 Ma (Kuriyama, 1985) was reported using a boring core sample collected east of the mylonite zone (Fig. 5), which is concordant with the fission-track data. The intrusion totally annealed the apatite grains in the granitic rock at Mitsuseki at ~22 Ma. Thus, the intrusion episode at ~22 Ma seems to have affected a rather large area.

The voluminous felsic volcanic activity that formed the Ogachi caldera began at ~2 Ma as determined by the zircon fission-track data in this study. This volcanic activity totally annealed the apatite fission-track system both at Akakurabashi and at Urinnai, although the thermal effect was stronger at

Akakurabashi, where it even affected the zircon fission-track system. This is well explained because Akakurabashi is located within the Ogachi caldera and Urinnai is located near the border of the caldera.

Finally, some felsic volcanic activity formed the Kabutoyama Formation and the Takamatsudake volcanic rocks during the Quaternary (Nishimura et al., 1976; Taniguchi et al., 1978; Kuriyama, 1985; Sakaguchi and Yamada, 1988).

6. Conclusions

The main conclusions obtained in this study are as follows:

1. The zircon fission-track age of the Torageyama Formation was determined as ~2 Ma using dacite core samples of a 400 m deep bore-hole at the Akinomiya site. Although the obtained age was younger than most of the ages previously determined by K-Ar and fission-track dating methods, it was not an apparently young age caused by thermal annealing, as was ascertained by evaluating the thermal effect on detrital zircons involved in the dacite. Thus the caldera-forming felsic volcanic eruption is thought to have occurred at ~2 Ma.
2. The zircon fission-track age of the granodiorite ~500 - 1000 m beneath the Ogachi site was determined as 31.2 ± 3.9 Ma, which is an apparently young age mainly due to thermal annealing by the felsic volcanic eruption that occurred at ~2 Ma. Some lateral heat flow should have caused the almost equivalent thermal effect on the zircon fission-track system of the granodiorite from ~500 m to 1000 m in depth.
3. The zero age obtained by the apatite fission-track method indicates that the temperature of the granodiorite ~580 m beneath the Ogachi site has been kept at ~140 ℃ for ~2 million years unless the temperature exceeded ~140 ℃ at some time since ~2 Ma.

4. The intrusion age of the sporadically distributed Neogene intrusive rocks was determined as ~22 Ma at three different localities. Thus the intrusion episode at ~22 Ma appears to be of rather wide areal extent.

5. Apatite fission-track ages of the granitic rocks at two localities (Akakurabashi and Urinnai) were ~2 Ma, which reflects the felsic volcanic activity that occurred at ~2 Ma. The thermal effect of this volcanic activity was stronger at Akakurabashi than at Urinnai, because it affected even the zircon fission-track system at Akakurabashi.

ACKNOWLEDGMENTS

I was able to perform the fission-track study of the North Kurikoma geothermal area as a member of CRIEPI's Hot Dry Rock project team under the supervision of Mr. Y. Hori. CRIEPI allowed me to study fission-track dating at La Trobe University, Australia. Prof. A.J.W. Gleadow gave me the opportunity to study the fission-track method at La Trobe University, where Dr. B.P. Kohn and Dr. P.B. O'Sullivan and Mr. A. Rasa helped me in the laboratory. Dr. D. Inoue and Mr. K. Kiho were helpful through this study. Dr. T. Tagami was helpful for the sample irradiation at the Kyoto University Research Reactor. I sincerely thank all of them.

REFERENCES

Dumitru, T.A., Duddy, I.R. and Green, P.F., 1994. Mesozoic-Cenozoic burial, uplift, and erosion history of the west-central Colorado Plateau. Geol., 22, 499-502.

Galbraith, R.F., 1981. On statistical models for fission track counts. Math. Geol., 13: 471-478.

Galbraith, R.F., 1990. The radial plot: graphical assessment of spread in ages. Nucl. Tracks Radiat. Meas., 17: 207-214.

Gleadow, A.J.W., 1981. Fission-track dating methods: What are the real alternatives?. Nucl. Tracks, 5: 3-14.

Gleadow, A.J.W. and Duddy, I.R., 1981. A natural long-term track annealing experiment for apatite. Nucl. Tracks, 5: 169-174.

Gleadow, A.J.W., Hurford, A.J. and Quaife, R.D., 1976. Fission track dating of zircon: improved etching techniques., Earth Planet Sci. Lett., 33: 273-276.

Green, P.F., 1981. A new look at statistics in the fission track dating. Nucl. Tracks, 5: 77-86.

Green, P.F., 1985. Comparison of zeta calibration baselines for fission track dating of apatite, zircon and sphene., Chem. Geol. (Isot. Geosci. Sect.), 58: 1-22.

Green, P.F., Duddy, I.R., Gleadow, A.J.W. and Lovering, J.F., 1989. Apatite fission-track analysis as a paleotemperature indicator for hydrocarbon exploration. In: N.D. Naeser and T.H. McCulloh (Editors), Thermal History of Sedimentary Basins, Springer-Verlag, New York, 181-195.

Harrison, T.M., Armstrong, R.L., Naeser, C.W. and Harakal, J.E., 1979. Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia. Can. J. Earth Sci., 16: 400-410.

Hori, Y., Kitano, K. and Kaieda, H., 1994. Outline of Ogachi project for HDR geothermal power in Japan., Geotherm. Resour. Council Transact., 18: 439-443.

Hurford, A.J., 1986. Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol., 92: 413-427.

Hurford, A.J. and Green, P.F., 1983. The zeta age calibration of fission track dating. Isotope Geosci., 1: 285-317.

Hurford, A.J. and Watkins, R.T., 1987. Fission track age of the tuffs of the Buluk Member, Bakate Formation, northern Kenya: a suitable fission track age standard. Chem. Geol. (Isot. Geosci. Sect.), 66: 209-216.

Ikeya, M., 1983. ESR studies of geothermal boring cores at Hachobara power station. Jpn. J. Appl. Phys., 22: 763-765.

Ito, H., 1993. Estimation of geothermal history by fission track method (1) Application to the Hijiori geothermal area, Yamagata Prefecture. Central Res. Inst. Electric Power Ind., Report No. U92041, pp39. *

Ito, H., Sorkhabi, R.B., Tagami, T. and Susumu, N., 1989. Tectonic history of granitic bodies in the South Fossa Magna region, central Japan: new evidence from fission-track analysis of zircon. Tectonophysics, 166:331-344.

Kato, I. and Shimada, I., 1953. On the green tuff geology of the southeastern foot of Kurikoma volcano and the origin of the Sanzugawa, Onikobe Uppermost Miocene basins. Jpn. Assoc. Min. Pet. Econ. Geol., J., 37: 178-190. *

Kawano, Y. and Ueda, Y., 1966. K-A dating on the igneous rocks in Japan (IV) -Granitic rocks in northeastern Japan-. Jpn. Assoc. Min. Pet. Ecno. Geol., J., 56: 41-55. *

Kimbara, K., 1988. Hydrothermal rock alteration and geothermal system in the North Kurikoma geothermal area Akita Prefecture, Northeast Japan. Rept. Geol. Surv. Jpn, 268: 245-262. *

Konda, T. and Ueda, Y., 1980. K-Ar age of the Tertiary volcanic rocks in the Tohoku area, Japan. Jpn. Assoc. Min. Pet. Ecno. Geol., J., special vol. 2, 343-346. *

Kondo, H., 1994. Development of a method for prediction of the extending direction of fractures created by hydraulic fracturing for hot dry rock power generation - characterization of natural fractures in jointed rockmass -. Central Res. Inst. Electric Power Ind., Report No. U93039, pp73. *

Kuriyama, T., 1985. Geothermal system in the Yuzawa-Ogachi area, northern Honshu. J. Geotherm. Res. Soc. Jpn., 7: 311-328. *

Lal, D., Rajan, R.S. and Tamhane, A.S., 1969. Chemical composition of nuclei of Z>22 in cosmic rays using meteoritic minerals as detectors. Nature (London), 221: 33-37.

Laslett, G.M., Kendall, W.S., Gleadow, A.J.W. and Duddy, I.R., 1982. Bias in measurement of fission-track length distributions. Nucl. Tracks, 6, 79-85.

Muto, A., 1965. The Neogene Tertiary stratigraphy in southeastern Akita prefecture, northeast Honshu. J. Geol. Soc. Jpn., 71: 389 - 400. *

Naeser, C.W. and Faul, H., 1969. Fission track annealing in apatite and sphene. J. Geophys. Res., 74:705-710.

Nishimura, S., Taniguchi, M. and Sumi, K., 1976. Fission-track ages of the volcanic rocks in Oyasu-Doroyu geothermal field, Akita Prefecture - Fission-track age of the igneous rocks associated with geothermal activities in Japan (1)-. Geol. Surv. Jpn., Bull., 27: 713-717. *

Ohguchi, T., 1974. Geology of the Neogene Tertiary system in the Akinomiya area, southeastern end of the Akita prefecture, northeast Honshu, Japan. -on the correlation of the fossil bearing beds, newly found in the Miocene Kobushizawa formation-. Akita Univ. Min. Dep. Rep., 42: 1-11. *

Oide, K. and Onuma, K., 1960. Igneous activity of the "Green tuff region" in Northeast Honshu, Japan. Assoc. Geol. Collaboration Jpn., J., (Chikyu Kagaku), 50-51: 36-55. *

Ozawa, A. and Sumi, K., 1961. Geological map of the Uzenkaneyama, scale 1: 50,000 and its explanatory text. Geol. Surv. Jpn., pp66. *

Sakaguchi, K. and Yamada, E., 1988. "The Kitagawa Dacite", pyroclastic flow deposits around the Onikobe caldera, northeast Japan. Rept. Geol. Surv. Jpn., 268: 37-59. *

Sasada, M., 1984. The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, northeastern Honshu, Japan -Part 1, Onikobe-Yuzawa Mylonite Zone-. J. Geol. Soc. Jpn., 90, 12: 865-874. *

Sasada, M., 1985. The pre-Neogene basement rocks of the Kamuro Yama-Kurikoma Yama area, Northeastern Honshu, Japan -Part 2, Boundary between the Abukuma and Kitakami Belts-. J. Geol. Soc. Jpn., 91: 1-17. *

Sasada, M., 1988. Onikobe-Yuzawa mylonite zone. Assoc. Geol. Collaboration Jpn., J., (Chikyu Kagaku), 42: 346-353. *

Smith, M.J. and Leigh-Jones, P., 1985. An automated microscope scanning stage for fission-track dating. Nucl. Tracks, 10: 395-400.

Smith, M., Potter, R., Brown, D. and Aamodt, R.L., 1973. Induction and growth of fractures in hot rock. In: P. Kruger and C. Otte (eds.), Geothermal energy, Stanford Univ. Press, 251-268.

Stimac, J.A., 1993. The HDR concept, its resource base, and potential. Inter. Conference Hot Dry Rock Geotherm. Energy, Abstracts, p19.

Sumii, T., Tagami, T. and Nishimura, S., 1987. Anisotropic etching character of spontaneous fission tracks in zircon. Nucl. Tracks Radiat. Meas., 13: 275-277.

Takashima, I., Honda, S. and Wada, T., 1987. Geothermal history and hydrothermal system of the Kakkonda-Omatsukurazawa and adjacent areas, Hachimantai geothermal field, northeast Japan -Application of thermoluminescence dating of altered rocks to geothermal exploration-. J. Geotherm. Res. Soc. Jpn., 9: 43-55. *

Takashima, I. and Honda, S., 1988. Alteration age mapping of some Japanese geothermal fields with improved thermoluminescence dating method. Geother. Resour. Council, TRANSACTIONS, 12: 313-319.

Takeno, N., 1988. Geology of the North Kurikoma geothermal area, Akita Prefecture, Northeast Japan. Rept. Geol. Surv. Jpn., 268: 191-210. *

Taniguchi, M., Okada, H. and Sumi, K., 1978. Geological study on hydrothermal rock-alteration in Kawarage geothermal field, Akita Prefecture, Japan. Rept. Geol. Surv. Jpn., 259: 311-340. *

Yamada, E., 1981. Volcanism and tectonism in the Onikobe caldera, with special reference to the evolution of the magma reservoir. 1981 IAVCEI Symposium on Arc Volcanism, Abstracts, 421-422.

Yamada, E., 1988. Geologic development of the Onikobe caldera, Northeast Japan, with special reference to its hydrothermal system. Rept. Geol. Surv. Jpn., 268: 61-190.

Yamada, E., Matsunaga, E. and Kuriyama, T., 1985. Geothrmal model of the Kurikomayama region. J. Geotherm. Res. Soc. Jpn., 7: 261-281. *

Yamada, R., Tagami, T., Nishimura, S. and Ito, H., 1995. Annealing kinetics of fission tracks in zircon: an experimentatal study. Chem. Geol. (Isot. Geosci. Sect.), 122: 249-258.

WoldeGabriel, G. and Goff, F., 1989. Temporal relations of volcanism and hydrothermal systems in two areas of the Jamez volcanic field, New Mexico. Geol., 17:986-989.

WoldeGabriel, G. and Goff, F., 1992. K/Ar dates of hydrothermal clays from core hole VC-2B, Valles Caldera, New Mexico and their relation to alteration in a large hydrothermal system. J. Volcanol. Geotherm. Res., 50: 207-230.

* in Japanese with English abstract

** in Japanese

主論文2

Part 2

Constraints on the thermal history of the Hijiori geothermal area, northeast Japan: evidence from fission-track analyses on a granodiorite

ABSTRACT

The thermal history of a pre-Tertiary granodiorite beneath and outside of the Hijiori caldera, northeast Japan, was estimated by fission-track analysis. From a 2.2 km deep bore-hole, HDR-1, which was drilled in the Hijiori caldera, three apparent zircon ages of 48-35 Ma and track length data from two samples showing the reduced track length ratios of 63-70 % were obtained from the granodiorite whose present temperature is ~240-270 ℃. An outcrop sample collected from the granodiorite outside of the caldera yielded a much older zircon age of 76 Ma with a reduced track length ratio of 63 %. Apatite fission-track ages were almost zero for the bore-hole samples and 4.3 Ma for the outcrop sample.

Considering the geology of this area, the granodiorite should have experienced two thermal events; namely a Miocene and a Holocene volcanic episode. The data obtained show that the thermal effect of the two volcanic activities on the granodiorite beneath the caldera was not so great as to reset zircon fission-track ages but large enough to reset apatite fission-track ages. However, the granodiorite outside of the caldera experienced only the Miocene thermal event. The temperature of the granodiorite beneath the Hijiori caldera seems to have been almost constant since ~10,000 years ago.

1. INTRODUCTION

The Hot Dry Rock Geothermal Energy (HDR) concept, which involves extracting thermal energy from rock that is hot but does not contain sufficient natural fluids for conventional geothermal development, mainly targets a granitic rock (e.g. Hijiori, Ogachi, Fenton Hill) that is thought to be the heat source for a geothermal area. For the development of HDR, one of many essential problems is the need to elucidate the thermal history of the granitic rock. This information can then be used to evaluate the geothermal system of the study area (e.g. to assess the most favorable location in the geothermal area, to evaluate the geothermal reservoir of the study area).

Radiometric age determinations have been used extensively to evaluate the thermal history of some geothermal areas using such methods as TL (Takashima et al., 1987), ESR (Ikeya, 1983; Ogoh et al., 1993), U-series (Goff and Shevenell, 1987), K-Ar (Tamanyu and Lamphere, 1983; WoldeGabriel and Goff, 1989, 1992) and Ar-Ar (Harrison et al, 1986; Spell et al., 1990). The fission-track dating (FTD) method can also be useful for evaluating the thermal history of a geothermal area and has been applied by some authors (e.g. Nishimura et al., 1976; Ito and Tanaka, 1995).

In comparison with other dating methods, FTD has the following merits:

1) Using FTD, the closure temperature for apatite is ~100 ℃ (Naeser and Faul, 1969; Gleadow and Duddy, 1981; Green et al, 1989) and for zircon it is 200 - 250 ℃ (Gleadow and Brooks, 1979; Hurford, 1986) over geological time-scales. These closure temperatures are higher than those of TL (Takashima et al., 1987) and ESR (Ikeya, 1983) methods and lower than those of K-Ar methods using hornblende and biotite (Nishimura and Mogi, 1986). Thus FTD can provide unique information on the temperature range of 100 - 250 ℃ over geological time-scales.

2) Temperature is by far the most dominant parameter that influences the fission-track dating system (Fleisher et al., 1965). For example, alteration by chemical solution affects the K-Ar dating system, whereas in FTD, the effect is negligible. Thus, FTD provides more reliable information on thermal events than K-Ar in cases where chemical alteration is suspected.

3) Because individual grain ages are obtained, it is easier to discriminate essential grains from contaminated grains. Thus it can be used not only on boring-core samples but also cuttings samples, which should contain more contaminated grains.

4) FTD can provide not only the age information but also spontaneous track length information (Gleadow et al., 1986; Ito et al., 1989), which constrains the interpretation of the thermal history.

Here, the FTD method has been applied to a granodiorite, which is the target of the HDR experiment at the Hijiori area, northeast Japan, in order to make some constraints on its thermal history.

2. GEOLOGICAL REVIEW

The Hijiori geothermal area (Fig. 1) is situated at Mogami county, Yamagata prefecture, northeast Japan. The Hijiori caldera, with a diameter of ~2 km, is present in this region. Hydrothermally altered areas are distributed within this caldera and many hot springs (Hijiori, Kanayama hot spring etc.) well out (Taniguchi et al., 1978).

The Hijiori caldera contains a dacitic pyroclastic flow deposit with a total volume of 1 km^3 (Ui, 1971). Using ^{14}C dating, it is estimated that recent geothermal activity commenced ~ 10,000 years ago with the eruption of the pyroclastic flow (Ui et al., 1973). Thick Miocene volcanic rocks, overlying a pre-Tertiary basement rock, are distributed beneath the pyroclastic flow (Fig. 2).

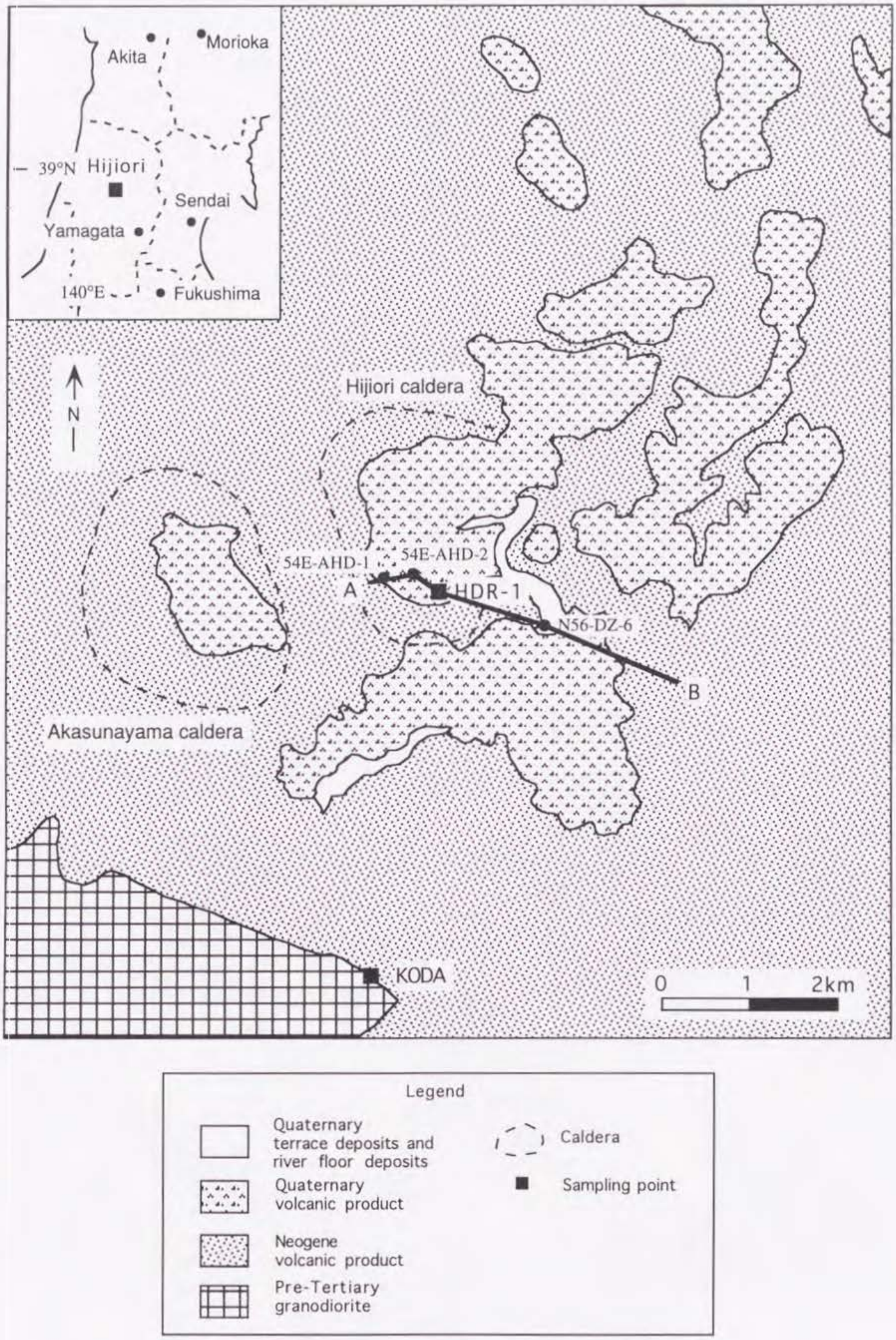

Fig. 1 Geological map of the Hijiori geothermal area (modified from Konda, 1974).

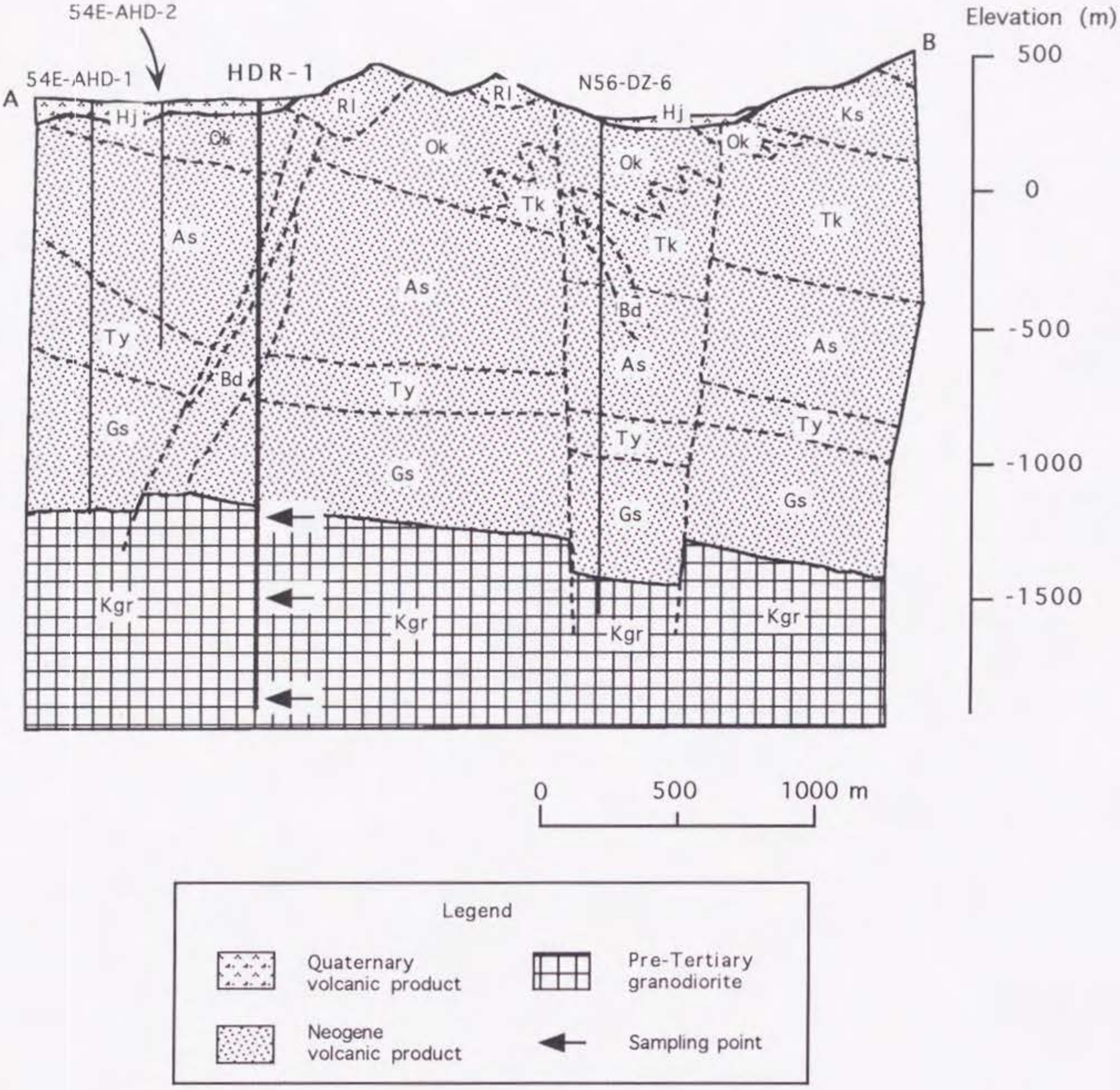

Fig. 2 A geological cross section of the Hijiori geothermal area (modified from NEDO, 1983).

A-B line corresponds to that in Fig. 1. Hj--Hijiori pyroclastic flow deposits (Holocene); Ks--Kusanagi Fm (Late Miocene); Ok--Okura silicious tuff Fm (Middle Miocene); Tk--Tsunokawa Fm (Middle Miocene); As--Aosawa Fm (Middle Miocene); Ty--Tachiyazawa Fm (Middle Miocene); Gs--Gassan Fm (Early Miocene); Kgr--Kodake granodiorite (Pre-Tertiary); Rl--Rhyolite and liparite; Bd--basalt and dolerite.

The HDR-1 bore-hole (Fig. 3) was drilled near the southern rim of the Hijiori caldera by New Energy and Industrial Technology Development Organization (NEDO) in order to develop techniques employing the HDR concept. The geology of this area is briefly reviewed as follows based on Konda (1974) and NEDO (1983).

The basement rock of this area is a pre-Tertiary granodiorite, the Kodake granodiorite, which is overlain by Miocene volcanic rocks. It is exposed mainly to the southwest of the Hijiori caldera (Fig. 1). It is leucocratic, medium-grained, hornblende-biotite granodiorite and locally shows a cataclastic texture (Matsunaga et al., 1993). Matsunaga et al. (1993) dated the Kodake granodiorite by K-Ar biotite and K-feldspar methods, and obtained ages of 97.1 Ma and 93.8 Ma respectively. The dating results show that the granodiorite belongs to the granitic rocks in the Abukuma zone (Matsunaga et al., 1993).

The Miocene volcanic rocks are > 1 km thick. They are the Gassan Formation, Tachiyazawa Formation, Aosawa Formation and Okura siliceous tuff Formation in ascending order. The Early Miocene Gassan Formation unconformably overlies the basement and comprises andesite and basalt. The Middle Miocene Tachiyazawa Formation comprises mudstone and tuff, conformably overlying the Gassan Formation. The Middle Miocene Aosawa Formation comprises basaltic pyroclastics intercalated with mudstone, siltstone and sandstone. This formation overlies the Tachiyazawa Formation conformably in some parts and is intruded by dolerite. The K-Ar age of the dolerite is 9.6 - 10.6 Ma (Konda and Ueda, 1980). The Middle Miocene Okura siliceous tuff Formation comprises dacitic tuff intercalated with mudstone.

Quaternary volcanic activity occurred at Hayama, Gassan and Hijiori volcanoes in this region. The Hayama and Gassan volcanoes were active since the Pliocene and erupted several times (NEDO, 1983).

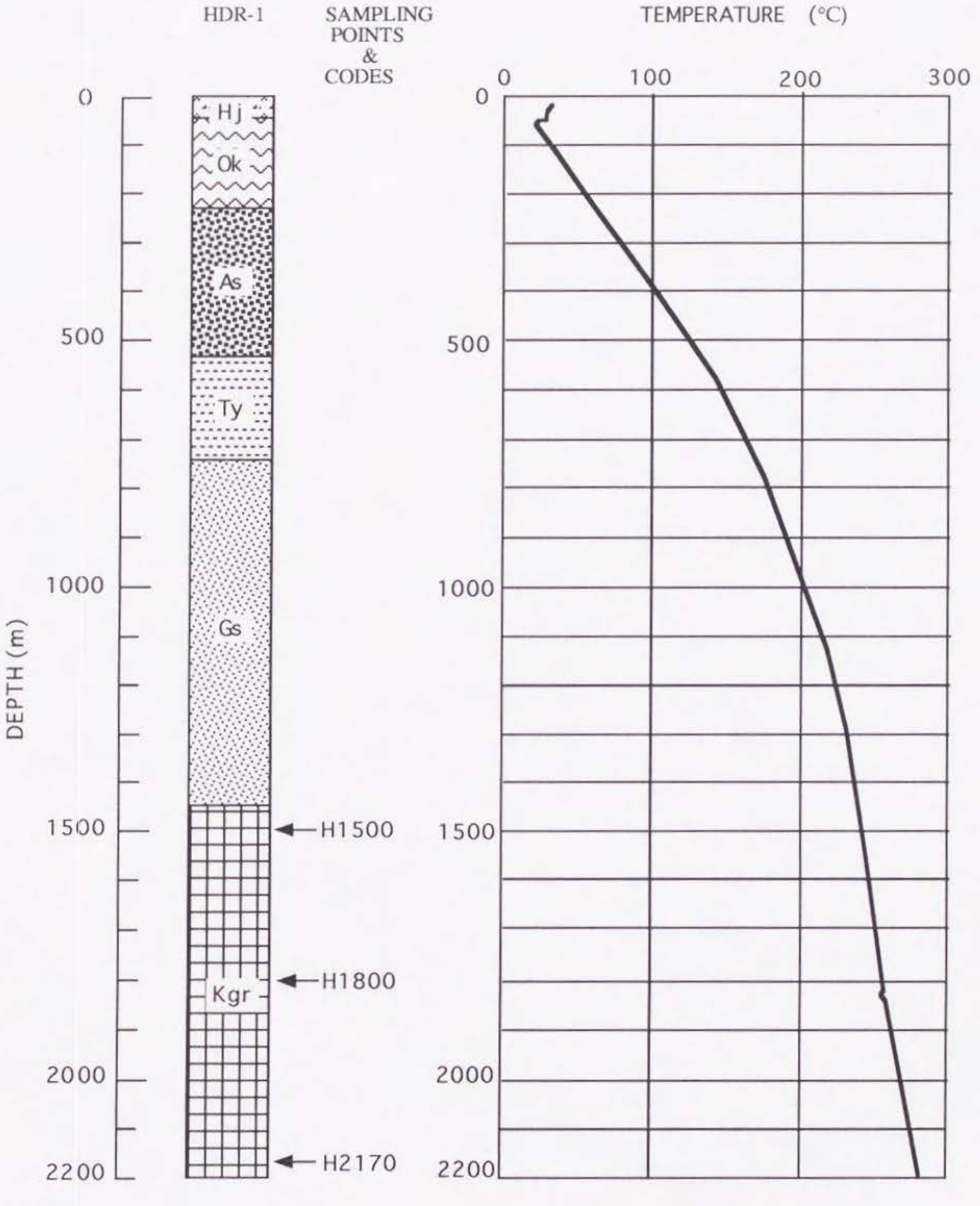

Fig. 3 Columnar section of the HDR-1 bore-hole and sampling points with a static temperature measurement result (modified from NEDO, 1989, 1990). Hj--Hijiori pyroclastic flow deposits; Ok--Okura silicious tuff Fm; As--Aosawa Fm; Ty--Tachiyazawa Fm; Gs--Gassan Fm; Kgr--Kodake granodiorite. Note the boundaries of Tachiyazawa Fm. are ambiguous (NEDO, 1989).

The Hijiori volcano comprises the Akasunayama caldera, Hijiori caldera and Imagami explosion crater. The Akasunayama caldera is situated to the west of the Hijiori caldera (Fig. 1) and is recognized as being older than the Hijiori caldera (NEDO, 1983).

The Hijiori caldera is assumed to have been formed at the same time as the eruption of the Hijiori pyroclastic flow and dacitic rocks. The eruption of the pyroclastic rocks continued after the caldera formation. The lowermost part of the pyroclastic flow deposit contains a large volume of granodioritic conglomerate. The granodiorite is thought to have been a wall of the magma chamber that produced the pyroclastic rocks (NEDO, 1983).

The Imagami explosion crater is situated to the northwest of the Hijiori caldera. It has a circular crater 600 m in diameter. The eruption that produced the crater is thought to have been almost contemporaneous with the formation of the Hijiori caldera (NEDO, 1983).

The activity of the Hijiori volcano is assumed to be divided into two stages. The Akasunayama caldera was formed at the earlier stage, possibly in the Late Pliocene, while the Hijiori caldera and the Imagami explosion crater were created at the later stage, ~10,000 years ago (NEDO, 1983). The magma chamber for the later stage is assumed to be still active (NEDO, 1983).

3. PREVIOUS WORKS

Many investigations associated with geothermal energy exploration have previously been carried out in this region (NEDO, 1983, 1989, 1990). They are briefly summarized as follows.

The heat flow of this area is 4.4 HFU on average, which is 3 - 4 times higher than ordinary areas which do not show any geothermal manifestations (NEDO, 1983).

A magnetic survey confirmed the presence of a caldera structure at the Hijiori caldera (NEDO, 1983).

The results of static temperature measurements of some bore-holes (e.g.. 54E-AHD-1, -2; Fig. 2) in the Hijiori caldera show a parabolic curve mainly in the Okura siliceous Formation. Thus, at this level, both thermal conduction and thermal convection are effective (NEDO, 1983).

Alteration mineral assemblage analyses show that diagenetic and hydrothermal alterations are observed in the Okura siliceous tuff Formation and the Aosawa Formation. Alterations that occurred in the Miocene, namely the Green Tuff alteration, are observed in the lower formations (NEDO, 1983).

The thermal fluids obtained from the N56-DZ-6 bore-hole (Fig. 2) are assumed to be created at a temperature of ~300 ℃ and a depth of ~3 km (NEDO, 1983). Since at that depth there should be a granodiorite, this indicates that there should be a hydrothermal reservoir in the granodiorite (NEDO, 1983).

Fluid inclusion microthermometry results for the Miocene volcanic rocks and the granodiorite basement rock showed that the temperature decreased after the formation of primary fluid inclusions, and the temperature at which secondary fluid inclusions were formed is close to the present temperature (NEDO, 1983). The present temperature for the basement rock at 1780 m depth in the bore-hole N56-DZ-6 is ~240 ℃ and the homogenization temperature is also ~240 ℃ (NEDO, 1983).

Matsunaga et al. (1993) carried out K-Ar radiometric dating on samples of granodiorite from the HDR-1, 2, 3 bore-holes, as well as one outcrop sample. They reported a K-Ar biotite age of 90.1 Ma and a K-Ar K-feldspar age of 76.6 Ma for the HDR-1 bore-hole at 2,033 m in depth. The K-Ar biotite and K-feldspar ages for the outcrop sample were 97.1 Ma and 93.8 Ma respectively. They also reported K-Ar sericite ages of less than 15

Ma from the bore-hole samples. Zircon FT ages of 11.6 - 12.6 Ma for the Aosawa Formation and 5.3 Ma for the Tachiyazawa Formation were reported by NEDO (1983). The discrepancy between the stratigraphy and the FT dating results was assumed to be due to the influence of detrital zircon grains or the effect of partial annealing (NEDO, 1983).

4. EXPERIMENTAL METHODS

Fission-track analyses were carried out on the granodiorite from the HDR-1 bore-hole at 1500 m, 1800 m and 2170 m in depth (sample codes: H1500, H1800 and H2170 respectively), as shown in Fig. 3. The bore-hole samples are all cuttings samples weighing 3 - 4 kg each. In order to compare the thermal history of the granodiorite in the Hijiori caldera with that of the granodiorite outside of the Hijiori caldera, a 3 - 4 kg outcrop sample (sample code: KODA) was collected ~4 km south of the Hijiori caldera (Fig. 1). This outcrop sample was collected in the vicinity of the one collected by Matsunaga et al. (1993). Microscopic observation of the KODA sample revealed that biotite and hornblende are largely chloritized and plagioclase is partly altered to sericite. Other cuttings samples, from 500 m depth (andesitic tuff of the Aosawa Formation) and 800 m depth (basaltic tuff of the Upper Gassan Formation) in the HDR-1 bore-hole, were also prepared but neither zircons nor apatites were obtained from these samples.

Samples from the HDR-1 bore-hole were prepared and analyzed at CRIEPI, while the outcrop sample was prepared and analyzed at La Trobe University, Australia. The experimental procedures at both laboratories are described in detail in Part 1. Hence, only specific procedures are described in this section.

For the HDR-1 samples, zircon etching was performed at 225 ± 2 ℃ for ~10 hours in a NaOH:KOH (1:1) etchant except for the H1500-1 sample.

Apatite etching was performed at 25 ℃ for 2 min. in 0.6% HNO_3 etchant. Zircons of the H1500-1 sample were etched at 235 ℃ for 5 hours in a NaOH:KOH (1:1) etchant. Zircon and apatite irradiations were performed for 77 hours at D_2O facility and for 4 hours at TcPn facility of Kyoto University Research Reactor (KUR) respectively.

For the outcrop sample, zircon etching was performed at ~235℃ for 4-5 hours in a NaOH:KOH (1:1) etchant and apatite etching was performed at 20℃ for 20 seconds in 5M HNO_3. The zircon and apatite irradiations were performed in the X7 facility of HIFAR (Lucas Heights, NSW) with 10^{15} thermal neutrons/cm^2 and 10^{16} thermal neutrons/cm^2 respectively.

Fission track ages were obtained using the external detector method and the zeta approach (Hurford and Green, 1983). A zeta value of 318.8 ± 9.4 (1 σ error) for dosimeter glass SRM 613 (Table. 1) was used for the zircons of the HDR-1 samples. A zeta value of 135.1 ±3.2 for dosimeter glass of CN-1 (Table 2) was used for zircons of the outcrop sample and a zeta value of 329.1 ±16.0 for dosimeter glass SRM612 (Table 3) was used for apatites of the outcrop sample.

Because there are some track-like dislocations in zircon grains, those track-like dislocations were sketched and checked before the etching procedure in some grains. The risk of mistaking a dislocation for a fission track was confirmed to be less than 2 - 3 %.

5. RESULTS

Small quantities (200 - 300 grains) of rather massive and partly chipped zircons, with diameters of 200 - 300 μm, were obtained from the three samples of the HDR-1 bore-hole. Much larger quantities of fairly euhedral apatite grains were obtained from the same samples. A large quantity of pyrite was recognized during the mineral separation procedure of

Table 1 Zeta (ζ) values of zircon age standards determined at CRIEPI.

Sample code	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	ζ ± 1σ
FCTZ -1	10	1029	1.07	1434	4.72	1001	3.29	3	362.3±18.7
FCTZ-2	9	1020	1.06	1467	6.33	873	3.76	2	311.6±16.5
BM-1	6	1012	1.06	402	1.36	366	1.24	60	279.7±22.0
TR-1	11	1004	1.05	1717	6.92	474	1.91	15	312.4±19.0
									318.8±9.4

Zeta value underlined, which is the weighted mean, is adopted. FCTZ-1, -2,: Fish Canyon Tuff (27.8±0.1 Ma), BM-1: Buluk Member 4 Tuff (16.2±0.1 Ma), TR-1: Tardree Rhyolite (58.7±0.6 Ma). Ages of the age standard samples are from Hurford and Watkins (1987). Dosimeter glass SRM 613 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

Table 2 Zeta (ζ) values of zircon age standards determined at La Trobe Univ..

Age standard	Sample code	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	$\zeta \pm 1\sigma$
Fish Canyon Tuff	FCT931(LU273)	8	1165	5.17	1645	5.37	2209	7.21	42.6	144.7±6.4
Fish Canyon Tuff	FCT932(LU273)	6	1178	5.23	951	3.98	1281	5.37	74.7	143.6±7.5
Fish Canyon Tuff	FCT934(LU279)	8	1166	5.17	698	5.23	982	7.36	97.3	151.5±8.7
Fish Canyon Tuff	FCT936(LU296)	6	2002	4.65	595	4.82	636	5.15	96.1	128.1±7.9
Fish Canyon Tuff	FCT937(LU296)	5	2002	4.65	435	5.49	459	5.79	32.7	126.4±8.9
Fish Canyon Tuff	FCT1(PT538-7)	6	1052	4.88	546	5.42	635	6.30	0.4	132.7±8.8
Fish Canyon Tuff	FCT2(PT538-10)	5	1052	4.88	517	5.36	556	5.76	2.8	122.7±8.4
Tardree Rhyolite	TD1(PT538-6)	10	1052	4.88	809	6.47	443	3.55	2	132.3±8.9
Tardree Rhyolite	TD2(PT538-9)	6	1052	4.88	495	6.11	274	3.38	93.6	133.7±11.0
										135.1±3.2

Zeta value underlined, which is the weighted mean, is adopted. The ages of the age standard samples are 27.8±0.1 Ma for Fish Canyon Tuff and 58.7±0.6 Ma for Tardree Rhyolite (Hurford and Watkins, 1987). Dosimeter glass CN-1 used. $P(\chi^2)$: Probability of obtaining χ^2 value for v degrees of freedom (where v = number of grains - 1) (Galbraith, 1981).

Table 3 Zeta (ζ) values of apatite age standards determined at La Trobe Univ..

Age standard	Sample code	Number of grains	Dosimeter number density ($x10^5 cm^{-2}$)		Spontaneous number density ($x10^5 cm^{-2}$)		Induced number density ($x10^5 cm^{-2}$)		$P(\chi^2)$ (%)	ζ ± 1σ
Fish Canyon Tuff	FCT93-2(LU267)	20	1686	1.497	297	2.20	2525	1.87	73	315.3±24.3
Fish Canyon Tuff	72N824(PT544)	15	3139	1.457	146	1.84	1176	1.48	51	308±27.6
Fish Canyon Tuff	FCT1(LU266)	13	3426	1.590	70	2.24	512	1.64	73	256.3±33.0
Fish Canyon Tuff	72N81(PT545)	15	3053	1.417	226	2.02	1807	1.61	93	314.4±22.9
Mt.Dromedary	MTD1(LU253)	18	1353	1.256	304	8.67	774	2.21	23	403.2±29.6
Mt.Dromedary	MTD2(LU253)	16	1377	1.277	289	7.60	800	2.11	66	431.2±31.9
Mt.Dromedary	MTD3(LU253)	15	1400	1.299	239	8.06	683	2.30	95	437.6±35.0
Mt.Dromedary	8322-42(PT544)	13	3139	1.457	421	5.25	1225	1.53	41	397.3±23.7
Mt.Dromedary	MTD4(LU266)	11	3241	1.504	124	7.99	314	2.02	46	334.9±36.1
Mt.Dromedary	8322-41(PT545)	15	3053	1.417	456	5.48	1375	1.65	69	423.3±24.3
Durango	DUR1(LU253)	16	1635	1.517	250	1.81	1474	1.07	32	244.7±17.9
Durango	DUR2(LU253)	9	1659	1.539	137	1.89	952	1.32	99	284.2±27.0
Durango	DUR3(LU253)	10	1682	1.560	153	1.78	1019	1.18	47	268.8±24.3
Durango	8122-3(PT544)	13	3139	1.457	186	1.76	1382	1.30	95	321.0±25.9
Durango	DUR4(LU266)	13	3117	1.447	98	1.81	706	1.30	81	313.4±34.4
Durango	81223(PT545)	15	3053	1.417	212	1.67	1707	1.35	100	357.7±27.1
										329.1±16.0

Zeta value underlined, which is the weighted mean, is adopted. The ages of the age standard samples are 27.8±0.1 Ma for Fish Canyon Tuff, 98.7±0.3 Ma for Mt. Dromedary and 31.4±0.3 Ma for Durango (Hurford and Watkins, 1987; Green, 1985). Dosimeter glass SRM612 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

the HDR-1 samples. Much larger quantities of zircon and apatite were obtained from the outcrop sample than from the bore-hole samples. Both massive and elongated zircons were observed, with diameters of 200 - 400 μm. Zircons and apatites of the outcrop sample were fairly euhedral in shape. Pyrite was rarely recognized during the mineral separation procedure for the outcrop sample.

The dating results are listed in Table 4. Results of a χ^2-test shown as $P(\chi^2)$ value are also included (Galbraith, 1981). If a $P(\chi^2)$ value is $< 5\%$, this indicates that there is greater uncertainty in the fission track counts than that allowed by Poisson variation. In this situation, the mean individual grain $\rho s/\rho i$ ratio was used to calculate the age and the uncertainty, which gives approximately the same age but makes allowance for the wider spread of individual grain ages (Green, 1981). Zircons of the H1500 sample were dated from two individual grain-mounted sheets. The ages were 39.7 ± 3.3 Ma for H1500-1 sheet and 45.6 ± 8.7 Ma for H1500-2 sheet. These ages are concordant within 1σ error and the weighted mean age of 40.4 ± 2.0 Ma was adopted. Zircons of H2170 and KODA samples were also dated using two individual sheets. The ages were also concordant within 1σ error and the weighted mean ages of 47.7 ± 1.6 Ma for H2170 and 76.0 ± 2.6 Ma for KODA were obtained. Sample H1800 yielded a zircon age of 35.3 ± 3.5 Ma, although only two grains were analyzed.

Apatites from H1500 and H2170 were etched and fission tracks were observed under the microscope. Because many apatite grains have no tracks (except for some grains which have some track-like pits and annealed tracks with 4-5 μm in length), the ages of apatites from the HDR-1 samples were regarded as zero ages. Apatites from the outcrop sample have some long (possibly not annealed) fission tracks. The apatite sample was dated as 4.3 ± 0.9 Ma.

Table 4 Fission track analytical data of the Hijiori geothermal area.

Sample code	Laboratory	Mineral	Bore-hole depth (m)	Temp. (°C)	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	Age ± 1σ (Ma)
H1500-1	CRIEPI	Zircon	1500	239	11	996	1.04	2436	12.5	1036	5.33	0.2	39.7±3.3
H1500-2	CRIEPI	Zircon	1500	239	4	988	1.03	683	16.2	267	6.33	0.4	45.6±8.7
H1500	CRIEPI	Zircon	1500	239	15								40.4±2.0
H1800	CRIEPI	Zircon	1800	256	2	980	1.02	404	9.16	186	4.22	20	35.3±3.5
H2170-1	CRIEPI	Zircon	2170	269	6	972	1.01	1729	15.3	599	5.30	50	46.5±2.7
H2170-2	CRIEPI	Zircon	2170	269	5	964	1.01	1111	14.5	357	4.66	15	49.7±3.4
H2170	CRIEPI	Zircon	2170	269	11								47.7±1.6
KODA-1	La Trobe	Zircon	------	10	10	1214	5.39	1750	6.58	847	3.19	0.1	79.7±7.0
KODA-3	La Trobe	Zircon	------	10	11	1227	5.44	2485	13.1	1220	6.45	0.9	74.1±5.0
KODA	La Trobe	Zircon	------	10	21								76.0±2.6
KODA-A	La Trobe	Apatite	------	10	23	1715	15.23	24	0.0194	1401	1.13	85	4.3±0.9

Ages are determined on individual grain-mounted sheet. Age of H1500 is weighted mean of H1500-1 and H1500-2. Age of H2170 is weighted mean of H2170-1 and H2170-2. Age of KODA is weighted mean of KODA-1 and KODA-3. Ages underlined are adopted.
Zircon ages analysed at CRIEPI using $\zeta=318.8\pm9.4$ (1σ error). Dosimeter glass SRM 613 used. Zircon ages analysed at La Trobe Univ. calculated using $\zeta=135.1\pm3.2$(1σ error). Dosimeter glass CN-1 used. Apatite age analysed at La Trobe Univ. using $\zeta=329.1\pm16.0$ (1σ error). Dosimeter glass SRM 612 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981). Mean ρs/ρi ratio used to calculate age and uncertainty where $P(\chi^2) < 5\%$ (ρs: spontaneous track density, ρi: induced track density). Mean ρs/ρi ratios of H1500-1, H1500-2, KODA-1 and KODA-3 are 2.41 ± 0.17, 2.78 ± 0.52, 2.20 ± 0.16 and 2.04 ± 0.07, respectively.

Track length measurements were performed on zircons from H1500, H2170 and KODA samples (Fig. 4). All three samples had short fission tracks, indicating some thermal annealing. The reduced track length ratios were 63 % for H1500, 70 % for H2170 and 63 % for KODA, assuming the non-annealed track length is 10.5 μm (Ito et al., 1989).

6. DISCUSSION

Thermal history of the granodiorite beneath the Hijiori caldera

The FT zircon age results of the HDR-1 samples were 40.4 ± 2.0 Ma for H1500, 35.3 ± 3.5 Ma for H1800 and 47.7 ± 1.6 Ma for H2170 (Table 4). The reduced track length ratios were 63 % for H1500 and 70 % for H2170 (Fig. 4). These data evidently indicate that the granodiorite in the Hijiori caldera experienced some thermal effect. Considering the geology of this area, the granodiorite experienced two thermal events. These are episodes of volcanic activity in the Miocene and the Holocene. The apparent FT zircon ages are older than the Miocene, so neither of the thermal events completely reset the FT zircon system.

The track length reduction is greater at 1,500 m (H1500) than at 2,170 m in depth (H2170). This fact indicates the thermal effect on the granodiorite was larger at 1,500 m than at 2,170 m, which should not have occurred if the granodiorite cooled only by simple thermal conduction. The greater thermal effect on the shallower part of the granodiorite could be due to some other thermal events such as hot fluids. The H1500 sample was obtained near the boundary with the overlying Neogene volcanic rocks, whereas the H2170 sample was obtained in the middle of the granodiorite. Therefore the position of sample H1500 makes it more susceptible to thermal fluids than that of H2170.

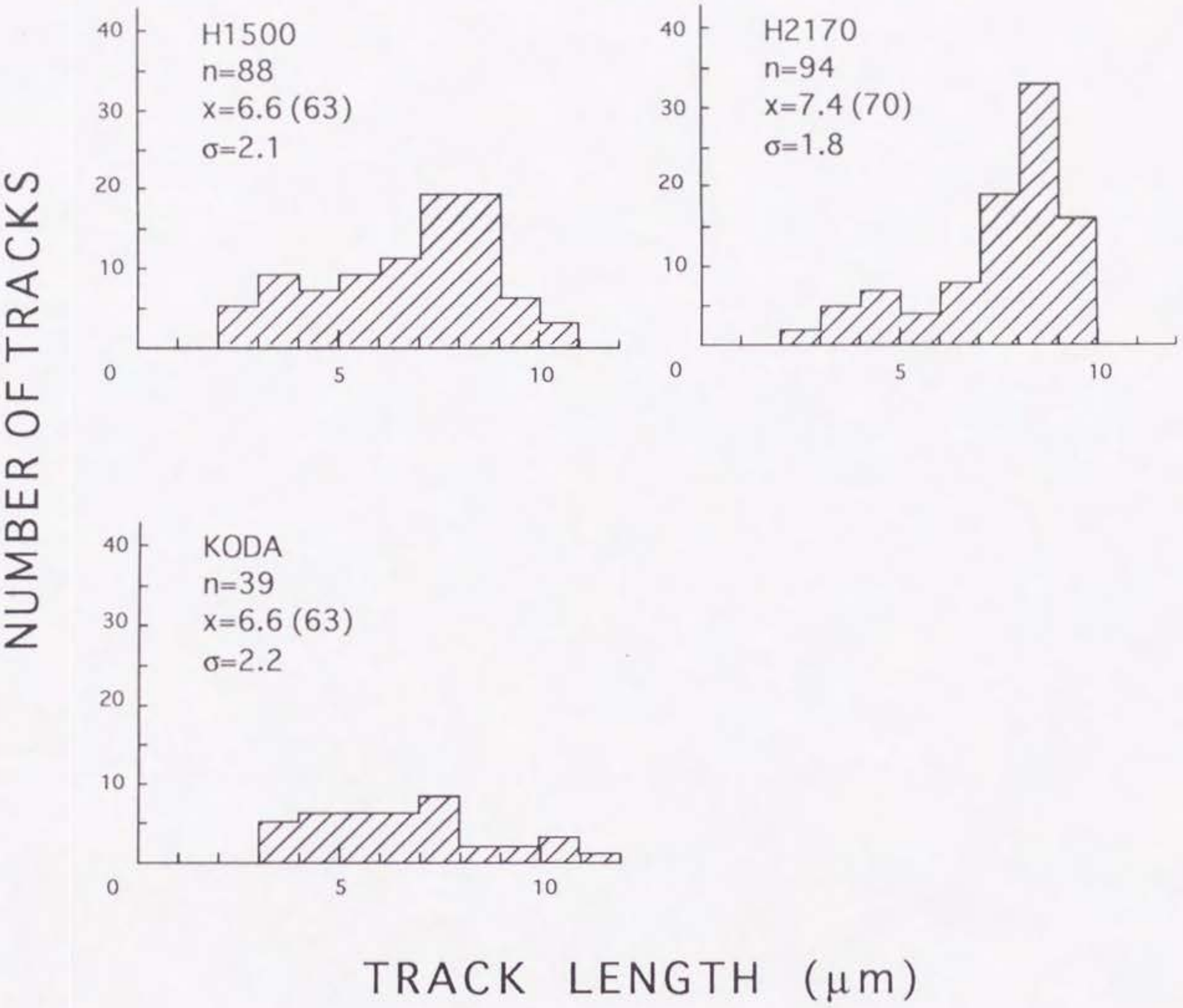

Fig. 4 Confined spontaneous track length distributions observed in zircons from the HDR-1 bore-hole samples and an outcrop sample.
n: number of tracks measured, x: mean track length and reduced track length ratio (%) in parentheses (non-annealed track length is assumed to be 10.5 μm), σ: standard deviation of track length distributions.

The FT apatite ages of the HDR-1 samples were regarded as almost zero age. Laboratory annealing experiments on apatite show that fission tracks in apatites will be completely erased (annealed) if subjected to ~250 ℃ for 1 year duration (Gleadow and Duddy, 1981). The present temperature of the HDR-1 samples is > ~240 ℃ (Table 4) and the heating duration is considered to be much longer than 1 year. Thus the zero age of the HDR-1 samples is well explained.

The fission track length data (Fig. 4) can be used to roughly determine the timing and intensity of the thermal effects. As mentioned above, the granodiorite experienced two thermal events: the Miocene and the Holocene volcanic episodes. The fission track length distributions for samples H1500 and H2170 show that non-annealed fission tracks (> ~10 μm in length) are small in number compared with annealed fission tracks (< ~10 μm in length). As time passes after an event that reduced the fission track lengths, the proportion of non-annealed fission tracks becomes larger as more non-annealed tracks are produced. Thus, the small proportion of the non-annealed fission tracks means that the thermal effect occurred recently. In this case, the most recent thermal effect that reduced fission tracks in zircon was probably the Holocene volcanic activity.

Matsunaga et al. (1993) reported K-Ar dating results for the granodiorite from the HDR-1 bore-hole. They determined a K-Ar biotite age of 90.1 Ma and a K-Ar K-feldspar age of 76.6 Ma for a core sample from 2,033 m depth. Sample H2170, with a zircon FT age of 47.7 ± 1.6 Ma, was located near the sampling position of the K-Ar study. Comparing these data with the K-Ar data of an outcrop sample (97.1 Ma for K-Ar biotite and 93.8 Ma for K-Ar K-feldspar; Matsunaga et al., 1993), the K-Ar biotite system was little affected by the later thermal event (the Miocene and the Holocene volcanic episodes) and the K-Ar K-feldspar system was less affected than the FT zircon system. This is significant because the closure temperature of the K-Ar K-feldspar system is estimated to be the same as that of the FT zircon system (Shibata et al., 1990). This should indicate that the K-Ar K-feldspar system is more thermally resistant than the FT zircon system in the case of a secondary thermal effect as mentioned by Matsunaga et al. (1993).

Thermal history of the granodiorite outside of the Hijiori caldera

The FT zircon age obtained from the outcrop sample was 76.0 ± 2.6 Ma (KODA in Table 4) and the reduced track length ratio was 63 % (Fig. 4). These data evidently indicate that the granodiorite outside of the Hijiori caldera also experienced some thermal effect. The FT apatite age of the outcrop sample (KODA-A in Table 4) was 4.3 ± 0.9 Ma and the fission tracks observed were long and resembled non-annealed fission tracks (e.g. fission tracks in Durango apatite). Because the closure temperature of the FT apatite system is estimated to be ~100 ℃ (Naeser and Faul, 1969; Gleadow and Duddy, 1981; Green et al., 1989), the granodiorite must have cooled below ~100 ℃ at 4.3 ± 0.9 Ma.

From these results, the outcrop sample of granodiorite experienced only the Miocene volcanic activity. The apparent FT zircon ages are older than the Miocene, thus the Miocene thermal effect did not completely reset the FT zircon system of the granodiorite at this locality.

Estimated cooling history of the granodiorite at the Hijiori geothermal area

From the above discussions, the cooling history of the granodiorite at the Hijiori geothermal area is estimated as follows (Fig. 5).

The K-Ar biotite ages of the granodiorite from the bore-hole and outcrop samples are 90.1 ± 4.5 Ma and 97.1 ± 4.9 Ma respectively (Matsunaga et al., 1993) and the closure temperature of the K-Ar biotite is estimated as ~300 ℃ (Hurford, 1986). Because the K-Ar biotite ages seem

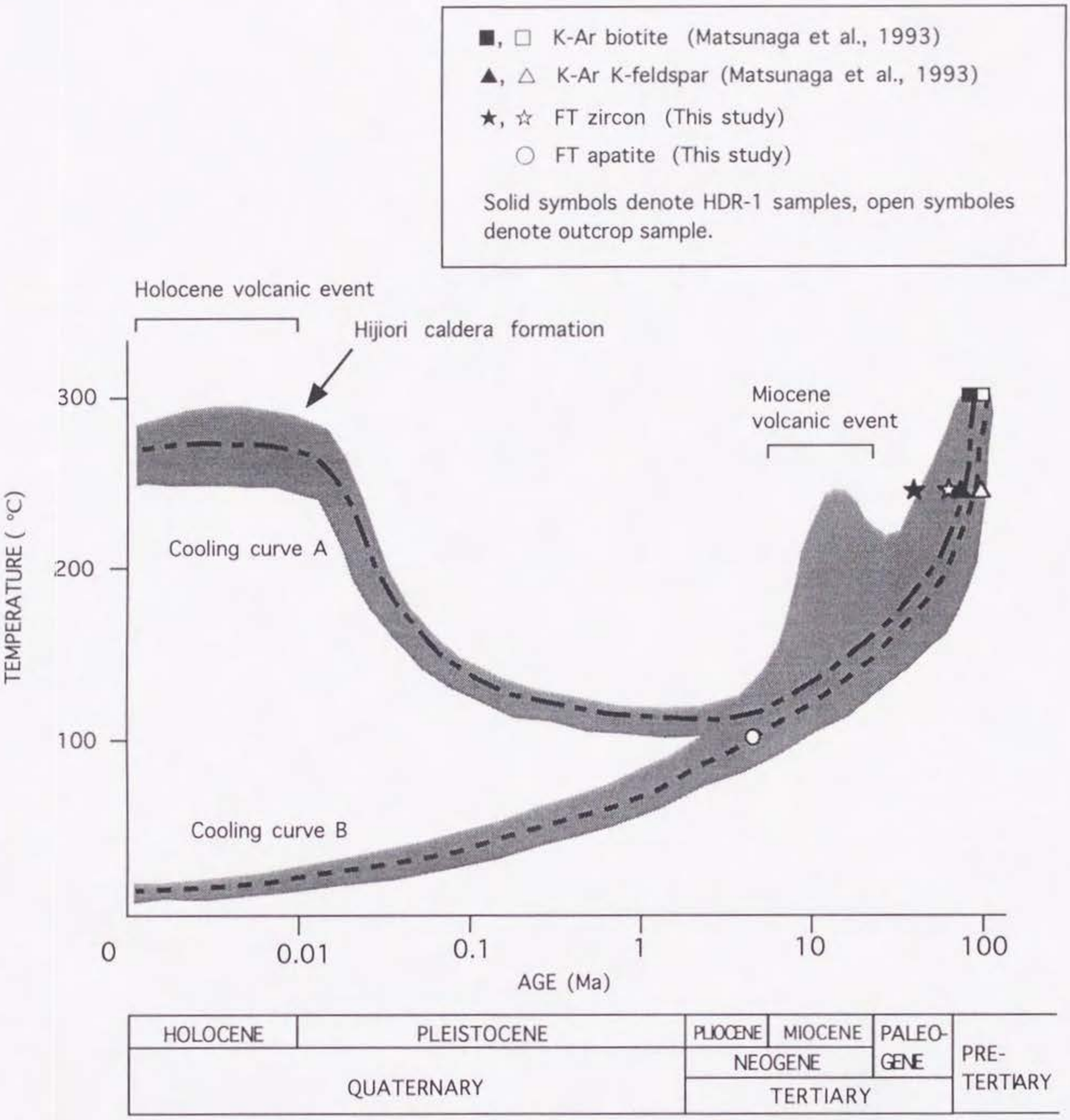

Fig. 5 Estimated cooling curves of the granodiorite beneath and outside of the Hijiori caldera.
The cooling curve A is that of the granodiorite which is 1.5 - 2.2 km in depth at the Hijiori caldera. The cooling curve B is that of the granodiorite which is exposed ~4 km south of the Hijiori caldera. The closure temperatures of K-Ar biotite, K-Ar K-feldspar, FT zircon and FT apatite are assumed to be ~300 °C, ~240 °C, ~240 °C and ~100 °C respectively (Hurford, 1986; Green et al., 1989). FT zircon ages are reduced ages affected by the later thermal events. Shaded range denotes the uncertainty of the estimation.

to be little affected by later thermal events, the granodiorite should have cooled below ~300 ℃ at 100 - 90 Ma.

In the Paleogene, the granodiorite should have cooled monotonically, because there do not seem to have been any thermal events during this time (NEDO, 1983). Volcanic activities occurred in the Neogene, especially in the Miocene. Although these volcanic activities should have been extensive because of the thick deposits in the Miocene (Fig. 2), the temperature of the granodiorite never exceeded the zircon closure temperature of ~240 ℃ (Hurford, 1986) in the Miocene. It may have been raised close to the zircon closure temperature as shown in Fig. 5. During this time, however, the granodiorite was located close to the ground surface especially just before the Gassan Formation was deposited, so its temperature may have been lower than during the Paleogene. Thus the cooling curve in the Neogene is estimated to be broad, as shown in Fig. 5.

In the Quaternary, it is assumed the volcanic activity that commenced ~10,000 years ago raised the temperature of the granodiorite beneath the Hijiori caldera to approximately the present temperature (~240 - 270 ℃) and the temperature has been kept almost constant since then. This is supported by a fluid inclusion study (NEDO, 1983), in which the maximum temperature of the granodiorite at 1780 m depth in the N56-DZ-6 bore-hole (Fig. 2) is estimated to be the same as the present temperature of ~240 ℃. Brandon and Vance (1992) estimated the temperatures required to produce 30 % ($Tz_{30\%}$) and 40 % ($Tz_{40\%}$) annealing of zircon fission tracks (corresponding to reduced track length of 70 % and 60 % respectively) for a heating duration of 10,000 years are calculated as 264 ℃ and 274 ℃ respectively. These temperatures are not so different from the present temperature of H1500 and are in good agreement with that of H2170. As the FT zircon closure temperature estimated by Brandon and Vance (1992) seems somewhat lower than that estimated from Part 3 in this study, the

Holocene cooling curve of the granodiorite beneath the Hijiori caldera was estimated as a broad range.

However, the granodiorite outside of the Hijiori caldera should have cooled to the present temperature from ~100 ℃ at 4.3 ± 0.9 Ma.

7. CONCLUSIONS

The fission track dating method was applied to a granodiorite beneath and outside of the Hijiori caldera in order to constrain the thermal history of the Hijiori geothermal area.

The following conclusions were obtained:

1) Samples from granodiorite in the 2.2 km deep bore-hole HDR-1, which was drilled in the Hijiori caldera, yield three apparent zircon fission-track ages of 48-35 Ma and track length data from two samples exhibit the reduced track length ratios of 63-70 %. The present temperatures at the sampling depths are ~240-270 ℃. The zircon ages obtained are thermally reduced ones.

2) Apatite fission-track ages from the bore-hole samples were regarded as zero ages, which is well explained by the annealing experiment discussed in section 6 above.

3) The thermal effect on the zircon fission-track system was larger at 1500 m in depth than at 2170 m in depth. This is probably because the granodiorite at 1500 m deep is near the contact with the overlying Miocene deposits and is therefore more susceptible to thermal fluids than the rock at 2170 m.

4) The small proportion of non-annealed fission tracks in the bore-hole samples should indicate that the Holocene thermal effect was large enough to reduce fission tracks in zircon.

5) Results from the HDR-1 bore-hole indicate that the K-Ar K-feldspar system is more thermally resistant than the fission-track zircon system in the case of a secondary thermal event.

6) An outcrop sample of the granodiorite, which was obtained outside of the Hijiori caldera, yielded an apparent zircon fission-track age of 76.0 ± 2.6 Ma and track length data showing the reduced track length ratio of 63 %. This zircon age is also thermally reduced.

7)The apatite fission-track age of the outcrop sample was 4.3 ± 0.9 Ma. Because fission tracks in the apatites do not seem to have been thermally affected, the granodiorite cooled below ~100 ℃ at 4.3 ± 0.9 Ma.

8) It was estimated that the temperature of the granodiorite at 1.5 - 2.2 km depth in the Hijiori caldera has been kept almost constant since ~10,000 years ago.

ACKNOWLEDGMENTS

I was able to receive the HDR-1 bore-hole samples with NEDO's permission and the assistance of Mr. M. Yagi. Mr. I. Matsunaga showed me a sampling locality where the granodiorite is exposed. Dr. T. Tagami was helpful for the sample irradiation at the Kyoto University Research Reactor. Prof. A.J.W. Gleadow gave me the opportunity to study the fission track dating method at La Trobe University, Australia. Dr. B.P. Kohn, Dr. P.B. O'Sullivan and Mr. A. Rasa helped me in the laboratory there. Dr. D. Inoue and Mr. K. Kiho were helpful throughout this study. I sincerely thank all of them.

REFERENCES

Brandon, M.T. and Vance, J.A., 1992. Tectonic evolution of the Cenozoic Olympic subduction complex, Washington State, as deduced from fission track ages for detrital zircons. Amer. J. Sci., 292: 565-636.

Fleischer, R.L., Price, P.B. and Walker, R.M., 1965. Effects of temperature, pressure, and ionization of the formation and stability of fission tracks in minerals and glasses. J. Geophys. Res., 70:1497-1502.

Galbraith, R.F., 1981. On statistical models of fission-track counts. Math. Geol., 13: 471-478.

Gleadow, A.J.W. and Brooks, C.K., 1979. Fission track dating, thermal histories and tectonics of igneous intrusions in East Greenland. Contrib. Mineral Petrol., 71: 45-60.

Gleadow, A.J.W. and Duddy, I.R., 1981. A natural long-term track annealing experiment for apatite. Nucl. Tracks, 5: 169-174.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. and Lovering, J.F., 1986. Confined fission track lengths in apatite:a diagnostic tool for thermal history analysis. Contrib. Mineral. Petrol., 94:405-415.

Green, P.F., 1981. A new look at statistics in the fission track dating. Nucl. Tracks, 5: 77-86.

Green, P.F., 1985. Comparison of zeta calibration baselines for fission-track dating of apatite, zircon and sphene. Chem. Geol. (Isot. Geos. Sect.), 58: 1-22.

Green, P.F., Duddy, I.R., Gleadow, A.J.W. and Lovering, J.F., 1989. Apatite fission-track analysis as a paleotemperature indicator for hydrocarbon exploration. In: N.D. Naeser and T.H. McCulloh (Editors), Thermal History of Sedimentary Basins, Springer-Verlag, New York, 181-195.

Goff, F. and Shevenell, L., 1987. Travertine deposits of Soda Dam, New Mexico, and their implications for the age and evolution of the Valles caldera hydrothermal system. Geol. Soc. Am. Bull., 99: 292-302.

Harrison, T.M., Morgan, P and Blackwell, D.D., 1986. Constraints on the age of heating at the Fenton Hill site, Valles caldera, New Mexico. J. Geophys. Res., 91: 1899-1908.

Hurford, A.J., 1986. Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol., 92:413-427.

Hurford, A.J. and Green, P.F., 1983. The zeta age calibration of fission-track dating. Isot. Geosci., 1: 285-317.

Hurford, A.J. and Watkins, R.T., 1987. Fission-track age of the tuffs of the Buluk Member, Bakate formation, Northern Kenya: a suitable fission-track age standard. Chem. Geol. (Isot. Geosci. Sect.), 66: 209-216.

Ikeya, M., 1983. ESR studies of geothermal boring cores at Hachobara power station. Jpn. J. Appl. Phys., 22: 763-765.

Ito, H. and Tanaka, K., 1995. Insights on the thermal history of the Valles caldera, New Mexico: evidence from zircon fission-track analysis., J. Volcanol. Geotherm. Res. (in press)

Ito, H., Sorkhabi R.B., Tagami, T. and Nishimura, S., 1989. Tectonic history of granitic bodies in the South Fossa Magna region, central Japan: new evidence from fission-track analysis of zircon. Tectonophysics, 166: 331-344.

Konda, T., 1974. Explanatory text of the geological map of Yamagata prefecture, scale 1: 50,000, Gassan, Yamagata prefectural government, pp. 38. (in Japanese)

Konda, T. and Ueda, Y., 1980. K-Ar age of the Tertiary volcanic rocks in the Tohoku area, Japan. Jpn. Assoc. Min. Pet. Ecno. Geol., J., special vol. 2: 343-346. (in Japanese with English abstract)

Matsunaga, I., Kobayashi, H. and Yamaguchi, T., 1993. Granodiorite basement at the Hijiori Caldera - Thermal history estimated from data of K-Ar dating -. Resources and Environment, 2: 565-573. (in Japanese with English abstract)

Naeser, C.W. and Faul, H., 1969. Fission track annealing in apatite and sphene. J. Geophys. Res., 74:705-710.

NEDO (New Energy Development Organization), 1983. Reports on an investigation of the geothermal development and promotion, the area of the lower reaches of Dozangawa River (Abstract), pp. 135 (in Japanese).

NEDO (New Energy and Industrial Technology Development Organization), 1989. Syowa 63 Nen-do Sun Shine Project Supplemental Work, NEDO report on the development of the hydrothermal power plant and the hot dry rock system, pp430. (in Japanese)

NEDO (New Energy and Industrial Technology Development Organization), 1990. Heisei 1 Nen-do Sun Shine Project Supplemental Work, NEDO report on the development of the hydrothermal power plant and the hot dry rock system, pp328. (in Japanese)

Nishimura, S. and Mogi, T., 1986. The interpretation of discordant ages of some granitic bodies. J. Geotherm. Res. Soc. Jpn., 8:145-164.

Nishimura, S., Taniguchi, M. and Sumi, K., 1976. Fission-track ages of the volcanic rocks in Oyasu-Doroyu geothermal field, Akita Prefecture- Fission-track age of the igneous rocks associated with geothermal activities in Japan (1)-. Geol. Surv. Jpn. Bull., 27: 713-717. (in Japanese with English abstract)

Ogoh, K., Toyoda, S., Ikeda, S., Ikeya, M. and Goff, F., 1993. Cooling history of the Valles Caldera, New Mexico using ESR dating method. Appl. Radiat. Isot., 44: 233-237.

Shibata, K., Danhara, T. and Takagi, H., 1990. Concordance between K-Ar ages of K-feldspar and fission-track ages of zircon in Cretaceous granitic rocks from Japan. Geochem. J., 24:187-192.

Spell, T. L., Harrison, T.M. and Wolff, J.A., 1990. ^{40}Ar/^{39}Ar dating of the Bandelier Tuff and San Diego Canyon Ignimbrites, Jamez Mountains, New Mexico; Temporal constraints on magmatic evolution. J. Volcanol. Geotherm. Res., 43: 175-193.

Tagami, T., Ito, H. and Nishimura, S., 1990. Thermal annealing characteristics of spontaneous fission tracks in zircon. Chem. Geol. (Isot. Geosci. Sect.), 80: 159-169.

Takashima, I., Honda, S. and Wada, T., 1987. Geothermal history and hydrothermal system of the Kakkonda-Omatsukurazawa and adjacent areas, Hachimantai geothermal field, northeast Japan -Application of thermoluminescence dating of altered rocks to geothermal exploration-. J. Geotherm. Res. Soc. Jpn., 9: 43-55. (in Japanese with English abstract)

Tamanyu, S. and Lanphere, M.A., 1983. Volcanic and geothermal history at the Hachimantai geothermal field in Japan - on the basis of K-Ar ages. J. Geol. Soc. Jpn., 89: 501-510.

Taniguchi, M., Makita, T. and Kawai, Y., 1978. Geological study on hydrothermal rock alteration in Hijiori geothermal area, Yamagata prefecture, Japan. Rept. Geol. Surv. Jpn., No. 259: 377-414. (in Japanese with English abstract)

Ui, T., 1971. Genesis of magma and structure of magma chamber of several pyroclastic flows in Japan. J. Fac. Sci., Univ. Tokyo, 2: 18: 53-127.

Ui, T., Sugimura, A. and Shibahashi, K., 1973. ^{14}C age of the Hijiori pyroclastic flow deposit, northeastern Honshu, Japan. Bull. Volc. Soc. Jpn., 2nd ser., 18: 171-172. (in Japanese)

WoldeGabriel, G. and Goff, F., 1989. Temporal relations of volcanism and hydrothermal systems in two areas of the Jamez volcanic field, New Mexico. Geology, 17:986-989.

WoldeGabriel, G. and Goff, F., 1992. K/Ar dates of hydrothermal clays from core hole VC-2B, Valles Caldera, New Mexico and their relation to alteration in a large hydrothermal system. J. Volcanol. Geotherm. Res., 50: 207-230.

Part 3

Insights on the thermal history of the Valles caldera, New Mexico, USA: evidence from zircon fission-track analysis

ABSTRACT

The zircon fission-track dating method was applied to the VC-2B core obtained from the active hydrothermal system at Sulphur Springs, Valles caldera, New Mexico. Four samples were analyzed to obtain both zircon ages and track length data from Permian strata to Precambrian quartz monzonite, the present temperatures of which are from 222 to 294 ℃. Zircon ages obtained from the deeper three samples indicate partially annealed ages of about 450-600 Ma. Thus, zircons from Permian strata probably originated from Precambrian rocks. The lack of correlation between FT ages and temperatures of the sampling points is probably due to hot fluid flow and/or hot vein emplacement associated with recent volcanic activity. Zircon ages of the shallowest sample were much younger than the Permian, the reason for which is unknown. The closure temperature of the zircon fission-track dating method seems to be higher than that previously determined from geological data.

1. INTRODUCTION

The Valles caldera, New Mexico, is a resurgent caldera that formed at 1.13 Ma and had accompanying post-caldera moat rhyolite emplacement until about 0.13 Ma (Gardner et al., 1986; Self et al., 1986; Spell et al, 1990). At present, an active hydrothermal system is observed in and around the 20-km-diameter Valles caldera. VC-2B, the third Continental Scientific Drilling Program (CSDP) core hole in the Valles caldera (Fig. 1), was drilled in the Sulphur Springs area, in the west-central portion of the caldera. It reached a depth of 5780 ft. (1761.7 m) and a bottom-hole temperature of 295 ℃. The hole penetrated all of the thick Valles intracaldera ignimbrite sequence as well as pre-caldera basement rocks, ranging in age from Miocene to Precambrian. The detailed geological description of this core was made by Hulen and Gardner (1989) and a summary of the Valles CSDP can be found in Goff et al. (1992).

One of many essential problems is to elucidate the thermal history of the caldera and determine when the present abnormally high geothermal gradient commenced in this area. So far, many studies have focused on these subjects using radiometric age determinations (Brookins et al., 1977; Spell et al., 1990; WoldeGabriel and Goff, 1992), paleomagnetism (Geissman, 1988), fluid inclusion microthermometry (Sasada, 1988; Hulen and Nielson, 1988), mineral alteration assemblages (Keith, 1988; Hulen and Nielson, 1988) and so on. Dating of spring deposits, core samples of vein minerals and altered host rocks by K-Ar (WoldeGabriel and Goff, 1989, 1992), Ar-Ar (Harrison et al,. 1986; Spell et al., 1990), U-series (Goff and Shevenell, 1987; Self et al., 1988) and ESR (Ogoh et al., 1993) revealed that the hydrothermal system was created at about 1.0 Ma and has been continuously active to the present.

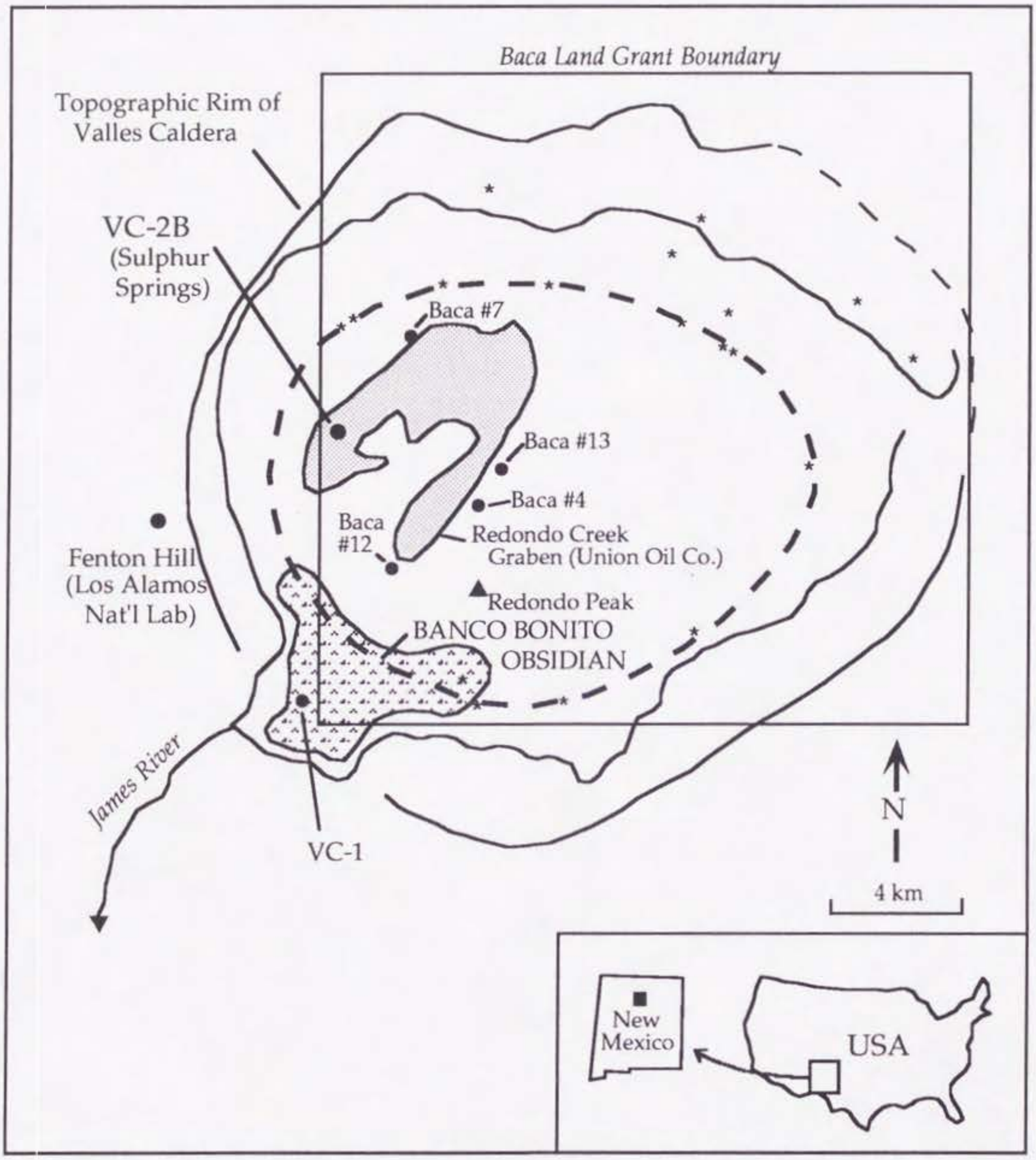

Fig.1 Location map of the Valles caldera and VC-2B core hole, Sulphur Springs area, New Mexico; v pattern shows Banco Bonito obsidian flow, stipple pattern shows area of intense intracaldera acid-sulfate alteration, stars denote intracaldera rhyolite vents and heavy dashed line shows the inferred position of the Valles ring fracture zone (modified from Goff et al., 1986).

The fission-track dating (FTD) method using zircon should be applicable to evaluate the thermal history of a geothermal area. This is because FTD using zircon has a much higher thermal resistivity than FTD using apatite. Apatite FTD has a closure temperature of about 100 ℃ (Naeser and Faul, 1969; Green et al., 1989), whereas the closure temperature for zircon FTD is about 200 ℃ (Zaun and Wagner, 1985; Nishimura and Mogi, 1986), although Hurford (1986) estimated it more broadly as 240 ± 50 ℃. The closure temperature of zircon FTD corresponds well with that of the K-Ar method using feldspar (Shibata et al., 1990).

In an active geothermal area where the temperature approaches 300 ℃, fission tracks in zircon must have been partially annealed, even in the case where fission tracks in apatite have been totally annealed, yielding a zero age. In such a case, zircon FTD should provide more geological information than apatite FTD. Thus this method will provide additional constraints on the thermal history of the Valles caldera.

It should be mentioned that there is still ambiguity about the closure temperature of zircon FTD, because its closure temperature exceeds 300 ℃ from experimentally derived results (Fleischer et al., 1965). This is about 100 ℃ higher than the estimate from geological data. It is therefore also important to apply zircon FTD to the VC-2B core, because it should also provide some important information about the closure temperature of the zircon FTD system. Moreover, FTD has other merits for geothermal applications. FTD can not only provide dating results but also spontaneous track length information (Gleadow et al., 1986; Ito et al., 1989), which constrains the interpretation of the dating results. Because FTD is applied to individual grains, it can also be used in the case of sedimentary rocks to discriminate between the types of host rocks that yielded the grains (Hurford et al., 1984).

2. EXPERIMENTAL METHODS

Samples of the VC-2B core were obtained from depths of 3005, 4003, 4978 and 5773 feet (Fig. 2). The sample at 3005 ft (VC2B1) is from the Permian Yeso Formation. It consists of dominantly hematitic, fine-grained, plane- to wavy-bedded, commonly bioturbated, locally argillaceous sandstone. The VC2B1 sample was taken from fairly laminated and non-laminated parts of the sandstone. The sample at 4003 ft (VC2B2) is from the Permian Abo Formation, which contains interbedded hematitic arkosic mudstones and sandstones. The VC2B2 sample was taken from dominantly thinly laminated and partly non-laminated parts of the sandstone. The sample at 4978 ft (VC2B3) is from the Pennsylvanian Sandia Formation, which is dominantly interbedded mudstone, siltstone, sandstone and argillaceous to sandy limestone. The VC2B3 sample was taken from sandstone to sandy limestone. The sample at 5773 ft (VC2B4) is from the Precambrian porphyritic biotite (+ hornblende) quartz monzonite. It consists of very distinctive coarsely porphyritic rock, with 20-25 % large potassium feldspar phenocrysts embedded in a medium-crystalline granitic matrix. Original magnetite (ilmenite ?) and sphene are now commonly converted to leucoxene. These lithological descriptions were taken from Hulen and Gardner (1989). Zircons were obtained from all the samples by conventional mineral separation techniques including both magnetic and heavy liquid separations.

Zircons from VC2B1 and VC2B2 consisted of many elongated grains 200-300 μm long and 50-100 μm wide. Some zircons were rather massive, rounded and 100-200 μm long. A small quantity of zircons was obtained from VC2B3. They were smaller in size compared with the other samples. Zircons from VC2B4 were mostly elongated grains 200-300 μm long and 50-100 μm wide.

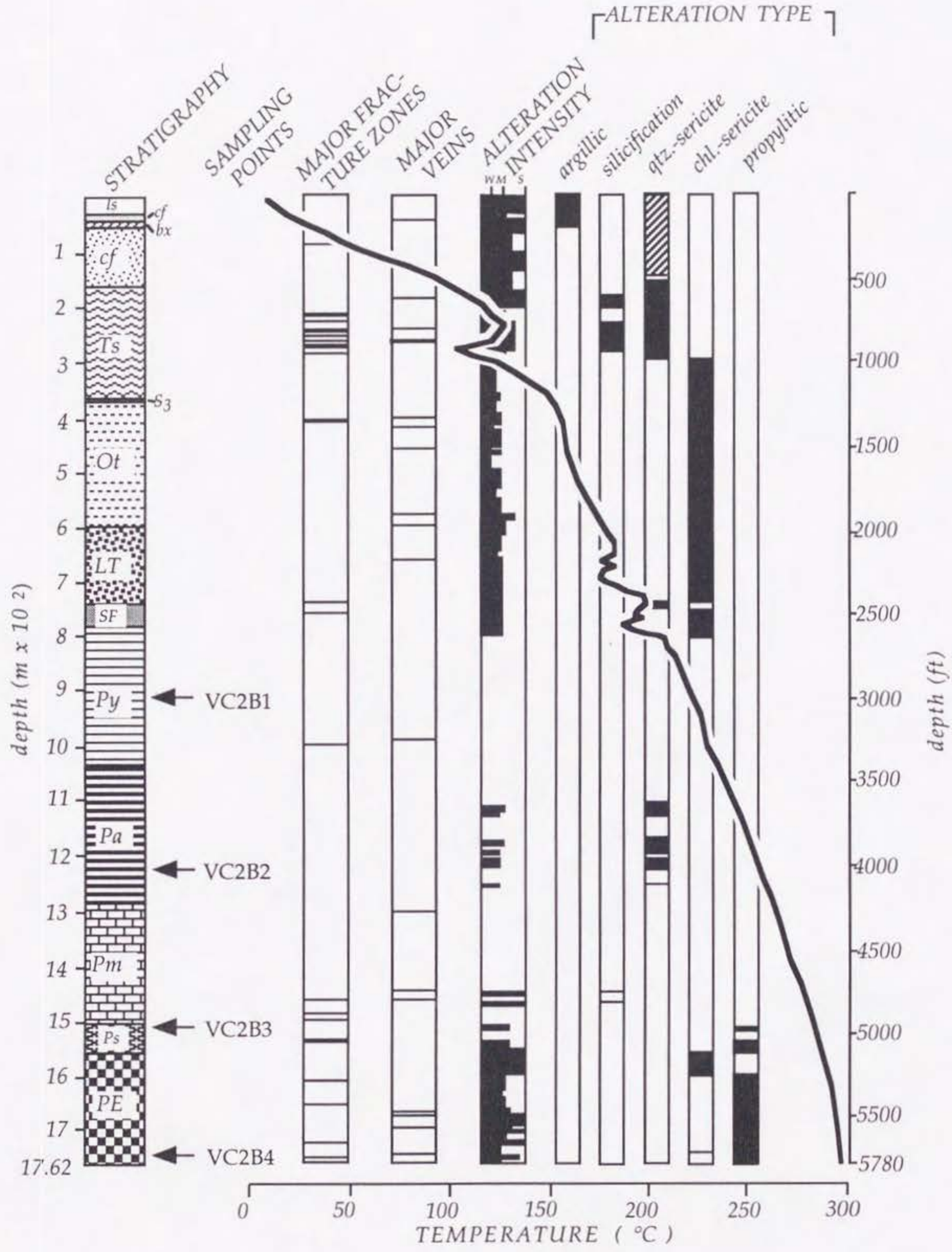

Fig.2 Summarized geologic log for VC-2B core hole and sampling points (modified from Hulen and Gardner, 1989).
ls--landslide debris; cf--caldera-fill clastic rocks; bx--hydrothermal breccia and dacite porphyry; Ts--Tshirege Member of Bandelier Tuff; S3--S3 clastic deposits; Ot--Otowi Member of Bandelier Tuff; LT--Lower Tuffs; SF--Santa Fe Group sandstone; Py--Permian Yeso Fm; Pa--Permian Abo Fm; Pm--Penn. Madera Limestone; Ps--Penn. Sandia Fm; PC--Precambrian quartz monzonite.

Zircons were mounted in PFA Teflon. They were polished in 6 μm diamond paste to a depth that ensures 4 π geometry and polished again with 1 μm diamond paste to cleanse the surface. They were etched in NaOH and KOH eutectic melt at 225 °C to reveal spontaneous fission tracks (Gleadow et al., 1976).

For some samples, spontaneous track density was very high ($>10^7 cm^{-2}$), so etching times were necessarily short to discriminate each track clearly (Table 2). A photo of an etched sample with high spontaneous track density is shown in Fig. 3.

Ages were determined using the external detector method (Gleadow, 1981), and the zeta approach (Hurford, 1990) was adopted. The samples were irradiated with some age standards and standard glass SRM-613 in the D_2O facility of Kyoto University Research Reactor (KUR). This facility has a thermal neutron flux of 3-4 x 10^9 $cm^{-2}s^{-1}$ and a Cd ratio of more than 5000 for Au (T. Tagami, personal communication, 1992).

Track age counting and spontaneous track length measurements were carried out under a microscope (Nikon Optiphot POL; x10 eyepiece, x100 dry objective). Only horizontal confined tracks were selected for track length measurement. Some zircons were etched up to 2 times longer than those etched for age determination in order to reveal confined tracks clearly.

The results of zeta values and age determinations are shown in Tables 1 and 2 respectively. The results of track length measurement are shown in Fig. 4. Zeta values were determined using three age standards listed in Table 1. They showed fairly good concordance, though the zeta for Buluk Member 4 Tuff is relatively low. The weighted mean zeta of 385.6 ± 8.4 (1σ error) was used for age calculations.

3. DISCUSSION

Fig.3 An etched zircon sample with high spontaneous track density ($>10^7$ cm^{-2}). This sample is from the Permian Abo Formation (VC2B2). Etching conditions are NaOH:KOH=1:1 at 225 °C for 6 hours.

Table 1 Zeta (ζ) values obtained from zircon age standards.

Sample code	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)	Spontaneous number density ($x10^6cm^{-2}$)	Induced number density ($x10^6cm^{-2}$)	$P(\chi^2)$ (%)	$\zeta \pm 1\sigma$
FCTZ 1	12	1924 1.154	1668 4.62	1391 3.85	30	402.8±17.3
FCTZ2	11	1924 1.154	1762 6.13	1358 4.72	3	372.2±15.9
FCTZ4	7	1924 1.154	1098 5.82	943 4.99	60	414.8±20.7
BM1	8	1924 1.154	483 1.24	559 1.44	15	325.4±21.5
TR1	11	1924 1.154	1717 6.92	686 2.76	50	410.5±20.8
						$\underline{385.6\pm8.4}$

Zeta value underlined, which is the weighted mean, is adopted. FCTZ1, 2, 4: Fish Canyon Tuff (27.8±0.1 Ma), BM1: Buluk Member 4 Tuff (16.2±0.1 Ma), TR1: Tardree Rhyolite (58.7±0.6 Ma). Ages of the age standard samples are from Hurford and Watkins (1987).Dosimeter glass SRM 613 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981).

Table 2 Zircon fission track analytical data of VC-2B core.

Sample code	Depth (ft.)	Depth (m)	Temp. (°C)	Etch. time (hr.)	Number of grains	Dosimeter number density ($x10^5cm^{-2}$)		Spontaneous number density ($x10^6cm^{-2}$)		Induced number density ($x10^6cm^{-2}$)		$P(\chi^2)$ (%)	Age ± 1σ (Ma)
VC2B1-1	3005	916	222	7	4	1163	1.156	455	10.79	85	2.02	15	118±14
VC2B1-2	3005	916	222	15	4	1158	1.151	546	4.75	235	2.04	<0.1	51.3±4.3
VC2B1-3	3005	916	222	16	6	1153	1.146	461	3.21	326	2.27	5	31.2±2.4
VC2B1	3005	916	222		14								
VC2B2	4003	1220	256	6	10	1168	1.161	2722	24.1	108	0.955	25	541±55
VC2B3-1	4978	1517	283	7	5	1177	1.170	447	24.5	17	0.934	5	567±141
VC2B3-2	4978	1517	283	13	4	1173	1.166	430	17.3	23	0.923	20	407±88
VC2B3	4978	1517	283		9								452±75
VC2B4-1	5773	1759	294	2.7	6	1187	1.180	1470	34.1	58	1.34	15	552±76
VC2B4-2	5773	1759	294	6	5	1182	1.175	1183	28.7	38	0.922	35	669±112
VC2B4	5773	1759	294		11								589±63

Samples are as follows, VC2B1: sandstone from the Permian Yeso Formation, VC2B2: sandstone from the Permian Abo Formation, VC2B3: sandstone to limestone from the Pennsylvanian Sandia Formation, VC2B4: Precambrian quartz monzonite. Ages calculated using ζ=385.6±8.4 (1σ error). Dosimeter glass SRM 613 used. $P(\chi^2)$: Probability of obtaining χ^2 value for ν degrees of freedom (where ν = number of grains - 1) (Galbraith, 1981). Ages underlined are adopted. Age of VC2B3 is weighted mean of VC2B3-1 and VC2B3-2. Age of VC2B4 is weighted mean of VC2B4-1 and VC2B4-2. Note ages of VC2B1-1, -2, -3 differ greatly according to etching time (or spontaneous track density).

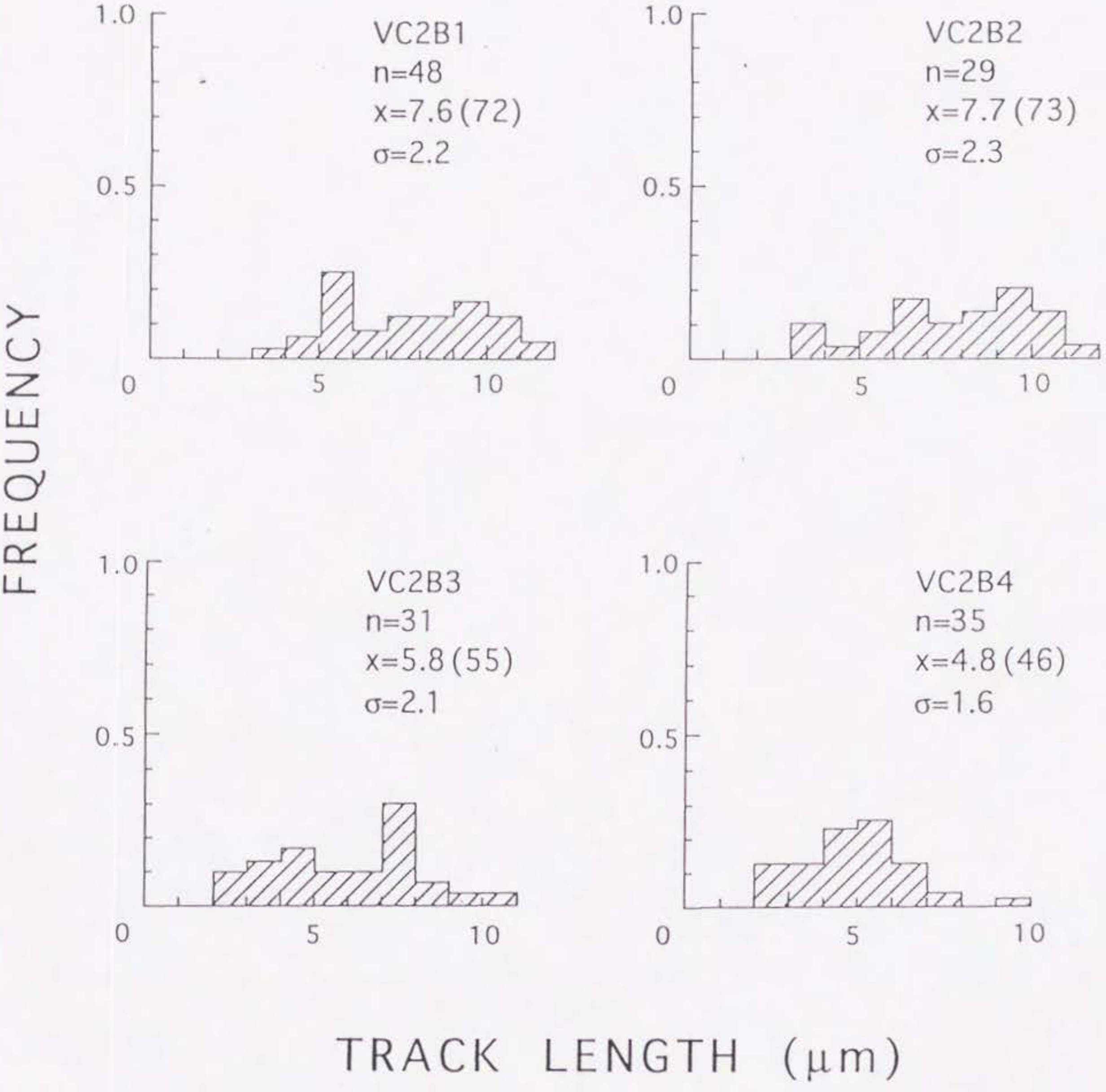

Fig.4 Confined spontaneous track length distributions observed in zircons from VC-2B core.
n: number of tracks measured, x: mean track length and reduced track length ratio (%) in parentheses (non-annealed track length is assumed to be 10.5 μm), σ: standard deviation of track length distributions.

The zircon FT ages obtained for VC2B2, VC2B3 and VC2B4 are about 450-600 Ma. These ages are obviously annealed to some extent, because track lengths are shorter than the non-annealed track length of about 10.5 μm for some granites (Ito et al., 1989). Though the rocks of both VC2B2 and VC2B3 belong to Permian formations, these ages range from Ordovician to Precambrian. It is very plausible that the original ages of these zircons are Precambrian, considering the annealing effect.

It is noticeable that the ages of VC2B2, VC2B3 and VC2B4 are approximately the same, regardless of the difference in sampling depth and present temperature. This contrasts well with the results of Zaun and Wagner (1985). They showed decreasing zircon ages with increasing sampling depth and temperature at Urach, southwest Germany, where very old (~100 Ma) subsidence-driven thermal input occurred.

However, the results of the Valles caldera are analogous to the results of the Hijiori caldera, northeast Japan (Ito, 1993), because zircon ages do not necessarily decrease with increasing depth and temperature. In both cases, the intense thermal activity that formed the calderas occurred very recently, i.e., ~1 Ma for the Valles caldera and ~10,000 years ago for the Hijiori caldera. In both cases, thermal input was caused by volcanic activity, which possibly affected zircon annealing by relatively shallow hot fluid flow and/or hot vein emplacement. In such cases, zircons need not be heated dominantly by thermal conduction from the deeper heat source. Thus, it is plausible that zircon apparent ages do not have any clear correlation with depth and temperature.

The ages obtained from VC2B1 sample seem more complicated. Three different ages, ranging from 31.2 to 118 Ma, were obtained using different spontaneous track etching times. It is clear that the higher the spontaneous track density (or the less etching time), the older the age becomes. It seems the thermal history of VC2B1 has been quite different from that of VC2B2, although both samples originate from similar Permian formations. As shown in Fig. 4, the spontaneous tracks of these two samples have almost the same reduced track length ratio and distribution pattern, but the ages obtained are significantly different. The ages of VC2B1 are much younger than the Permian, whereas that of VC2B2 is much older than the Permian. A possible explanation is that zircons of VC2B1 (Permian Yeso Formation) were completely annealed at some time in the Mesozoic era (~130 Ma?), as the oldest age of VC2B1 is 118 Ma. This explanation seems quite unrealistic, however, because the samples at greater depths do not show any affects of an intense thermal event in the Mesozoic era; their ages are older than the Mesozoic.

The different ages determined for VC2B1 could be explained by the following alternatives. One is that zircons of VC2B1 came from different sources, and the other is that the annealing character for zircons of VC2B1 is different. It seems that the former is more plausible because the age discrepancies seem too large to be explained by differences in annealing character.

The closure temperature of zircon FTD can be implied as follows. In order to estimate the closure temperature, it is necessary to determine a heating time and corresponding temperature for a sample, based on the following equation:

$$\Delta t = A_0 \exp (A_1 + A_2 / T)$$

where Δt = heating time (t),

T = temperature (K),

A_0 = constant (t), A_1 = constant, A_2 = constant (K),

It is assumed that the Valles caldera has been continuously hot since ~1 Ma because many radiometric age determinations on spring deposits, core samples of vein minerals and altered host rocks by K-Ar, Ar-Ar, U-series and paleomagnetic methods produce ages in the range of ~1 Ma to the present (See Table 6 in Goff et al., 1992). As for the temperature estimate, fluid inclusion studies indicate that the maximum temperatures in the Paleozoic Madera and Sandia strata from corehole VC-1 (Fig. 1) reached between 270 and 285 ℃ (Sasada, 1988; Hulen and Nielsen, 1988), while the maximum temperature of intracaldera rocks from 42-164 m depth of corehole VC-2A at Sulpher Springs was about 200 ℃ (Hulen et al., 1987). Paleomagnetic studies (Geismann, 1988) and clay mineral assemblages (Keith, 1988) on Paleozoic strata from corehole VC-1 also indicate that the maximum temperature caused by the Valles caldera hydrothermal activity was approximately 300 ℃. These data all indicate that the heating time of all the samples is about 1 million years and the temperature of each sample has remained approximately the same as its present temperature.

From this assumption and using the data of sample VC2B4, a reduced fission track length ratio of 46% was obtained under isothermal conditions at 294 ℃ for 10^6 years. Brandon and Vance (1992) estimated that the reduced track density ratio in zircon is 10 % under 262 ℃ isothermal condition for 10^6 years, which means fission tracks are almost completely annealed in these conditions. Brandon and Vance (1992) calculated the zircon closure temperatures to be 212 - 258 ℃ for cooling rates of 1 - 100 ℃/my. Brandon and Vance (1992)'s closure temperatures are in concordance with or higher than those previously determined from geological data (e.g. Harrison et al., 1979; Zaun and Wagner, 1985). Thus, the closure temperature of zircon FTD implied from our data seems higher than the closure temperatures previously determined from geological data.

4. CONCLUSIONS

1. Zircon FTD ages from the Permian Abo Formation to Precambrian quartz monzonite indicated partially annealed ages of about 450-600 Ma.

Although the zircons were obtained from Permian strata, they probably originated from Precambrian rocks.

2. The fact that there is no correlation between zircon ages and sampling depth is probably due to hot fluid flow and/or hot vein emplacement associated with recent volcanic activity.

3. Zircon FTD ages from the Permian Yeso Formation indicate much younger ages than the Permian, the reason of which is unknown. These zircons seem to have come from different source areas, because ages among zircon grains differ greatly.

4. The closure temperature of zircon FTD implied from VC2B data seems to be higher than that previously determined from geological data.

5. Zircon FTD studies on VC-2B core offer some insight not only into thermal history, but also source rocks of zircons in pre-Valles caldera strata.

ACKNOWLEDGMENTS

Dr. K. Tanaka provided me with information on the CSDP project and supported this study. Dr. J.N. Gardner provided me with the VC-2B core samples and important geological information on the Valles caldera. Dr. F. Goff reviewed the manuscript and provided me with a great deal of important geological information. Dr. T. Tagami supervised the irradiation at KUR. Prof. S. Nishimura, Dr. A.W. Laughlin and Dr. P.B. O'Sullivan reviewed the manuscript, greatly contributing to its improvement.

I sincerely thank all of these people.

REFERENCES

Brandon, M.T. and Vance, J.A., 1992. Tectonic evolution of the Cenozoic Olympic subduction complex, Washington State, as deduced from fission track ages for detrital zircons. Amer. J. Sci., 292:565-636.

Brookins, D.G., Forbes, R.B., Turner, D.L., Laughlin, A.W. and Naeser, C.W., 1977. Rb-Sr, K-Ar, and fission-track geochronological studies of samples from LASL drill holes GT-1, GT-2, and EE-1. Los Alamos Natl. Lab. Rep., LA-6829-MS, 22pp.

Fleischer, R.L., Price, P.B. and Walker, R.M., 1965. Effects of temperature, pressure, and ionization of the formation and stability of fission tracks in minerals and glasses. J. Geophys. Res., 70:1497-1502.

Galbraith, R.F., 1981. On statistical models for fission track counts. Math. Geol., 13:471-478.

Gardner, J. N., Goff, F., Garcia, S. and Hagan, R. C., 1986. Stratigraphic relations and lithologic variations in the Jamez volcanic field, New Mexico. J. Geophys. Res., 91: 1763-1778.

Geissman, J.W., 1988. Paleomagnetism and rock magnetism of Quaternary volcanic rocks and late Paleozoic strata, VC-1 core hole, Valles Caldera, New Mexico, with emphasis on remagnetization of late Paleozoic strata. J. Geophys. Res., 93:6001-6025.

Gleadow, A.J.W., 1981. Fission-track dating methods: What are the real alternatives?. Nucl. Tracks, 5:3-14.

Gleadow, A.J.W., Hurford, A.J. and Quaife, R.D., 1976. Fission track dating of zircon: improved etching techniques, Earth Planet Sci. Lett., 33: 273-276.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. and Lovering, J.F., 1986. Confined fission track lengths in apatite:a diagnostic tool for thermal history analysis. Contrib. Mineral. Petrol., 94:405-415.

Goff, F. and Shevenell, L., 1987. Travertine deposits of Soda Dam, New Mexico, and their implications for the age and evolution of the Valles caldera hydrothermal system. Geol. Soc. Am. Bull., 99: 292-302.

Goff, F., Rowley, J., Gardner, J.N., Hawkins, W. and Goff, S., 1986. Initial results from VC-1, first continental scientific drilling program core hole in Valles Caldera, New Mexico. J. Geophys. Res., 91: 1742-1752.

Goff, F., Gardner, J.N., Hulen, J.B., Nielson, D.L., Charles, R., WoldeGabriel, Giday, Vuataz, F.D., Musgrave, J.A., Shevenell, L. and Kennedy, B.M., 1992. The Valles caldera hydrothermal system, past and present, New Mexico, USA. Scientific Drilling, 3: 181-204.

Green, P.F., Duddy, I.R., Gleadow, A.J.W. and Lovering, J.F., 1989. Apatite fission-track analysis as a paleotemperature indicator for hydrocarbon exploration. In: N.D. Naeser and T.H. McCulloh (Editors), Thermal History of Sedimentary Basins, Springer-Verlag, New York, pp. 181-195.

Harrison , T.M., Armstrong, R.L., Naeser, C.W. and Harakal, J.E., 1979. Geochronology and thermal history of the Coast plutonic complex, near Prince Rupert, British Columbia. Can. J. Earth Sci., 16: 400-410.

Harrison, T.M., Morgan, P and Blackwell, D.D., 1986. Constraints on the age of heating at the Fenton Hill site, Valles caldera, New Mexico. J. Geophys. Res., 91: 1899-1908.

Hulen, J.B. and Gardner, J.N., 1989. Field geologic log for continental scientific drilling program corehole VC-2B Valles caldera, New Mexico. Earth Sci. Lab. Univ. Utah Research Inst., 92pp.

Hulen, J.B. and Nielson, D.L., 1988. Hydrothermal brecciation in the Jamez fault zone, Valles caldera, New Mexico: Results from Continental Scientific Drilling Program core hole VC-1. J. Geophys. Res., 93:6077-6089.

Hulen, J.B., Nielson, D.L., Goff, F., Gardner, J.N. and Charles, R.W., 1987. Molybdenum mineralization in an active geothermal system, Valles caldera, New Mexico. Geology, 15: 748-752.

Hurford, A.J., 1986. Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol., 92:413-427.

Hurford, A.J., 1990. Standardization of fission track dating calibration: Recommendation by the Fission Track Working Group of the I.U.G.S. Subcommission on Geochronology. Chem. Geol. (Isot. Geosci. Sect.), 80:171-178.

Hurford, A.J. and Watkins, R.T., 1987. Fission-track age of the tuffs of the Buluk Member, Bakate Formation, northern Kenya: a suitable fission-track age standard., Chem. Geol. (Isot. Geosci. Sect.), 66, 209-216.

Hurford, A.J., Fitch, F.J. and Clarke, A., 1984. Resolution of the age structure of the detrital zircon populations of two Lower Cretaceous sandstones from the Weald of England by fission track dating. Geol. Mag., 121 (4):269-277.

Ito, H., 1993. Estimation of geothermal history by fission track method (1) Application to the Hijiori geothermal area, Yamagata Prefecture. Central Res. Inst. Electric Power Ind., Report No. U92041, 39pp (in Japanese with English abstract)

Ito, H., Sorkhabi, R. B., Tagami, T. and Susumu, N., 1989. Tectonic history of granitic bodies in the South Fossa Magna region, central Japan: new evidence from fission-track analysis of zircon. Tectonophysics, 166:331-344.

Keith, T.E.C., 1988. Alteration in the Madera Limestone and Sandia Formation from core hole VC-1, Valles caldera, New Mexico, J. Geophys. Res., 93:6068-6076.

Naeser, C.W. and Faul, H., 1969. Fission track annealing in apatite and sphene. J. Geophys.. Res., 74:705-710.

Nishimura, S. and Mogi, T., 1986. The interpretation of discordant ages of some granitic bodies. J. Geotherm. Res. Soc. Jpn., 8:145-164.

Ogoh, K., Toyoda, S., Ikeda, S., Ikeya, M. and Goff, F., 1993. Cooling history of the Valles Caldera, New Mexico using ESR dating method. Appl. Radiat. Isot., 44: 233-237.

Sasada, M., 1988. Microthermometry of fluid inclusions from the VC-1 core hole in Valles caldera, New Mexico. J. Geophys. Res., 93:6091-6096.

Self, S., Goff, F., Gardner, J. N., Wright, J. V. and Kite, W. M., 1986. Explosive rhyolitic volcanism in the James Mountains: Vent locations, caldera development and relation to regional structure. J. Geophys. Res., 91:1779-1798.

Self, S., Kircher, D.E. and Wolff, J.A., 1988. The El Cajete Series, Valles caldera, New Mexico: Jour. Geophys. Res., 93: 6113-6127.

Shibata, K., Danhara, T. and Takagi, H., 1990. Concordance between K-Ar ages of K-feldspar and fission-track ages of zircon in Cretaceous granitic rocks from Japan. Geochem. J., 24:187-192.

Spell, T. L., Harrison, T.M. and Wolff, J.A., 1990. $^{40}Ar/^{39}Ar$ dating of the Bandelier Tuff and San Diego Canyon Ignimbrites, Jamez Mountains, New Mexico; Temporal constraints on magmatic evolution. J. Volcanol. Geotherm. Res., 43: 175-193.

WoldeGabriel, G. and Goff, F., 1989. Temporal relations of volcanism and hydrothermal systems in two areas of the Jamez volcanic field, New Mexico. Geology, 17:986-989.

WoldeGabriel, G. and Goff, F., 1992. K/Ar dates of hydrothermal clays from core hole VC-2B, Valles Caldera, New Mexico and their relation to alteration in a large hydrothermal system. J. Volcanol. Geotherm. Res., 50: 207-230.

Zaun, P.E. and Wagner, G.A., 1985. Fission-track stability in zircons under geological conditions. Nucl. Tracks, 10:303-307.