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Thermoluminescence dating of volcanic rocks and alteration minerals and their application to geothermal history

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Abstract: Thermoluminescence (TL) of the following four kinds of samples from seven fields was measured for dating.

(1) Quartz phenocrysts from fresh and altered volcanic rocks.
(2) Plagioclase phenocrysts from fresh volcanic rocks.
(3) Secondary quartz from altered rocks.
(4) Mixture of various alteration minerals.

Samples (1) and (2) were used for the determination of the age of eruption, and (1), (3) and (4) were used for that of alteration. The obtained data were calibrated by using standard samples. It was proved that the ages obtained by TL method coincide with K–Ar and fission-track (FT) ages within the limit of $\pm 30\%$ for volcanic rocks. There are no age standard for altered rocks but the errors of TL ages are in the same order or slightly larger than those for volcanic rocks.

TL dating of volcanic rocks by quartz phenocryst was carried out for Tamagawa Welded Tuff, Akita and Iwate Prefectures, and Kurofuji volcanic rocks, Yamanashi Prefecture. The FT ages of six samples of Tamagawa Welded Tuff are known and they were used as standards for age determination of other areas. All TL ages were calculated by the standard curve of the above FT ages versus calibrated TL values, and in some case, corrected by existing age data of respective areas. As the TL dating of Tamagawa Welded Tuff was the basis of all other TL dating, many kinds of tests were carried out. From these tests, no critical phenomena were found and the error of TL age for Tamagawa Welded Tuff is inferred to be ± 0.3 Ma for 1.0 Ma sample. In Tamagawa area, quartz phenocrysts in altered rocks are preserved well. For the determination of the age of alteration, stability of TL during hydrothermal process was tested. At the temperature of 300°C, stored TL is easily discharged within a few hours and substantially decreases even at 200°C. Therefore, the results of TL dating for rocks which suffered alteration by fluid above 200°C will indicate the alteration ages. The TL ages of six altered samples from Tamagawa area are 0.05 to 0.70 Ma.

TL ages of Kurofuji volcano were evaluated 0.62 to 1.05 Ma. These do not contradict the geologic evidences and the duration of volcanic activities of about 400,000 years is reasonable value for medium scale volcanic group.

Dating of volcanic rocks by plagioclase was carried out for some rocks from Noya geothermal area, Oita Prefecture. The method of dating was almost the same as for quartz phenocrysts. However, plagioclase easily alters and the saturation level of TL is lower than that of quartz. The ages obtained for seven samples were 0.24 to 0.78 Ma and coincide with existing data within the error of $\pm 30\%$ except one sample.

Secondary quartz separated from silicified rocks of Kurikoma, Iwate Prefecture, and Azuma, Yamagata Prefecture, was used for TL dating. TL ages of three samples from Kurikoma are 0.11 to 0.16 Ma, and those of eight samples from Azuma are 0.05 to 3.13 Ma. Although there are no other age data to compare, the results are believed to be reliable from the following reasons.

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(1) Alteration ages do not exceed those of host rocks except for few samples (Kurikoma and Azuma).

(2) Almost identical ages were obtained for the samples collected from the same alteration halos even if the ages of original rocks are different (Kurikoma and Azuma).

(3) Successive changes of alteration ages from west to east are observed and that direction coincides with the trend of volcanism (Azuma).

Mixtures of alteration minerals were used for alteration age dating of samples from Kuju, Oita and Kumamoto Prefectures, and Izu, Shizuoka Prefecture. The procedure of sample preparation is very simple. However, the results were not as reliable as other methods because some unusual values were obtained. The evaluation of the accuracy of this method is very difficult but similar or slightly lower reliability is expected by the same reasons as secondary quartz. TL ages of nine samples from Kuju are 0.19 to 1.52 Ma and those of six samples from Izu are 0.40 to 4.11 Ma, which are except few samples with unusual ages.

Based on the TL dating of altered rocks, geothermal histories of the Hachimantai field in Akita and Iwate Prefectures and the Kuju field in Oita and Kumamoto Prefectures are considered.

At the Hachimantai field, large scale hydrothermal activity related to the magma of Tamagawa Welded Tuff was ended about 700,000 years ago followed by the development of other small scale hydrothermal systems. Some of them are found near Gojumagari (360,000 years ago) and Yudamata (120,000 to 150,000 years ago). The alteration ages of presently active areas are normally less than 200,000 years B. P.

At the Kuju field, some hydrothermal systems were formed about 500,000 to 400,000 and 400,000 to 300,000 years ago. The former group apparently has closely related to the volcanism of Bungo, and the latter ones to the activities of old Kuju volcanos. The hydrothermal activities of present geothermal areas (Otake, Hatchobaru and Takenoyu) started about 200,000 years ago.

I. Introduction

Hydrothermally altered areas are good indicators for geothermal activity and are widely studied in many ways. Figure 1 is the schematic diagram of survey methods and expected results. Major methods used for the study of surface alteration are distribution survey, mineral assemblage study and alteration age determination. Hydrothermal alteration of drill cores is also studied for the determination

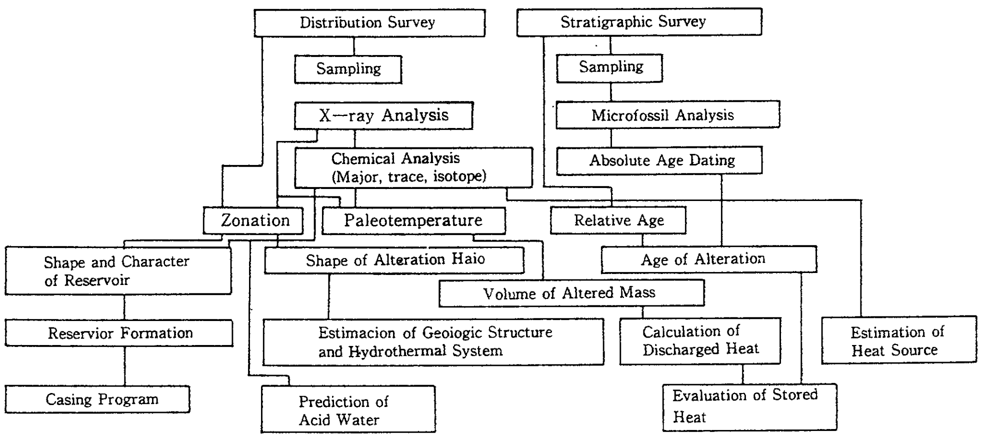


Fig. 1 Schematic diagram of alteration survey and expected results (Revised from SUMI and TAKASHIMA, 1976)

of production zones and hydrological properties of subsurface formations. Consideration of hydrothermal alteration is very important in both mineral and geothermal exploration, but the time factor is very different. In geothermal exploration, alteration age is the important factor because the residual heat is a function of time.

The most widely used method of determining the alteration or mineralization ages is K–Ar dating of some alteration minerals (SHIBATA and ISHIHARA, 1974; ISHIHARA *et al.*, 1980). However, this method is most effective for Tertiary or older ages. For the determination of Quaternary ages, K–Ar, fission track (FT) or ^{14}C methods are used. The ages of original, associated volcanic rocks and carbonaceous materials in sedimentary rocks are determined and then the alteration ages are inferred by the stratigraphic principles. The techniques have been applied to some Japanese geothermal fields and interesting results have been obtained (SUMI and TAKASHIMA, 1976). Those methods are, however, indirect ways of determining the alteration ages and sometimes it is difficult to find the suitable samples.

Thermoluminescence (TL) is an unique technique which is applied for various purposes such as mineral exploration (HAYAKAWA, 1958; GUNTER, 1963), geothermometry (MACDIARMID, 1963), intrusive body identification (McDOUGALL, 1954; JOHNSON, 1963), sample discrimination (LEACH and FANKHAUSER, 1978), meteorite (JINGXIAN *et al.*, 1980; SEARS and DURRANI, 1980; MELCHER, 1981) and dating.

TL dating was originally applied to archeological studies and the method for dating of pottery was already established (AITKEN *et al.*, 1968; MICHELS, 1973; ICHIKAWA and NAGATOMO, 1974). For the geological purposes, TL dating was applied to many minerals such as calcite (ZELLER *et al.*, 1957; JOHNSON, 1967; OVCHINNIKOV and MAKSENKOV, 1969), plagioclase (BERRY, 1967; MAY, 1977; GUÉRIN and VALLADES, 1980), quartz (GÖKSU *et al.*, 1974; HAYAKAWA *et al.*, 1976; LI *et al.*, 1977), siliceous material from ocean sediments (WINTLE and HUNTLEY, 1980). But many unsolved problems remain in TL dating, which prevented the application of this method in geology. Although some uncertainties remain, TL dating is most suitable for determining the alteration ages and is indispensable for geothermal exploration because of the following reasons.

(1) Applicable to many alteration minerals
(2) Easy to take samples and measurement
(3) Directly indicate the alteration ages

The effective range of age determined by TL method is another favorable character of this method for geothermal purposes. The most effective age range is from few thousand to one million years. This is the age range directly related to heat source evaluation and it is difficult to determine by other dating methods. The minerals used are quartz or plagioclases which are common rock forming minerals and canbe found in most of volcanic rocks.

Age data are important in historical trace of geothermal activity. However, there are only few cases where this has been actually applied. The life time of one steam or fumarole vent is in the order of 10 to 10^2 years (LOVERING, 1957; SUMI, 1972) and that of one hot spring area is considered to be over 10^3 years (SUMI, 1972). As for the estimation of the length of geothermal activity, the order of 10^3–10^4 years is estimated by ^{14}C method and a part of history is identified to be over 5,000 years at Matsukawa (SUMI, 1971), over 33,000 years at Tamagawa (SUMI and TAKASHIMA, 1972) and over 30,000 years at Takenoyu (TAKASHIMA, 1974). Same order of lifetime in hot spring activity is postulated by AVERIEV (1967) based on the data of Lower Geyser Basin of Yellowstone Park, Taupo Zone in New Zealand and Geyser Valley in Kamchatka. Longer history is defined at Steamboat Spring where geothermal activity started over 700,000 years ago and even now that is active (WHITE *et al.*, 1964).

The determination of alteration ages is the basis for stored heat and discharged energy evaluation. The total discharged energy was calculated by use of chemical leaching of some elements and actually applied to few geothermal areas such as Ugusu (IWAO, 1963), Matsukawa (TAKASHIMA and SUMI, 1974) and

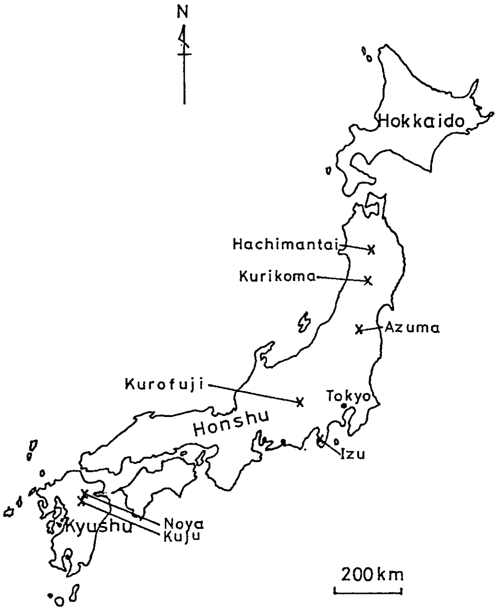


Fig. 2 Locality map of studied areas.

Onuma (KUBOTA, 1979). However, duration of hydrothermal activity is necessary for the evaluation of annual discharge rate or the size of the geothermal field which is directly comparable to present geothermal fields.

In this report, the problems concerning TL dating of various samples are discussed. Then the historical traces of geothermal activities of some fields are attempted on the basis of dating results with combination of geological, mineralogical, chemical and geophysical data.

Figure 2 is the locality map of the fields studied in this report.

II. Thermoluminescence dating method

II. 1 Theoretical basis

Thermoluminescence is an emission of light not due directly to incandescence but occurs at temperatures below those of incandescent bodies. This phenomenon occurs by the following process. When minerals are exposed to high energy radiation, some electrons are trapped in the crystal lattices and stabilized in the excited state at high energy level. These electrons are released from the trap by the heating, return to the original state and then light is emitted. The crystals which underwent thermoluminescence are not repeat this process. The amount of light emitted from crystals is proportional to the amount of electrons captured in the traps and the amount of captured electrons is proportional to total dose of high energy radiation such as alpha, beta, gamma and cosmic rays.

The TL dating method is based on the above assumptions. The amount of light emitted from natural samples (L(natural)) and that from samples artificially exposed to gamma rays (L(artificial)) after heating is expressed as follows.

$$L(\text{natural}) = Dn \cdot T \quad \text{......} (1)$$

$$L(\text{artificial}) = Da \cdot t \quad \text{......} (2)$$

Where Dn is the radiation dose of crystals received under natural conditions, T is the geologic time, Da is the dose of artificial gamma rays and t is the time of exposure of gamma rays to the samples after heating. Thus let R represent L(natural)/L(artificial) and the geologic time is calculated by the following equation.

$$T = R \cdot Da \cdot t / Dn \quad \text{......} (3)$$

Figure 3 is a schematic diagram of the TL dating method and actual procedure is explained as follows.

(1) The acquistion of natural TL is the first stage. It is assumed that there were no stored TL in the mineral at time of its formation after volcanic eruption or alteration. Then it is assumed that TL accumulated linearly with time.

(2) The separated minerals are ground to powder. Then the TL accumulated in geologic time is measured by a TL apparatus.

(3) The sample heated by above measurement is exposed to artificial gamma ray source after cooling and then the TL is measured in order to obtain TL sensitivity of the sample to radioactive sources.

(4) Natural dose rate of samples is assessed by the amounts of U, Th and K.

Basic theory and measuring procedure are very simple as described above. However, there are many factors which influence the dating results. Such problems are summarized in the

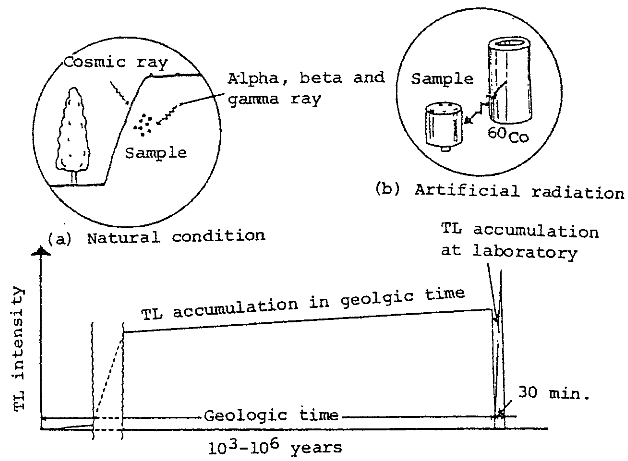


Fig. 3 Schematic explanation for TL dating.

book edited by McDougall (1968). Followings are the examples of them refered from that book and some other papers.

(1) Linearity of TL accumulation—The number of traps is limited in a crystal and in some cases unstable. Therefore, the TL accumulation is not linear as shown in Figure 4. Superlinear phenomenon sometimes occurs with artificial radiation which use high power radiation source but this occurs very rarely in natural condition. On the other hand, saturation of TL is common in natural samples and this determines the maximum age limit of TL dating. The best way to avoid this effect is to use non-saturated samples, whereas Zeller (1968) indicated the method of correcting this effect.

(2) Stability of captured electrons in traps —The probability of escape from a trap of depth E at temperature T(K) is given by the following equation.

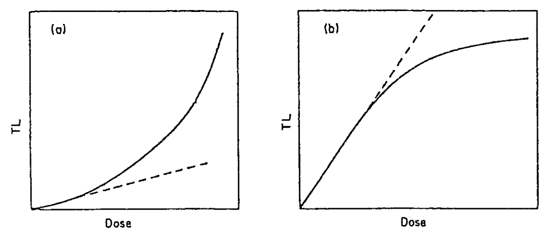


Fig. 4 Non-linearrity of TL growth. (a) Superlinear (b) Saturation.

$p=s\cdot\exp(-E/kT)$

Where the frequency factor s is about 10^{12} to 10^{13} sec^{-1}, Boltzmann's constant k equals 8.6×10^{-5} eV/K. Then the lifetime τ of an electron in such a trap is shown by the following equation.

$\tau=1/p=\exp(E/kT)/s$

If Tp(K) is the temperature at $\tau=1$ sec., then above equation is written as follows.

$\log_{10}\tau=((Tp/T)-1)\log_{10}(s)$

From this equation, the lifetime of TL glow of Tp(K) peak at the preservation temperature of 20 °C is calculated. For normal conditions and minerals, maximum limit of dating is over few million years. Figure 5 is the one example of that evaluation (Ikeya, 1981). The line in this figure is drawn by the conditions of s equals 3.3×10^{13} sec^{-1}. In the case of alteration, the trapped electrons are easily discharged at high temperatures during alteration.

(3) Evaluation of natural dose rate—Effective dose of radiation to the minerals is one of the important factors in TL dating. A mineral in the rock suffers alpha, beta, gamma and cosmic radiations as shown in Figure 6. Because of the difference in the character of each radiation, effectiveness to a crystal must be evaluated carefully. Alpha rays have the largest portion of radiation dose in rocks. However, the effective dose is small because alpha particles can travel only very short distances. Accordingly, dose from alpha rays

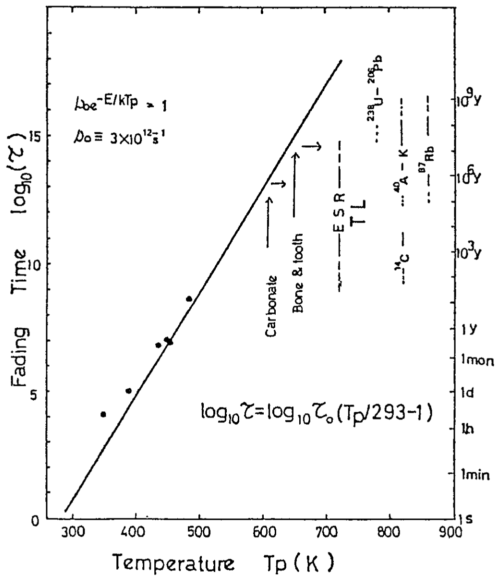


Fig. 5 Fading time of TL glow peak with temperature of Tp(K) kept at room temperature (After IKEYA, 1981).

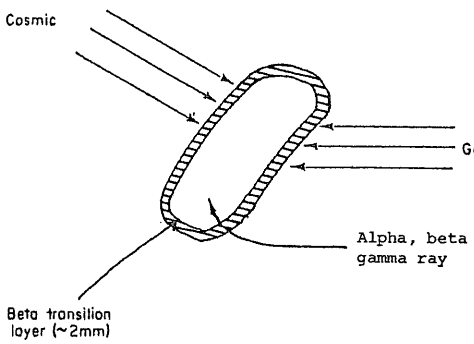


Fig. 6 Evaluation of effective radiation to minerals.

can be neglected in TL dating using large crystals like quartz or plagioclase phenocrysts. On the other hand, alpha ray contribution from U and Th in the crystals must be evaluated. In the case of quartz, the contents of U and Th in the crystals are very small and alpha ray contribution is negligible, but it may contribute to some extent in plagioclases.

(4) Artificial radiation—Normal radiation sources of X or gamma rays are different from the natural sources of radiation of alpha, beta and gamma rays with which the minerals were irradiated during geologic times. Therefore, the minerals sometimes show different response to different kinds of radiation sources. Especially, X-rays show inequivalent interaction with the minerals and are not suitable for use as artificial radiation sources (Table 1).

(5) Sample preparation—Crushing and grinding cause of artificial TL other than naturally Stored TL for some minerals. However, those TL of quartz are negligibly small and cause no problem for TL dating. The extra TL caused by sample preparation in plagioclase is slightly larger than that of quartz. These effects, however, cause only a few percent errors for relatively old rock samples. In some cases, the pre-heated rock is crushed, ground and measured its TL to compensate for this effect. For the younger aged samples, grain size must be carefully selected to reduce this effect.

(6) Oxidation TL of organic materials or sulphur—To prevent this phenomenon, nitrogen gas is introduced to the measuring chamber.

(7) Effect of pressure—The mineral placed under high pressure emits extra TL. This

Table 1 Efficency factor of absorption radioactivity.

Energy \ Materials	Water	Carbon	Aluminum	Calcium
0.02	0.881	0.341	5.32	21.0
0.05	0.892	0.511	3.98	17.0
0.10	0.948	0.801	1.39	4.17
1.0	0.965	0.869	0.828	0.865
10.0	0.935	0.826	1.007	1.21

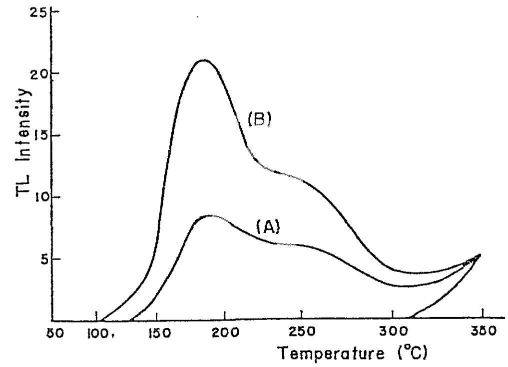


Fig. 7 TL measurement to the thermally unstable minerals. (A) Natural (B) Gamma ray assisted

phenomenon is significant with calcite but small for other minerals.

(8) Change of mineral characteristics—For TL measurements, minerals are heated above 500 °C which causes the change of their trap conditions in some cases. In order to prevent this effect, stable minerals such as quartz or plagioclases are selected for TL measurement. Another way is to evaluate the sensitivity by comparing natural TL with gamma ray assisted TL as shown in Figure 7.

(9) Others—Errors in chemical analysis, TL measurement, fading effect by sun or fluorescent light etc. must be considered.

II. 2 Apparatus

The laboratory equipments unique to TL dating and not used in normal geologic work are TL measuring devise and ^{60}Co gamma radiation systems.

In this work, TL was measured by two TL measuring instruments shown in Figures 8 and 9. The former (TLI–A) is a hand made electric furnace with a photomultiplier tube container and normal scientific instruments such as DC amplifier, recorder, high voltage supply and temperature controller. The latter (TLI–B) is the complete set for TL measurement used for medical or environmental radiation monitoring. The principles of the above two is almost same and schematic diagram is shown in Figure 10. The photomultiplier tube of TLI–A is interchangeable so that tubes with maximum efficiency for the particular wavelengths can be used. Photomultiplier tube of TLI–B cannot be changed but it is easy to operate and has a reference photo source excited by ^{14}C radiation. Therefore, most of the measurements were done by this TLI–B instrument except for some measurements specially commented. The name and major specifications of this instrument are as follows.

(1) Name: Kyokko type 1200 special version

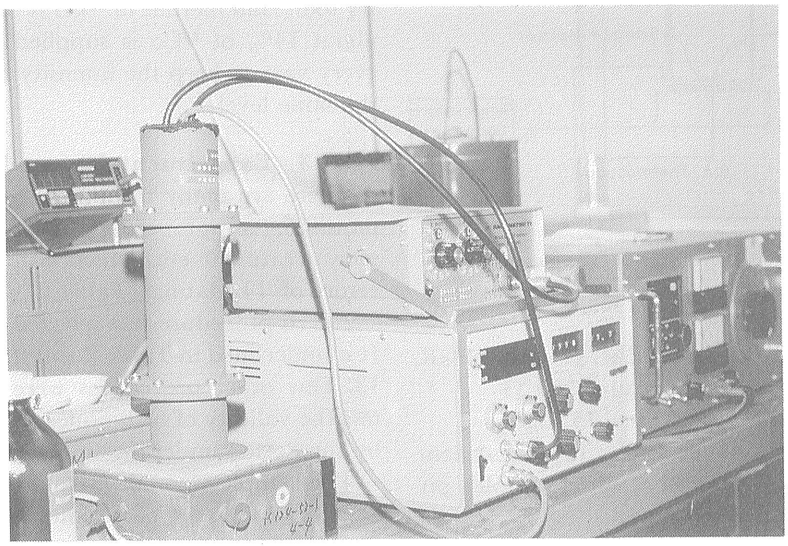


Fig. 8 TL measuring instrument (TLI–A).

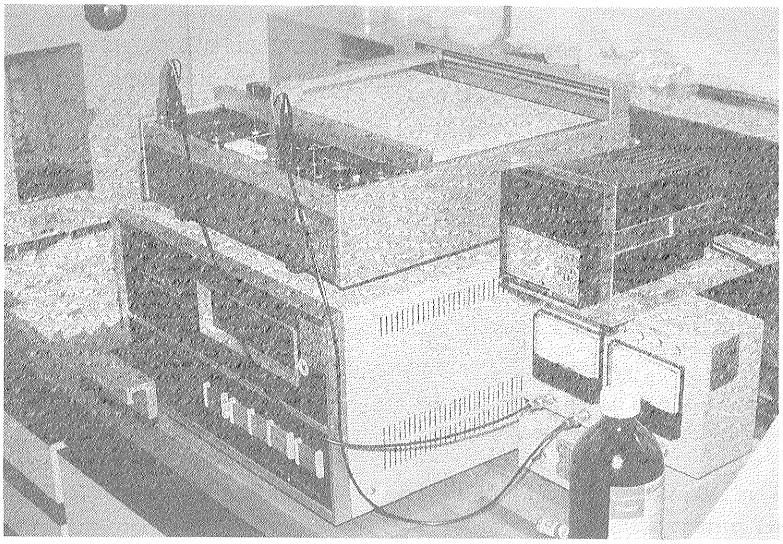


Fig. 9 TL measuring instrument (TLI-B).

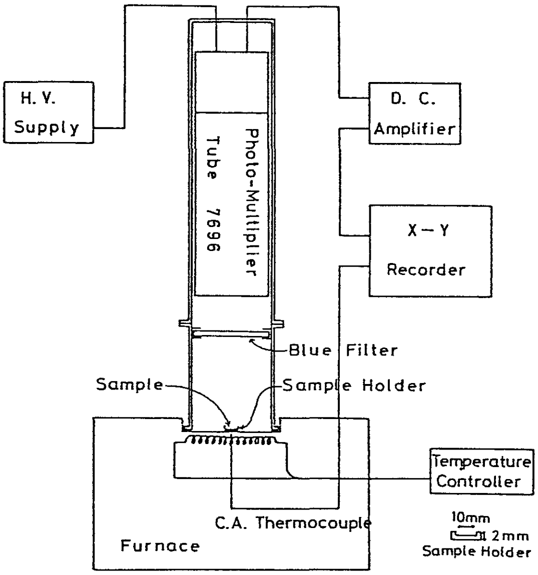


Fig. 10 Schmatic diagram of TL measuring instrument.

(2) Range of measurement: 0.1 mR–10 kR

(3) Maximum temperature: 560 °C

(4) Heating rate: 2 °C/sec–25 °C/sec

(5) Heating system: Direct heating system of plate heater (Fig. 11) with sample pit (10 mm in diameter)

(6) Photomultiplier tube: R-366 with maximum sensitivity at 340 nm.

(7) Calibration of glow: Standard light excited by ^{14}C

(8) Atmosphere of measuring chamber: Air or N_2 gas condition

Gamma ray source is 3,000 Curie of ^{60}Co and samples are set on the pit of the turntable. The pit and turntable are both rotating to equalize the radiation dose (Fig. 12). The dose rate is calibrated by TL dosimeter(TLD) system using synthesized BeO powder in glass capsule and TL dosimeter which are the standard dosimetry tool. Half lifetime of ^{60}Co is 5.2 years. Thus about 14% of ^{60}Co is supplied to the source every year to keep the intensity of radiation at the same level.

II. 3 Experimental procedure

There are many techniques for sample preparation, sample sizing, TL measurement, glow treatment etc. which will minimize the errors of TL dating (Table 2). However, one standard procedure was selected for this study. It is underlined in Table 2 and shown in Figure 13. Few other procedures were attempted to test the validity of techniques. They are shown by the dotted underlines in Table 2.

The sample was taken from non weathered part. The amount of samples was about 10 g to 1 kg which depend on the content of respective minerals and analytical methods of radio-

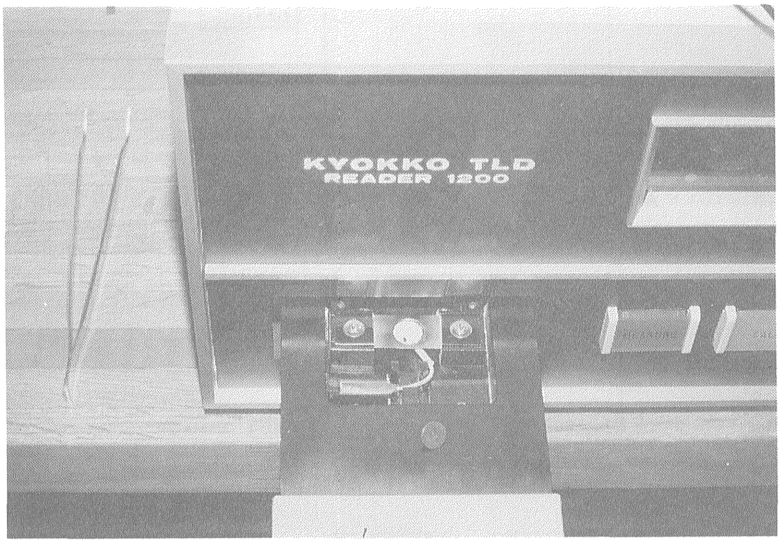


Fig. 11 Molybdenum heater with sample pit. Surface of sample powder is smoothed by stainless steel plate.

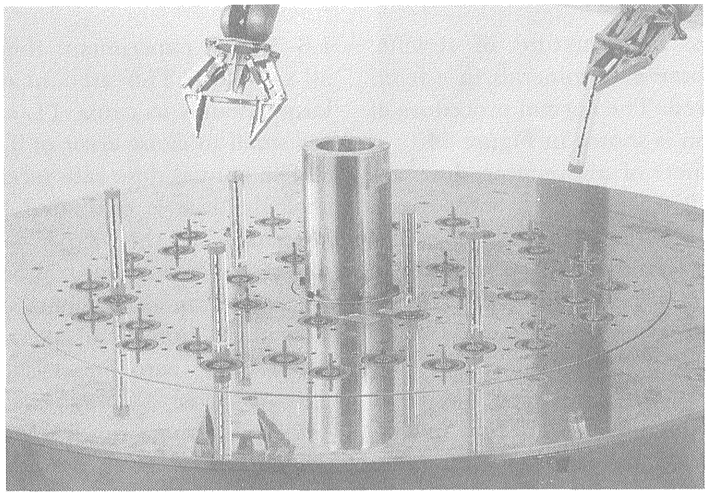


Fig. 12 Gamma ray radiation turntable. 3000 Curie of ^{60}Co are set in the center pole.

active elements. For example, in the case of alteration age determination of silicified rocks, quartz are easily gathered and U, Th and K are analyzed by wet processes, then the requirement of sample is less than 10 g. On the other hand, volcanic rocks with very small amount of plagioclases need 1 kg of samples.

Crush and sieve systems are also dependent on the samples. In the case of quartz or plagioclase phenocrystr with grain size of few millimeters, hand picking is the best way to obtain pure crystals. Therefore, samples are crushed so as to get maximum amount of 0.5 to 1 mm grains. For the altered rocks, it is better to selected over 74 microns grains to reduce unknown factors of alpha ray contribution to respective minerals. The minerals which have strong and stable TL character is desirable. In the present study, quartz and plagioclase phenocrysts in volcanic rocks and altered rocks,

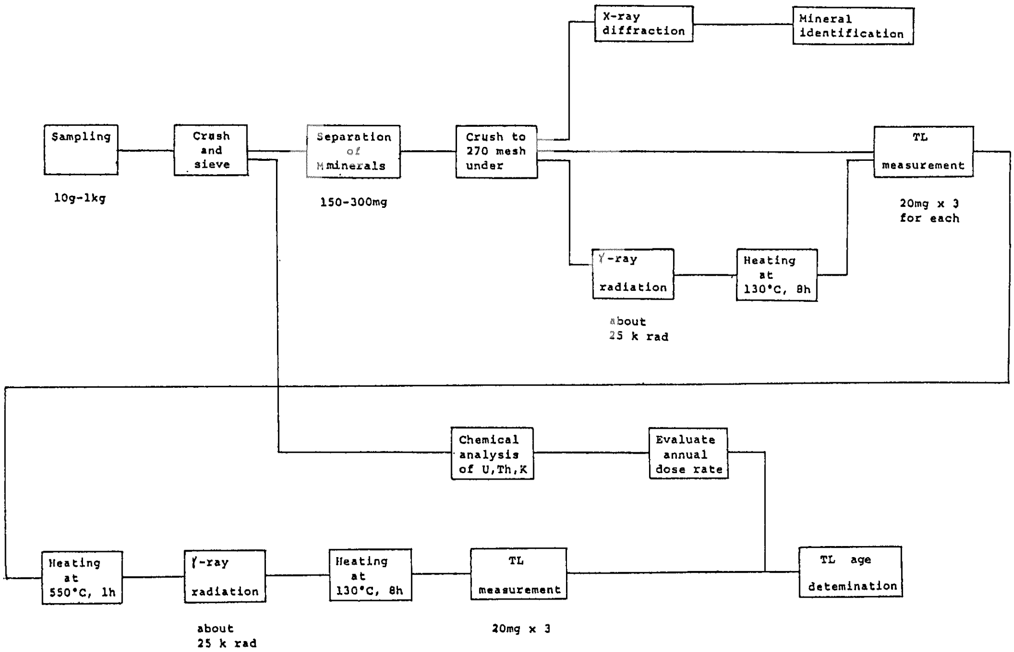


Fig. 13 Diagram of TL dating processes.

secondary quartz, and mixture of sericite, cristobalite and some clay minerals in altered rocks were measured. The normal procedure of sample preparation is shown in Figure 14.

The final products of above procedure are powders of under 270 mesh. These samples are used for X-ray diffraction, gamma ray radiation and TL measurement. The artificially radiated samples are heated at 130°C for 8 hours to reduce low energy (low temperature) glow.

Twenty milligrams of powdered sample is set in the sample pit which is 10 mm in diameter and smoothed by stainless steel plate (Fig. 11). TL value of each sample is the average of three measurements.

After measurement, the sample is heated at 550°C for one hour to discharge all trapped electrons. Approximately 100 mg of samples are sealed by aluminum foil and placed at the holder which is made by acrylic acid resin (Fig. 15) to get enough secondary electron balance. Then the holder is set 30 cm from the gamma ray source where gamma ray intensity is about 50 kR/h. The sample is exposed there for exactly 30 minutes to receive about 25 k rad as the absorption coefficient is assumed to be 1.0 (in this experiment, this value is used for all samples). This amount of radiation is not large enough to cause TL saturation and not too small to cause error of TL measurement.

The annual dose rate received by crystals in geologic time is evaluated by U, Th and K contents. In this experiment, gamma ray spectrometry and wet process are used for determination of contents of those elements. The interaction of alpha ray fraction is supposed to be zero for crystals larger than 74 microns (over 200 mesh). The effectiveness of beta and gamma ray fractions is evaluated by the work of Bell (1976) and shown in Table 3.

In this experiment, ages are obtained by reference curve of the specific TL intensity which is normalized by TL sensitivity and annual dose rate versus their ages determined by other methods (Refer to Fig. 26 and Table 6 in chapter III). The reason for the above treatment is that the natural sample is irradiated long enough to the state of TL stability whereas artificial TL is not stable and changes its intensity corresponding to the conditions of heating treatment before measurement (normally 130°C and 8 hours). This means that the apparent sensitivity in the excitement by

Table 2 The variation of sample processing and measurement in TL dating.

Sample preparation	Sample size	TL measurement	TL glow treatment	Artificial radiation	Annual dose evaluation
Separation	Larger than 74 microns	Atmosphere (1) Air (2) Ar (3) N_2	Area	Source (1) Beta (2) Gamma (3) X-ray	Chemical analysis (1) Wet process (2) Gamma ray spectrometry (3) SIMS (4) Others
Slide to thin section	Less than 74 microns	Grain size (1) Less than 74 microns (2) 74 to 250 microns (3) Thin section	Peak height	Radiation sample (1) Heated sample (2) Natural sample	
Non-separation		Weave length (1) Visible (2) Ultra-violet	Plateau		In situ measurement TLD method

(1) The items with underline are mainly used in this report. (2) The items with dashed underline are partly used in this report.

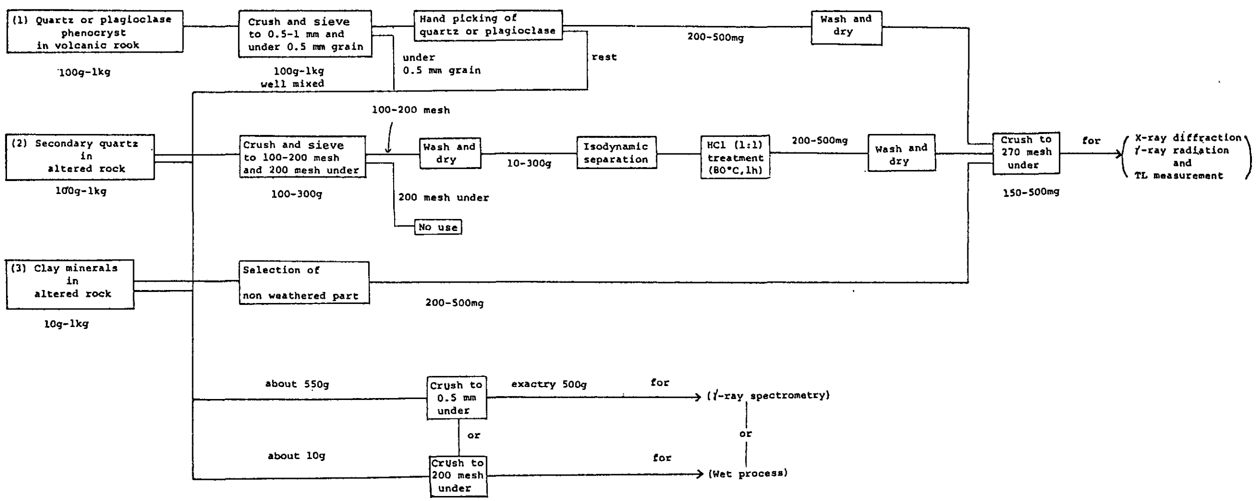


Fig. 14 Diagram of sample preparing processes.

natural and artificial sources is different. However, the ratios of the above two are almost always the same if the heating conditions do not change. Therefore, the ratio of glow is used for TL age determination.

II. 4 Test of varidity of TL dating

For the confirmation of initial values of the

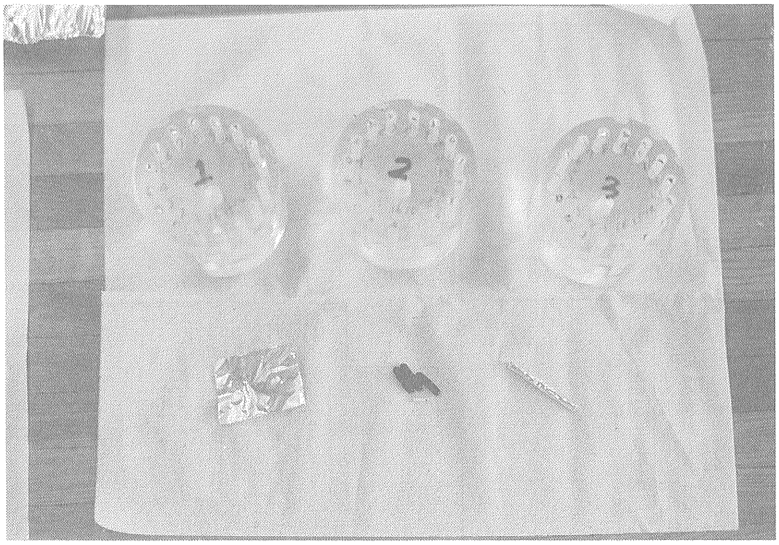


Fig. 15 Acrylic acid resin sample holder for gamma ray radiation. In front of holder, TLD capsule and enveloped samples are placed.

Table 3 Radiation dose rate of U, Th, K (After BELL, 1976).

Element	Content	Radioactive Ray	Radiation Dose (rad/y)		
U	1 ppm	α	0.2783	0.3056 (total)	0.0273 (α≒0)
		β	0.0146		
		γ	0.0127		
Th	1 ppm	α	0.0740	0.0819 (total)	0.0079 (α=0)
		β	0.0029		
		γ	0.0050		
K	1 % (K_2O)	β	0.0682	0.0887 (total)	—
		γ	0.0205		

samples, TL values of synthesized quartz and quartz separated from central cone lava of Akita Yakeyama were measured (Fig. 16). Former sample was synthesized in an autoclave at 230 °C and for two weeks. The starting material was amorphous silica reagent for gas chromatography and reacting fluid was 0.1 Mol. of NaOH solution. The central cone lava from which quartz crystal was separated is considered to be the youngest eruption product of that volcanic group. The exact age is unknown but younger that 26,900 years by ^{14}C dating of related formations in Tamagawa hot spring area (SUMI and TAKASHIMA, 1972).

The intensity of TL glow for synthesized quartz is very weak whereas that of original amorphous silica is relatively large (Fig. 16-a). Also, the TL amount of quartz from Akita Yakeyama is weak (Fig. 16-b). This figure shows three different TL patterns of samples with different pre-treatment. The first is the 100–200 mesh grain with no grinding. The second is the −270 mesh sample with grinding by agate mortal and sieved. The third is the sample heated at 550 °C for 1 hour for discharging all stored TL then crushed and sieved to −270 mesh. It is clear that the fine grinding is the cause of error for TL measurement and not suitable for young and low TL samples. However, fine grinding of samples reduces the error of TL emission itself. Therefore, the selection of pre-treatment process is dependent

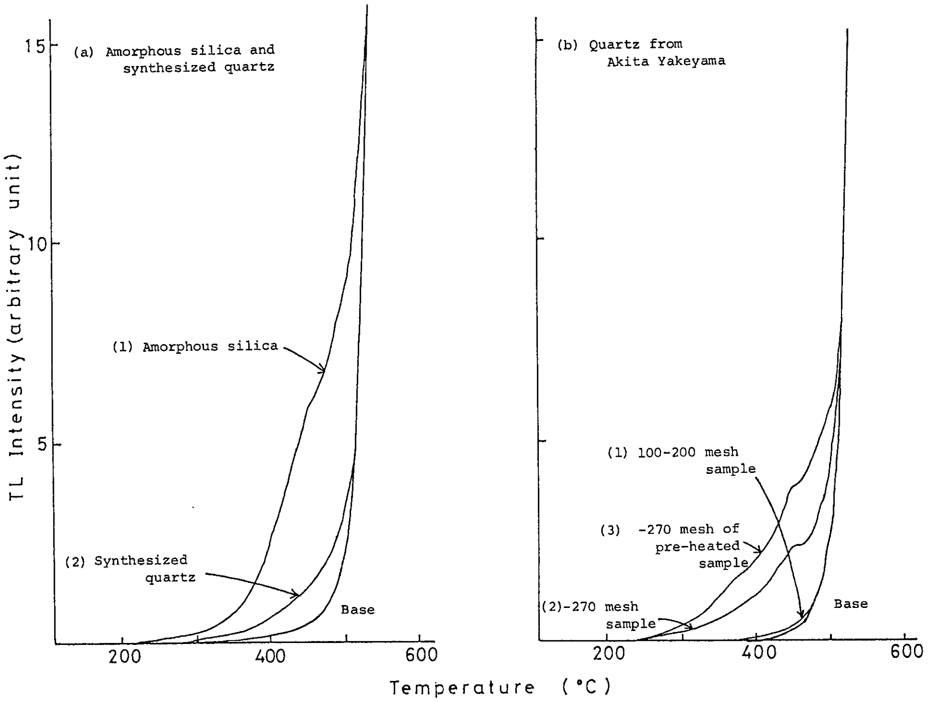


Fig. 16 TL glow curves for synthesized quartz and quartz from Yakeyama central cone lava.

on the age of respective samples.

TL saturation was not tested. However, it is about 5×10^6 rad for normal quartz phenocrysts (INAGAKI, 1972). This is equivalent to the order of few million years because the annual dose rate of normal volcanic rocks is less than 0.7 rad/year.

The effects of the grain size, sample weight, fading and grinding are alredy discussed and sum of them were less than 5% of natural TL glow (TAKASHIMA, 1979).

For the estimation of the temperature effect during alteration to TL glow of quartz crystals, the sample was heated from 150 to 300 °C for one or two days. The change of TL glows is shown in Figure 17. This shows that the TL glow decrease rapidly at 300 °C and it may disappear after long duration of time even at 200 °C. Therefore, the quartz crystals which suffered hydrothermal alteration and kept at about 200 °C for a long time will lose all TL which was accumulated before alteration. As this was proved experimentally, the TL ages of altered samples correspond to alteration ages. This is the basis for alteration age determination by TL measurement (TAKASHIMA, 1979).

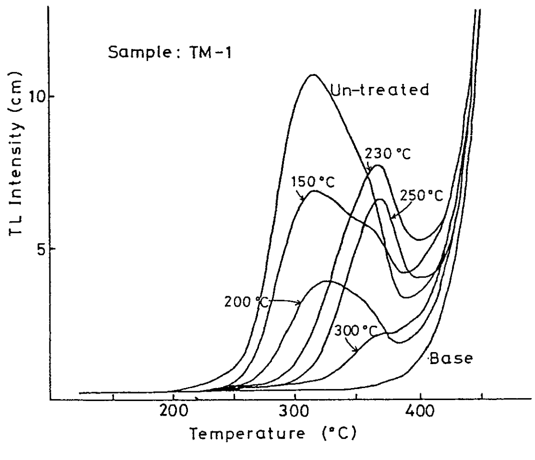


Fig. 17 Changes of TL glow curves by heating (After TAKASHIMA, 1979).

There are two ways to evaluate TL intensity. The first is the measurement of total area of glow curve and the other is the peak height of specific temperature. Figure 18 is the reference

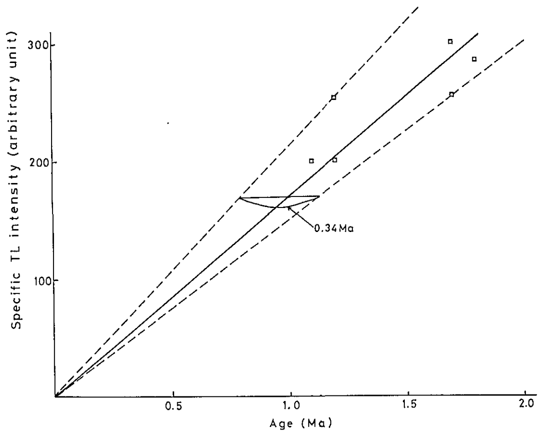


Fig. 18 The relation between specific TL intensity and FT age. Specific TL intensity is calculated by the peak height of artificial glow.

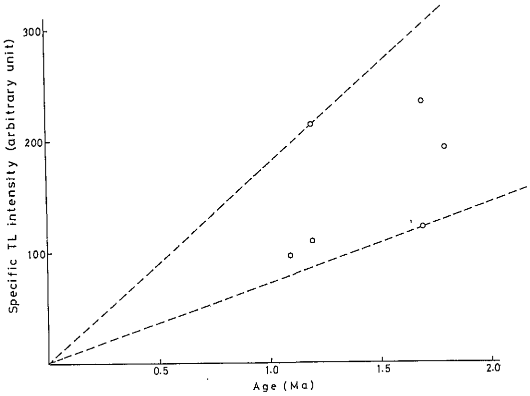


Fig. 20 The relation between specific TL intensity and FT age. Specific TL intensity is calculated by the annual dose rate of TLD capsule.

curve drawn by the same way as Figure 26, but use the peak height of artificial TL. The results seemed to be almost the same or slightly better than Figure 26. However, it is very difficult to identify the peak position in some samples. Therefore, TL glow area is used for the evaluation of specific TL except for some special samples.

Evaluation of annual dose rate is very important factor in TL dating. In some cases, it is measured by TLD capsules set in rock or rock powder. The TLD capsule used in this measurement is a small glass tube containing synthesized $CaSO_4$ powder doped by trace of Tm and can detect less than 1 milli rad of radiation. The normal procedure of this measurement is very simple. Few TLD capsules are set in the pit of outcrop where the sample is collected or are set in powdered rocks which are covered by lead container to prevent environmental radioactivities (Fig. 19). They are left for about one to six months and then the total radiation received is measured by a TLD dosimeter. Figure 20 is the reference curve drawn by the use of annual dose rate evaluation of this powdered rock TLD method. The line is not as good as that of Figure 26 which was drawn by the data of gamma ray spectroscopic analysis. The reason for this discrepancy is considered to be an error in beta ray counting in a TLD capsule which can detect only a part of beta rays because it is covered by glass.

There are many kinds of patterns in TL glow curves even for the same kind of minerals. For quartz crystals, difference in TL patterns of some Japanese samples are reported (HAYAKAWA *et al.*, 1976). These phenomena

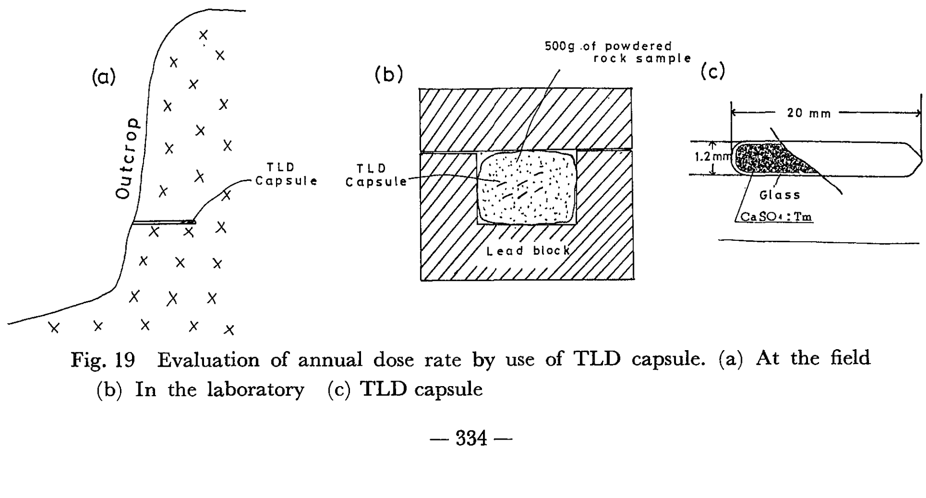


Fig. 19 Evaluation of annual dose rate by use of TLD capsule. (a) At the field (b) In the laboratory (c) TLD capsule

are conspicuous in artificially radiated samples. The theoretical basis of this diversity is very complex and it is difficult to find suitable resolution for TL dating. The simplest way to prevent it is to use only the samples which show the similar patterns in both natural and artificial TL.

The influence of impurity in samples is tested for TM–1 which is not well separated and contain few percent of clay fractions. The color of powdered sample is not as white as that of pure quartz and TL intensity is smaller than pure quartz sample. However, the TL age is almost the same as the pure quartz sample No. 1 in Table 6.

Same as the case of quartz phenocrysts, check of initial TL values of plagioclase phenocrysts were carried out for lavas from Komagatake, Akita Prefecture and Yufudake, Oita Prefecture. Former lava is the product of eruption in 1970 and latter one is the product of the latest Quaternary activity. Figure 21 is the TL glow curves of above samples.

Figure 21-a is the three TL glow curves of plagioclases separated from the same lava but different in procedure as already described in the dating of quartz phenocrysts. The results are almost the same as quartz but slightly higher TL values are observed for finely ground samples and even for 100–200 mesh grains whereas near zero TL values are expected because the age of this sample is only 12 years. Therefore, special attention must be taken for the plagioclase samples. Especially in the case of dating of young volcanic rocks, the techniques to reduce or compensate for this effect must be applied. The examples are the use of relatively coarse grained samples to TL measurement or TL measurement of preheated samples with the same separation and crushing procedure to natural samples for compensate above effect. The TL glows of plagioclases collected from Yufudake show almost the same results as Komagatake but slightly higher TL value than the Komagatake samples because the age is in the order of few tens of thousand years.

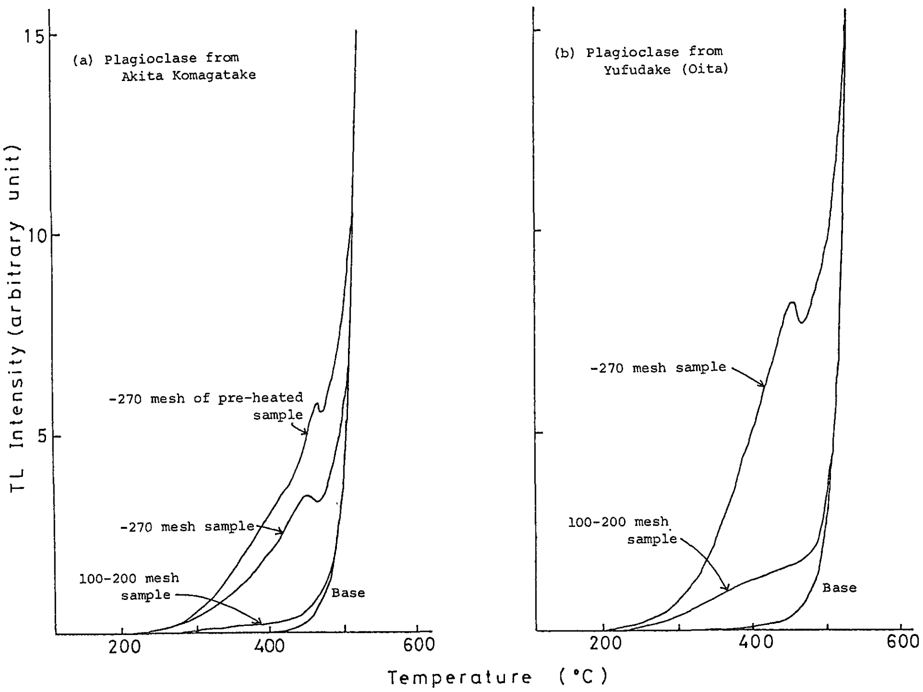


Fig. 21 TL glow curves for plagioclases from Komagatake and Yufudake lavas.

III. TL dating of volcanic and altered rocks

III. 1 Dating of volcanic rocks by quartz phenocrysts

III. 1. 1 Location and description of samples

The most suitable mineral for TL dating is quartz because of its thermal stability, purity in chemical composition, high TL sensitivity and relatively wide distribution in volcanic and altered rocks. In this section, TL dating of volcanic rocks mainly by quartz phenocrysts is described. The samples were collected from Tamagawa Welded Tuff, which is distributed around Hachimantai geothermal field, Akita and Iwate Prefectures, and dacitic pyroclastic flow and dacite lava of Kurofuji volcano, Yamanashi Prefecture. The sampling points of both fields are shown in Figures. 22 and 23.

Tamagawa Welded Tuff is the rhyo-dacitic tuff formation of early Pleistocene. This welded tuff is widely distributed in and around Hachimantai geothermal field and the residual magma is believed to be a part of heat source of geothermal activities. The rock has large amount of quartz phenocrysts and their size is about 5 to 10 mm. It is very convenient for separation of pure quartz.

The ages of Tamagawa Welded Tuff were assigned to 1.1 to 2.0 Ma by FT method

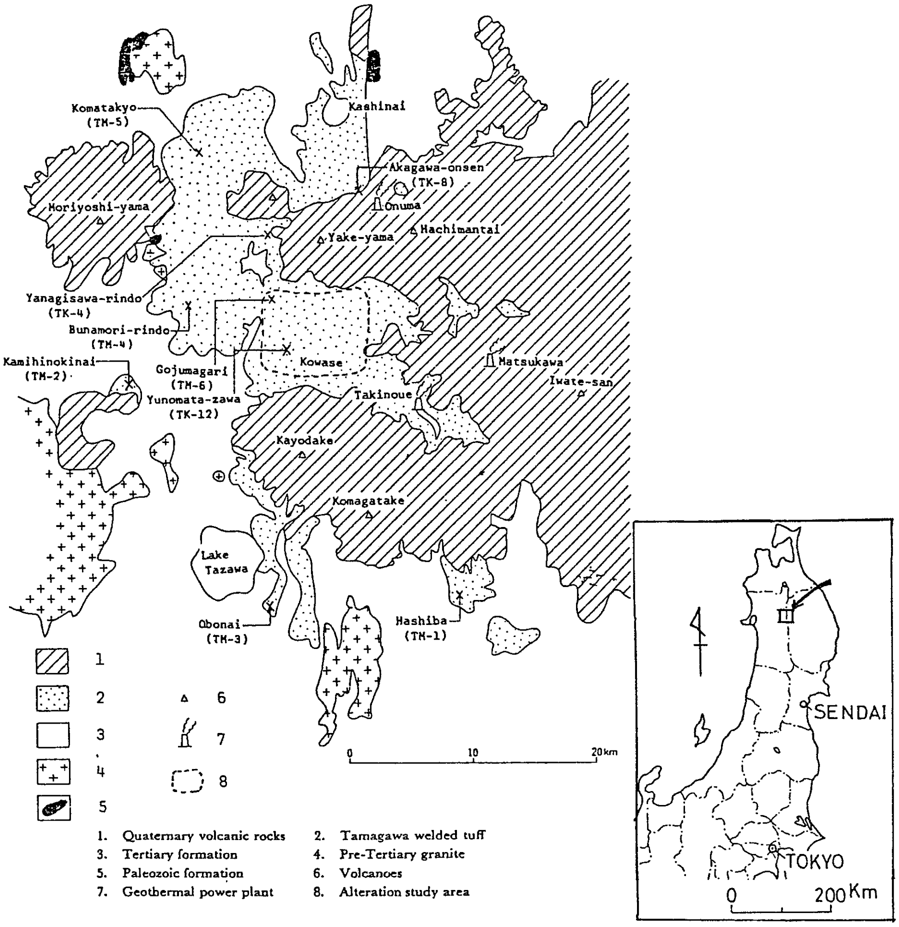


Fig. 22 Simplified geologic map with locality of TL dating samples of Hachimantai area (After TAMANYU and SUTO, 1978).

(TAMANYU and SUTO, 1978). In this study, the same rocks were used and reference curve of age versus specific TL intensity was drawn from these data. Table 4 is the outline of stratigraphy with sampled positions.

Kurofuji vlocano is one of the typical Quaternary volcanoes whose ages are unknown. The samples for TL measurement were collected from dacitic pyroclastic rocks shown in Table 5 (MIMURA, unpublished data). These rocks have quartz phenocrysts of few millimeter in size and easy to separate them. However, as the sizeis smaller than Tamagawa Welded Tuff, plagioclase particles were mixed with quartz in some case.

III. 1. 2 Experimental results

Samples were processed and measured by the flow chart shown in Figures. 13 and 14 and techniques described in section II. 3. The glow curves of typical samples for both Tamagawa Welded Tuff and Kurofuji volcanic rocks are shown in Figurs. 24 and 25. The conditions of these TL measurements were as follows.

(1) Temperature range: Room temperature to 560°C

(2) Heating rate: 350°C/min.

(3) Atmosphere of measring chamber: Air

For the determination of annual dose rate, chemical analyses of U, Th and K were carried out by the gamma ray spectrometry or wet process. The radiation dose rate of each element of unit content is shown in Table 3 which was evaluated by BELL's method (1976). The results of chemical analysis, annual dose rate evalua-

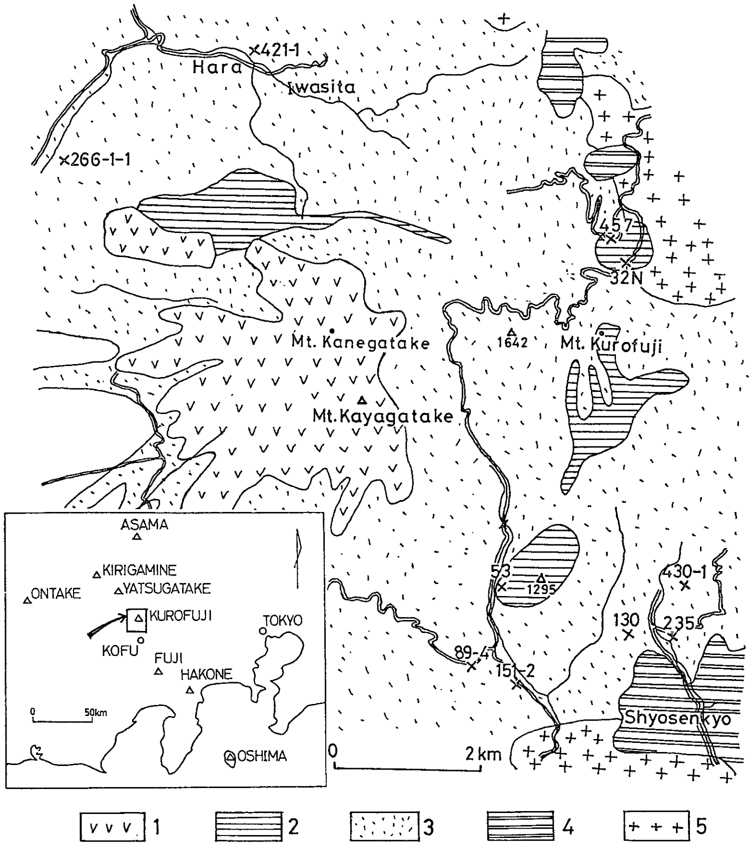


Fig. 23 Simplified geologic map with locality of TL dating samples of Kurofuji area (After MIMURA, 1967). 1: Younger volcanics 2: Lava domes and dikes of Kurofuji volcano 3: Pyroclastic flow of Kurofuji volcano 4: Tertiary volcanics 5: Cretaceous granite

Table 4 Stratigraphic sequence of Tamagawa Welded Tuff (After Tamanyu and Suto, 1978).

Geologic time		Formation	
Quaternary	Holocene	Andesitic volcanic rocks	
Quaternary	Pleistocene	Upper dacitic WT (TK-4)	
Quaternary	Pleistocene	Middle rhyolitic WT (TM-3,TM-5)	Upper rhyolitic WT (TM-1,TM-2,TM-6) Middle rhyolitic WT
Quaternary	Pleistocene	Lower dacitic WT	Lower rhyolitic WT (TM-4)
Tertiary	Miocene-Pliocene	Tertiary formation	

Table 5 Stratigraphic sequence of Kurofuji volcanoes (Mimura, unpublished data).

Geologic time	Formation	Sample No.	TL age (Ma)*1 A	TL age (Ma)*1 B
Quaternary	Lava domes and dikes	53	(0.95)	
		457	0.62	
		32 N	0.77	
	Pyroclastic flow (5 th stage)			
	〃 (4 th stage)	89-4	(0.86)	
	〃 (3 rd stage)	151-2	0.78	
		430-1	(1.19)	
		421-1	0.72	
	〃 (2 nd stage)	130	1.18	
		235	0.99	
	〃 (1 st stage)	266-1-1	1.05	

*1 Age A is obtained by the reference curve of Fig. 26.

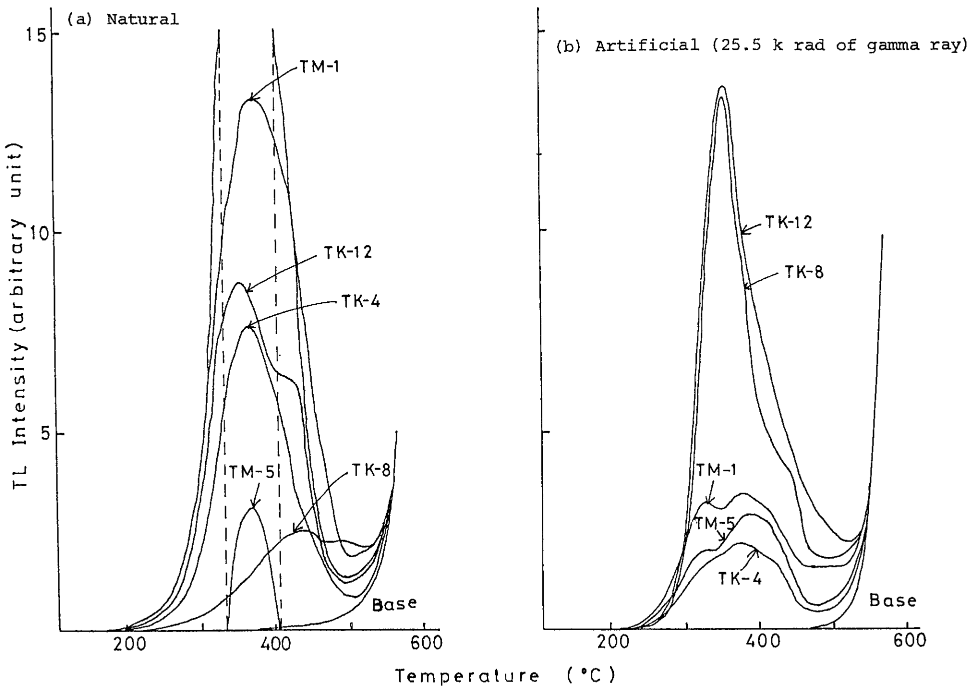


Fig. 24 TL glow curves for quartz from Tamagawa Welded Tuff.

Table 6 Summary of TL dating of Tamagawa Welded Tuff.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			F T		
1	TM-1	Q	1.2	4.0	1.48	0.1957	1324.5		288.5		23.46	1.1		
2	TK-4	Q	0.8	2.7	1.11	0.1416	774.4		142.0		38.51	1.2		
3	TM-2	Q	2.2	6.8	2.37	0.3240	1594.4		191.6		25.68	1.2		
4	TM-3	Q	1.2	4.8	1.62	0.2144	1153.3		176.6		30.46	1.7		
5	TM-4	Q	1.4	4.7	1.48	0.2066	1713.3		197.8		41.93	1.7		
6	TM-5	Q	1.3	4.4	1.55	0.2078	1694.1		176.0		46.32	1.8		
7	TM-6	Q	1.3	4.0	2.13	0.2560	468.6		214.4		8.56	2.0		Altered
8	TK-8	Q	1.5	5.6	4.46	0.4808	297.5		576.0		1.07			Altered
9	TK-12	Q	2.0	7.1	4.21	0.4841	953.7		665.7		2.96			Altered
10	TM-1(T)	Q+Clay	1.2	4.0	1.48	0.1957	1103.5		119.5		28.26			Test

(Chemical analysis: Gamma ray spectrometry by H. KANAYA)

*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.

*2 FT ages are reported by TAMANYU and SUTO (1978) and samples of TL measurement are same as FT dating ones.

Table 7 Summary of TL dating of Kurofuji volcanic rocks.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	053	Q.Cr.Pl	0.5	0.3	1.04	0.1083	541.2		219.8		22.74	0.95		
2	457	Q.Pl	0.5	0.4	1.17	0.1206	265.8		150.3		14.66	0.62		
3	32N	Q	0.6	0.6	1.41	0.1462	461.8		172.5		18.31	0.77		
4	89-4	Q.Pl	0.5	0.4	1.24	0.1268	454.0		174.6		20.51	0.86		
5	151-2	Q	0.7	0.6	1.36	0.1445	491.8		183.9		18.51	0.78		
6	430-1	Q.Pl	0.7	0.5	1.63	0.1676	606.4		127.4		28.40	1.19		
7	421-1	Q.Pl	0.7	0.4	1.33	0.1403	513.2		211.0		17.34	0.72		
8	130	Q.Pl	0.3	0.4	1.21	0.1187	410.8		123.0		28.14	1.18		
9	235	Q.Pl	0.9	0.4	1.33	0.1457	526.8		153.1		23.62	0.99		
10	266-1-1	Q.Pl	1.2	0.4	1.24	0.1459	714.2		194.6		25.15	1.05		

(Chemical analysis: Wet process by Mitsubishi Metal Research Institute)

*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.

*2 Age A is obtained by the reference curve of Fig. 26.

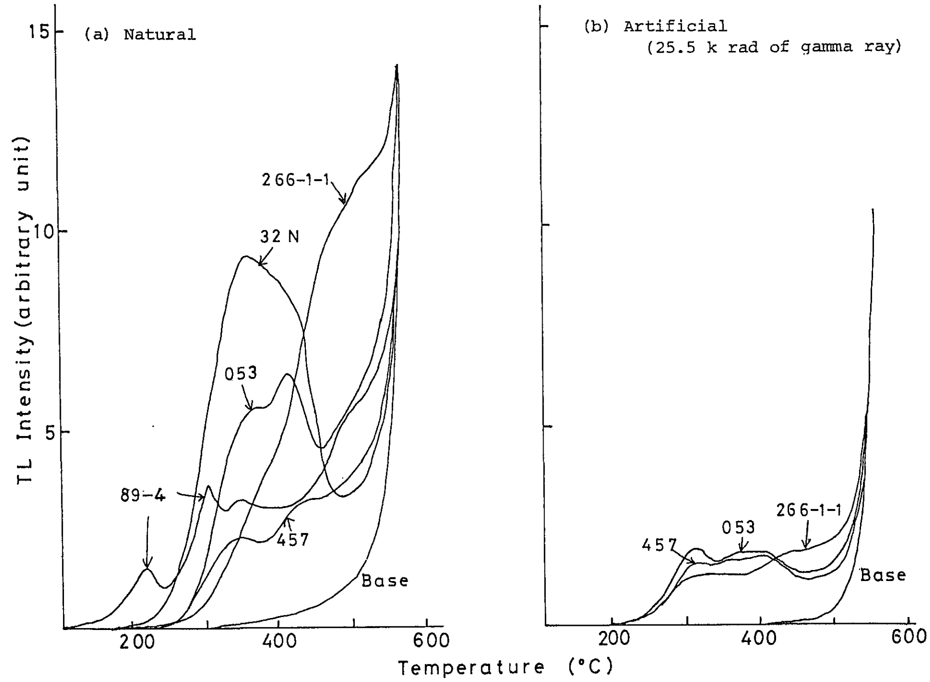


Fig. 25 TL glow curves for quartz (+plagioclase) from Kurofuji volcanic rocks.

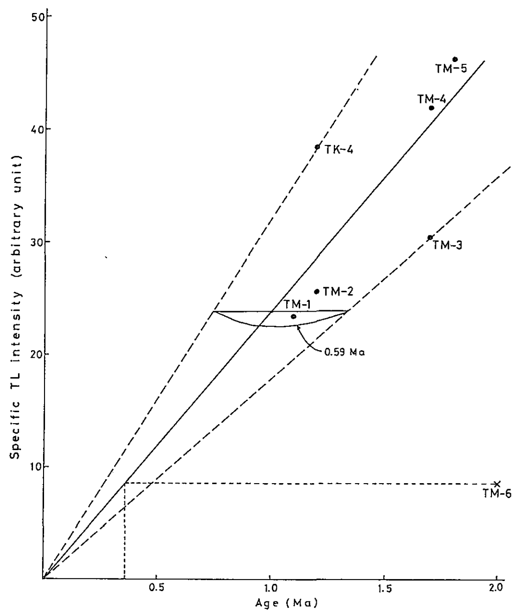


Fig. 26 The relation between specific TL intensity and FT age of Tamagawa Welded Tuff.

tion and TL measurement of both areas are shown in Tables 6 and 7.

Figure 26 is the reference curve of specific TL versus FT ages. Although it does not show good linearity because there are possibilities of errors in both FT and TL methods, this figure is used as the standard for evaluating the ages of other areas if there are no age known data among them. The ages of Kurofuji volcano shown Table 7 are thus obtained.

III. 2 Dating of volcanic rocks by plagioclase phenocrysts

III. 2. 1 Location and description of samples

Plagioclase is one of the most common rock forming minerals in volcanic rocks. Therefore, plagioclase must be widely used for TL dating of volcanic rocks in geothermal fields where the ages are important for geothermal exploration (TAKASHIMA, 1982b). However, plagioclases alter easily, contain more radiogenic elements in crystals which increase the difficulty in annual dose evaluation, fades anomalously (WINTLE, 1977) and are easy to saturate compared to quartz. The upper limit of TL ages is about 0.2 Ma by normal procedure using plagioclase in Hawaiian basalts from TL

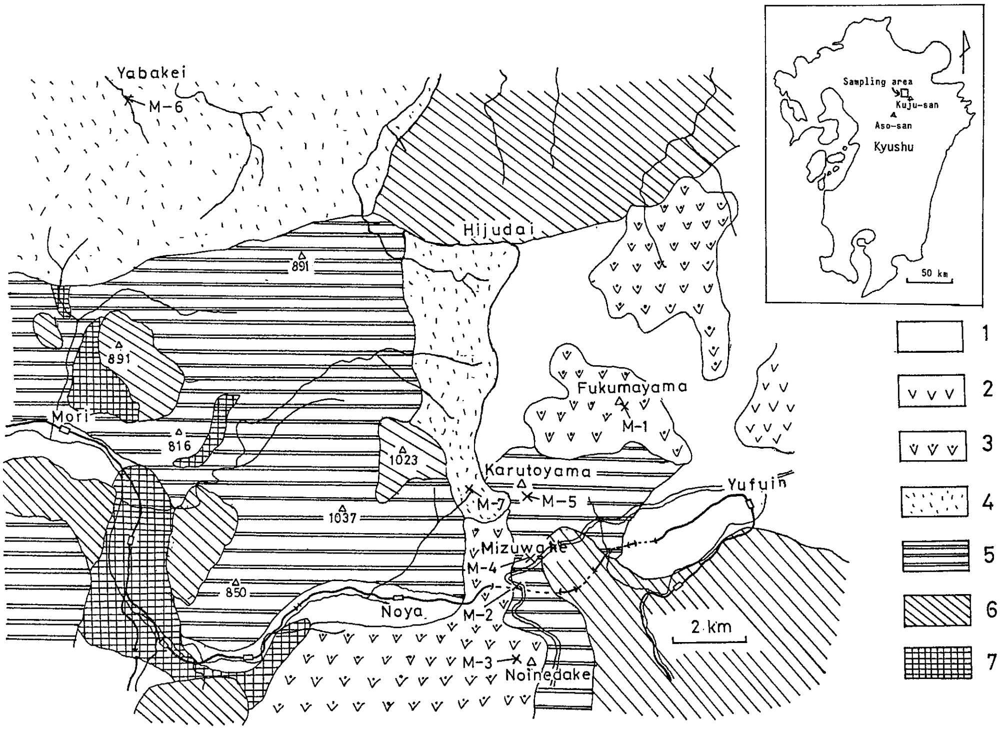


Fig. 27 Simplified geologic map with locality of TL dating samples of Noya area (After GEOLOGICAL SURVEY of JAPAN, 1982).
1: Aso pyroclastic flow, fan and talus deposits and alluvium 2: Late Kuju volcano 3: Early Kuju volcano 4: Yabakei welded tuff 5: Bungo volcanics 6: Hohi volcanics 7: Kusu group

saturation (MAY, 1977). In some cases, TL of plagioclase is used for the determination of weathering grade (OGELMAN and KAPUR, 1982). For preventing these effects, the plateau method which detects stable high temperature glow by photomultiplier with ultra violet zone and treats that stable glow is effective (GUÉRIN and VALLADES, 1980).

In this section, the validity and upper limit of TL dating of plagiocases are discussed for the volcanic rocks from Noya geothermal area, Oita Prefecture based on the work of TAKASHIMA (1982a). Figure 27 is the locality map of samples and Table 8 is the outline of stratigraphy, rock type and age data with sample number.

III. 2. 2 Experimental results

The conditions of measurement are the same as quartz except for the additional measurement of gamma ray assisted samples for TL saturation check.

Figure 28 is some examples of TL glow curves of natural, gamma ray assisted and artificially radiated samples. The radiation dose rate of 10.35 k rad is smaller than the normal amount of 25 k rad in other experiments. Therefore, the reference line of Tamagawa Welded Tuff are drawn by the results under the same conditions (Fig. 29). The TL glow of plagioclase has its peak at higher temperature than quartz which is very close to base line of high temperature area. Because of this character of TL glow, TL measurement of plagioclase must be continued to higher temperature than quartz in order to discharge all accumulated TL in geologic time and artificial radiation.

Table 9 is the summary of TL dating of plagioclases with the TL dating data of Tamagawa Welded Tuff. Chemical analyses were done by gamma ray spectroscopic method for all samples.

Table 8 Stratigraphic sequence of Noya geothermal area (After TAKASHIMA and MURAOKA, 1980).

Geologic time		Stratigraphy		Lithrology	Sample No.	Age (Ma)	
						TL	others
Quaternary	Pleistocene	Handa pmice flow		Hornblende dacite			
		Aso welded tuff		Pyroxene andesite			
		Lower kuju	Fokuma-yama lava	Hornblende andesite	MZ 78102701	(0.78)	
			Noine dake lava	Hornblende andesite	MZ 78102801 MZ 78102802	0.43 0.48	0.4(FT,Same sample) 1)
			Karuto-yama lava	Hornblende andesite	MZ 78102702	0.27	0.38(FT,Same sample) 2) 1.9(K-Ar) 3)
		Yabakei welded tuff		Hornblende andesite	MZ 78101201 MZ 78102703	0.35 0.24	0.4(FT) 4)
		Haneyama lava		Biotite-hornblende rhyolite, dacite	MZ 78110401	0.47	0.41-0.53(K-Ar,FT) 5)
		Hyugami lava		Hornblende andesite			
		Hohi volcanic complex		Pyroxene andesite			

1) TAKASHIMA (1980b) 2) TAKASHIMA (Unpublished data) 3) WATANABE *et al.* (1981)
4) MATSUMOTO *et al.* (1977) 5) MATSUMOTO *et al.* (1977), Iso and IKEDA (1979)

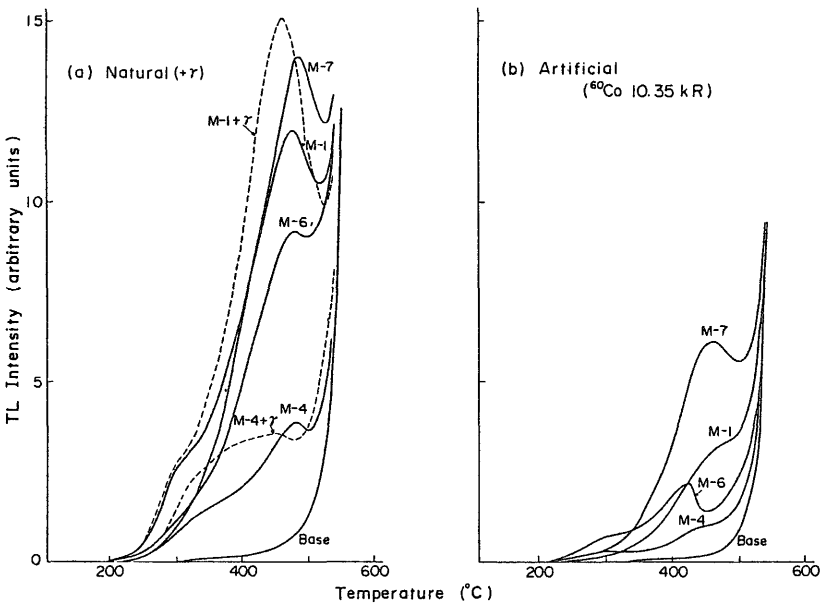


Fig. 28 TL glow curves of plagioclase from volcanic rocks of Noya area (After TAKASHIMA, 1982 a).

Table 9 Summary of TL dating of Quaternary volcanic rocks in Noya geothermal area (After TAKASHIMA, 1982 a).

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) original	(B) γ-assist	(C) Artificial			A	B	
M-1	MZ 78102701	Plagioclase	0.9	3.7	1.65	0.2036	791.2	906.4	155.2	0.74	25.04	0.66	0.78	
2	〃 102801	〃	1.4	6.2	2.42	0.3080	529.6	539.6	123.9	0.08	13.88	0.37	0.43	
3	〃 102802	〃	1.2	4.9	1.87	0.2418	845.0	866.4	226.3	0.10	15.44	0.41	0.48	
4	〃 110401	〃	1.4	5.5	2.06	0.2693	213.2	268.7	52.4	1.06	15.11	0.40	0.47	Age standard for B
5	〃 102702	〃	1.2	5.2	2.01	0.2572	530.0	712.6	230.2	0.79	8.95	0.23	0.27	
6	〃 101201	〃	1.4	7.5	2.28	0.3082	595.2	704.4	168.2	0.65	11.48	0.30	0.35	
7	〃 102703	〃	2.0	8.6	2.74	0.3739	831.6	992.4	281.4	0.57	7.90	0.20	0.24	
T-1	TM-1	Quartz	1.2	4.0	1.48	0.1957	1324.5	1327.3	153.8	0.02	44.01	(1.1)*3		
2	TK-4	〃	0.8	2.7	1.11	0.1416	774.4	867.6	114.8	0.81	47.64	(1.2)		
3	TM-2	〃	2.2	6.8	2.37	0.3240	1591.4	1641.0	152.8	0.30	32.21	(1.2)		
4	TM-3	〃	1.2	4.8	1.62	0.2144	1153.3	1195.6	108.1	0.39	49.76	(1.7)		
5	TM-4	〃	1.4	4.7	1.48	0.2066	1713.3	1699.2	184.7	—	44.90	(1.7)		
6	TM-5	〃	1.3	4.4	1.55	0.2078	1694.1	1797.6	110.5	0.94	73.78	(1.8)		

(Chemical analysis: Gamma ray spectrometry by H. KANAYA)
*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.
*2 Age A is calculated by the results of Tamagawa Welded Tuff and age B is calculated by that of M-4.
*3 Fission-track data of Tamagawa Welded Tuff (TAMANYU and SUTO, 1978).

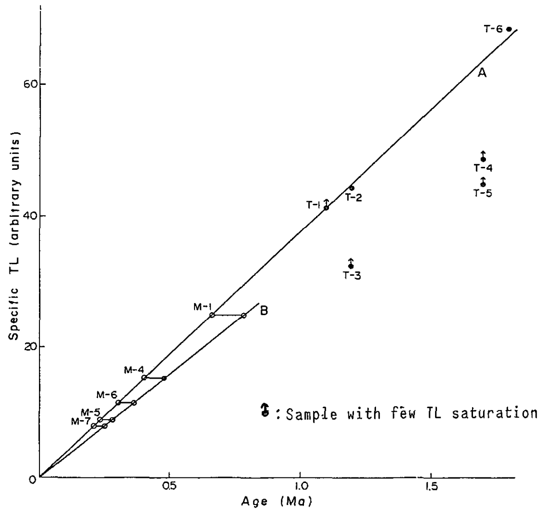


Fig. 29 Relation between specific TL intensity and FT age. Line A is drawn from Tamagawa Welded Tuffs and line B is drawn from average of FT and K–Ar ages of M–4 sample (After TAKASHIMA, 1982a).

III. 3 Determination of alteration ages by secondary quartz

III. 3. 1 Location and description of samples

The quartz samples for alteration age determination are secondary quartz in altered rocks from silicified zone and in some cases residual phenocrysts in altered dacite or rhyolite. The areas of study in this section are Kurikoma, Iwate Prefecture and Azuma, Yamagata Prefecture, both are well known geothermal areas. The sampled locations of the two areas are shown in Figures 30 and 31. All samples were collected from strongly silicified altered rocks.

The original rocks of Kurikoma and Azuma areas are Quaternary lava (no. 1 sample in Fig. 30 and nos. 1 to 5 in Fig. 31) and Tertiary green tuff formation (nos. 2 and 3 in Fig. 30 and nos. 6 to 8 in Fig. 31). In case of alteration age determination, the age of the original rock has no relation to the dating results. However, the data of the fresh rocks are used for the check of obtained alteration age values.

III. 3. 2 Experimental results

The procedure for sample preparation of altered rocks is shown in Figure 13 The quartz samples separated by this procedure are

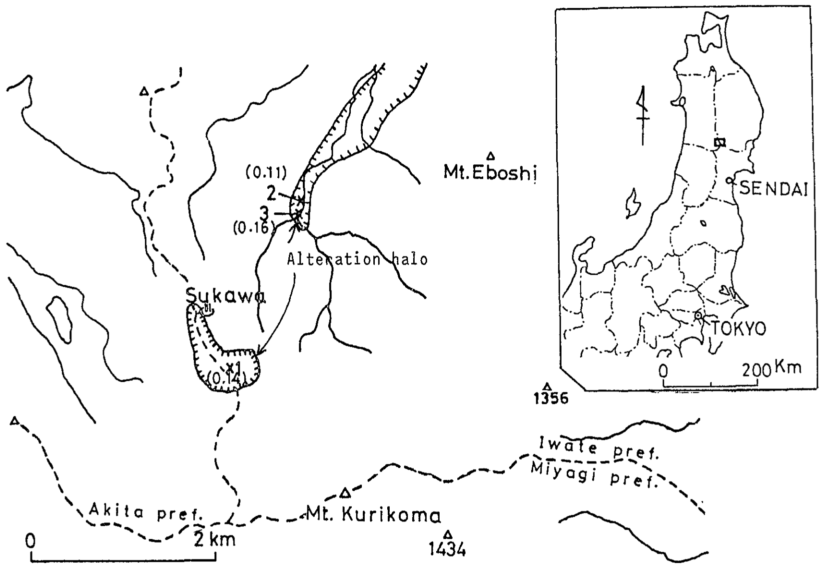


Fig. 30 Location of altered samples for TL dating at Kurikoma area. The numbers in parenthesis are ages of alteration (Ma).

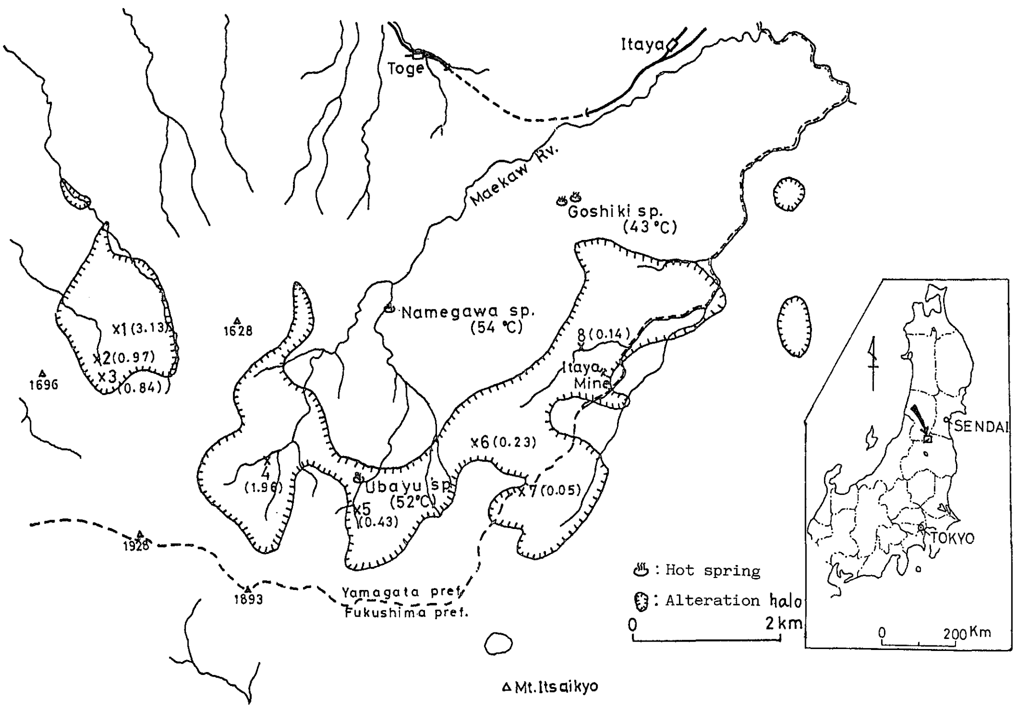


Fig. 31 Location of altered samples for TL dating at Azuma area. The numbers in parenthesis are ages of alteration (Ma).

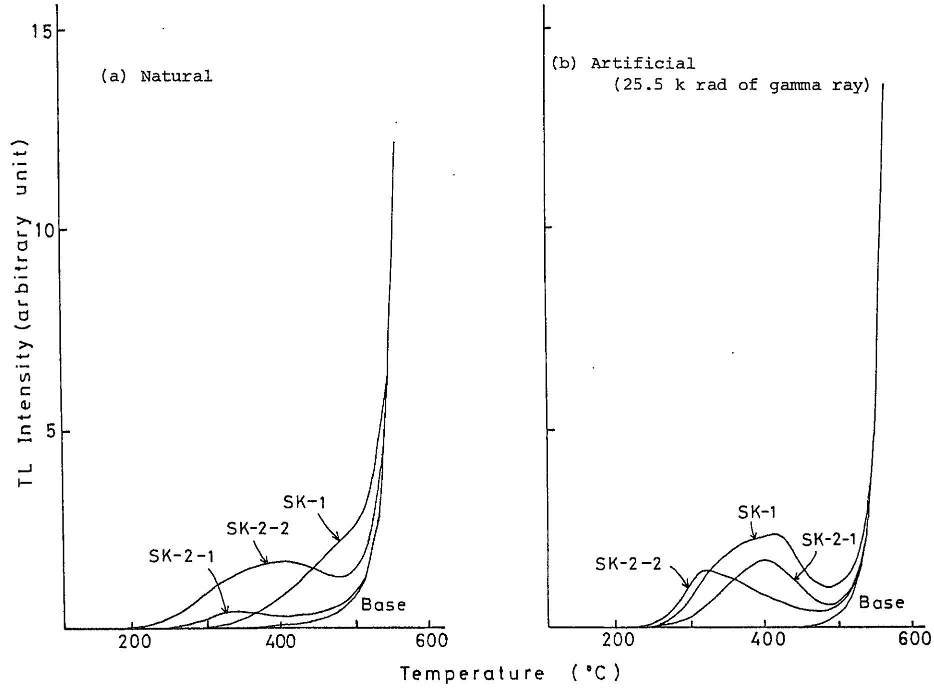


Fig. 32 TL glow curves of alteration minerals from Kurikoma area.

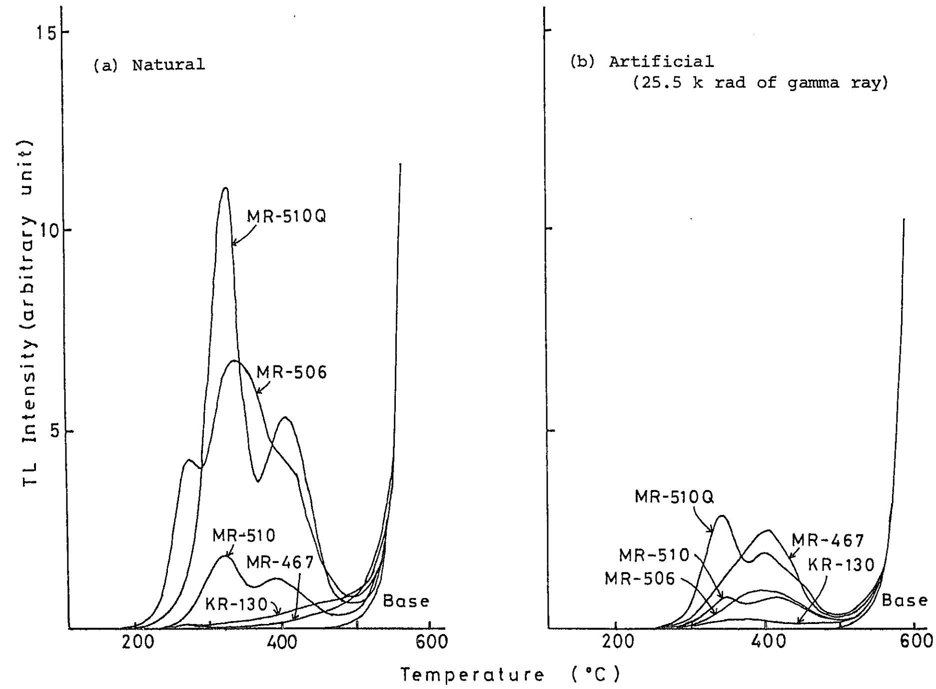


Fig. 33 TL glow curves of alteration minerals from Azuma area.

Table 10 Summary of TL dating of Kurikoma alteration zones.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	SK-1	Q+Cri	9.3	0.4	0.024	0.2592	141.7		165.5		3.302	0.14		
2	SK-2-1	Q+(Ka)	5.2	2.5	0.024	0.1639	40.5		99.3		2.489	0.11		
3	SK-2-2	Q+(KF)	16.9	2.2	1.32	0.5959	179.0		81.8		3.675	0.16		

(Chemical analysis: Wet process by Mitsubishi Metal Research Institute)

*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.

*2 Age A is obtained by the reference curve of Fig. 21.

Table 11 Summary of TL dating of Azuma alteration zones.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	YR-227	Q	7.0	0.5	0.012	0.1962	1018.4		75.2		69.01	(3.13)		
2	MR-506	Q+Alu	2.3	2.9	2.85	0.3369	405.0		52.1		23.06	0.97		
3	MR-510	Q+KF	2.8	0.4	0.277	0.1042	93.6		44.6		20.15	0.84		
4	YR-214	Q	1.8	0.4	0.024	0.0544	53.3		21.0		46.69	(1.96)		
5	WR-115	Q	1.7	0.4	0.024	0.0517	33.5		62.8		10.31	0.43		
6	HR-387	Q+(KF)	11.6	0.6	0.005	0.3234	43.3		25.0		5.35	0.23		
7	MR-467	Q+(KF)	9.7	1.0	0.036	0.2759	38.2		120.9		1.15	0.05		
8	KR-130	Cri+Q	20.8	8.8	0.024	0.6394	53.7		25.0		3.36	0.14		
9	MR-510Q	Q	2.8	0.4	0.277	0.1042	400.4		159.5		24.09	1.01		
10	MR-510T	Q+KF+(Alu)	2.8	0.4	0.277	0.1042	60.2		30.0		19.29	0.81		} Test

(Chemical analysis: Wet process by Mitsubishi Metal Research Institute)

*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.

*2 Age A is obtained by the reference curve of Fig. 21. The data in parenthesis are low reliability in the results.

aggregates of small quartz grains with few clay minerals. The mineral compositions of the separated samples are checked by X-ray diffractometer to evaluate the purity.

Figures 32 and 33 show some examples of the TL glow curves of secondary quartz separated from altered rocks. But some of themure mixture of quartz and other clay minerals or alunite, K-feldspar or cristobalite. The separation of these minerals is very difficult by normal procedure shown in Figure 13 and in some cases dating is carried out for mixture of quartz and other minerals. TL intensities of some mineral mixtures are very low (for example KR-130 in Fig. 33). These low TL result in larger error in measurement and are not suitable for dating.

The TL glow of MR–510Q is higher than that of MR–510. The former sample is residual quartz phenocryst and the latter is secondary quartz. From this figure, it is concluded that the residual quartz phenocryst is the best sample for TL measurement of altered rocks.

Tables 10 and 11 are the summary of TL dating. Chemical analyses of U, Th and K were done by wet process and annual dose rate was calculated as alpha ray fraction equals zero.

III. 4 Determination of alteration ages by alteration minerals

III. 4. 1 Location and description of samples

In this section, TL age dating using non-separated alteration minerals is described for checking the validity of mineral separation and selection of minerals. Clay minerals show fairly good TL glow as reported by FERRARESSO (1967). Therefore, it may be possible to use them for TL dating. The samples were collected from Kuju and Izu areas (Figs. 34 and 35) and the altered rocks are consisted of quartz, cristobalite, tridymite, sericite, kaolin, montmorillonite, K-feldspar and alunite.

The argillized or silicified rocks from Kuju area were formed as the result of alteration by hydrothermal activities during various periods and those from Izu are considered to be the products of mineralization in Tertiary age

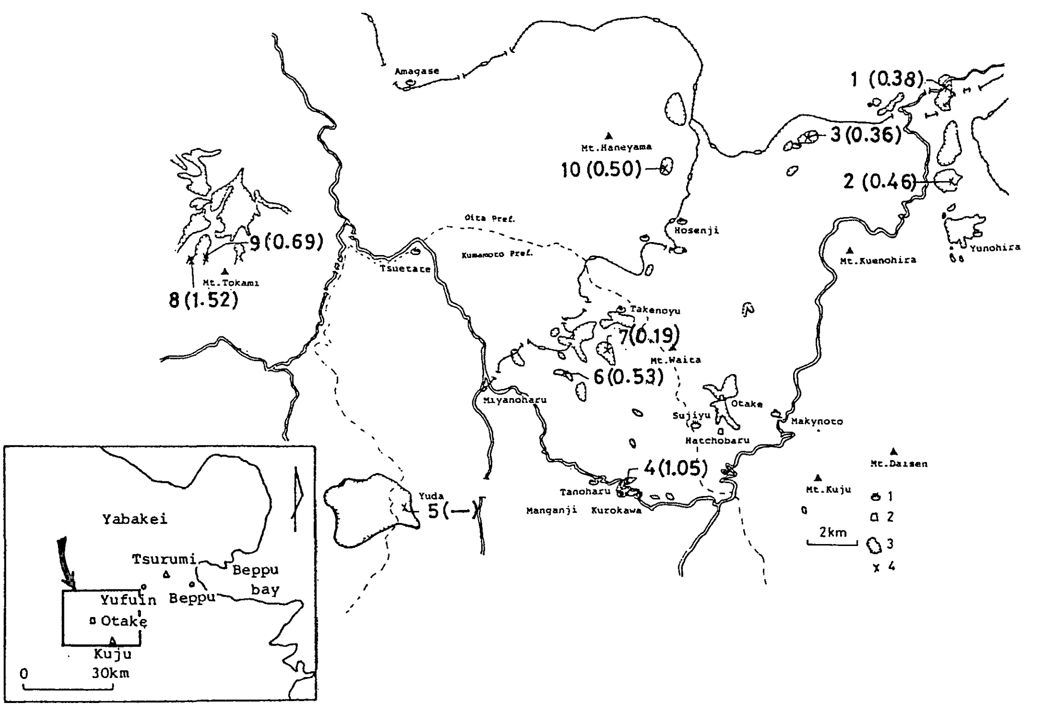


Fig. 34 Location of altered samples for TL dating at Kuju and Noya areas (Revised from TAKASHIMA, 1980a).
1: Hot spring (Above 60 °C) 2: Geothermal power plant 3: Alteration zone 4: Sample No. (Alteration age-Ma)

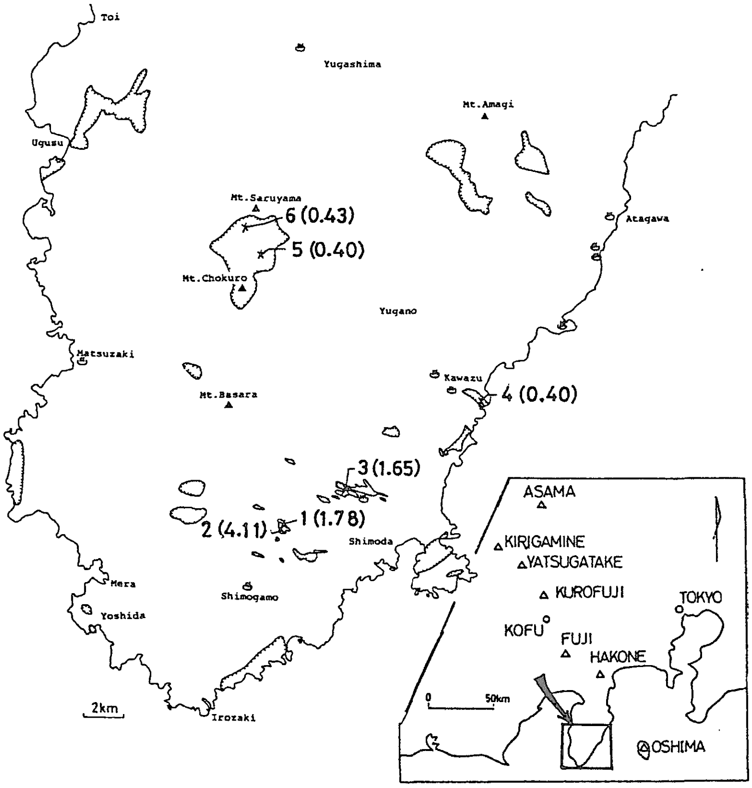


Fig. 35 Location of altered samples for TL dating at Izu area. Symbols are same as Fig. 34 (Revised from TAKASHIMA, 1980a).

(TAKASHIMA, 1980a; TAKASHIMA *et al.*, 1978b). The original rocks of Kuju area are considered to be Quaternary lava and pyroclastics except for two samples (MT77101605 and MT77101901) which are the alteration products of Tertiary formation. The original rocks of Izu area are all Tertiary lava and pyroclastics.

III. 4. 2 Experimental results

TL measurement procedure used was almost the same as that described in the previous sections except that minerals were not separated and X-rays were used for artificial radiation source. The source of X-rays was the high power diffractometer with rotary copper target. In general, X-rays are not suitable for artificial radiation source described in section II. 1. However, X-ray diffractmeter is very populer instrument and easy to use it in many laboratories. Therefore, the aim of use of X-rays is to verify their availability. The sample was spread on a slide glass and set at normal position for diffraction studies. The irradiation time was 6 minutes at 40 kV and and 150 mA. The total radiation dose was roughly estimated to be about 1×10^5 rad by comparison with standard gamma ray source.

Some examples of TL glow curves of alteration minerals are shown in Figures 36 and 37. Characteristics of these patterns are the very low intensities in most of Kuju samples. The TL glow of alteration minerals are very low compared with quartz or plagioclase phenocrysts. Therefore, TL must be carefully measured for alteration minerals and artificial radiation dose must be larger than that of quartz or plagioclase samples.

The results of TL dating by alteration minerals are summarized in Tables 12 and 13. In these tables, the annual dose rate was calculated as the contribution of alpha particles equals to 10% of total alpha ray contribu-

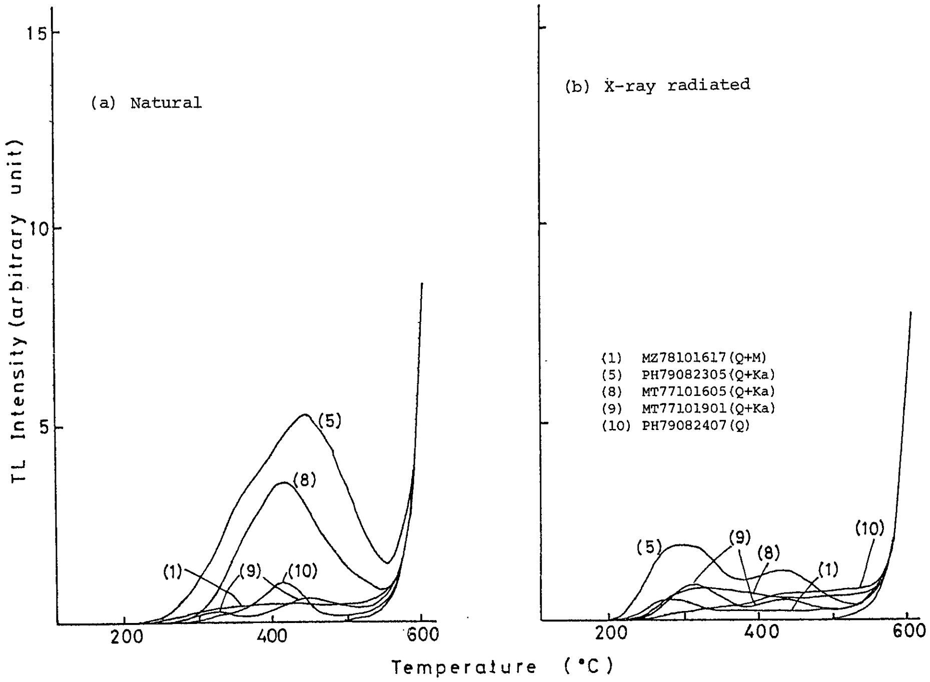


Fig. 36 TL glow curves of alteration minerals from and Noya areas.

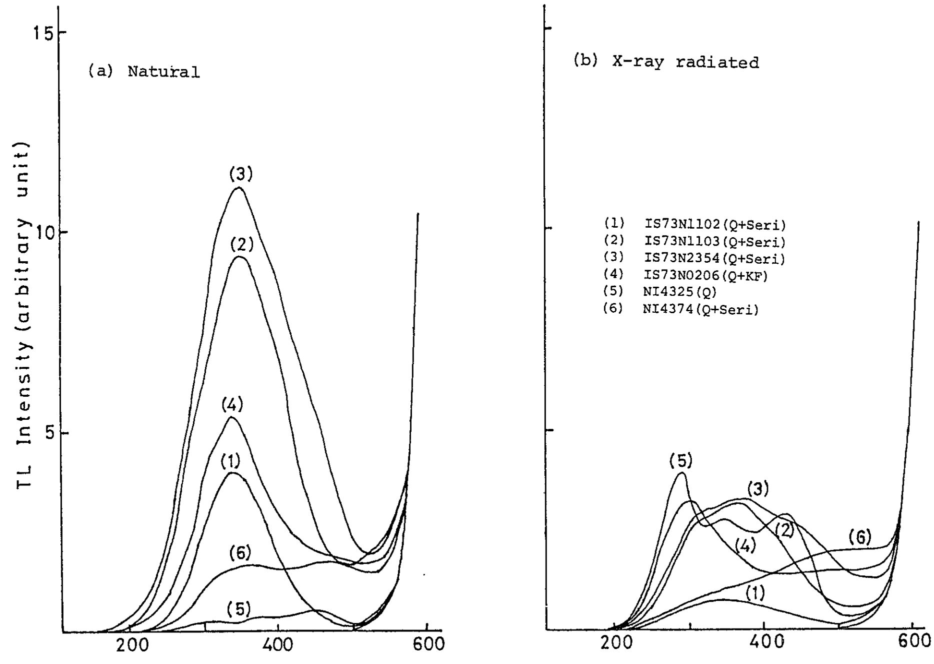


Fig. 37 TL glow curves of alteration minerals from Izu area.

Table 12 Summary of TL dating of Kuji and Noya alteration zones.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	MZ78101617	Q+M	1.9	6.4	4.22	0.5844	91		95		1.64	0.38		
2	MZ78101408	Q+Alu	1.4	2.5	3.85	0.4569	160		181		1.93	0.45		
3	WT75102308	Q	1.6	1.8	2.07	0.2993	15		32		1.57	0.36		
4	GK76102401	Ka	1.3	2.1	0.19	0.1206	50		92		4.51	1.05		
5	PH79082305	Q+Ka	0.6	1.9	0.12	0.0728	667		313		29.27	(6.79)		
6	PH79081312	Cri	1.8	4.0	1.39	0.2837	49		75		2.30	0.54		
7	WT75102805	Tri	2.4	3.4	1.76	0.3403	49		173		0.83	0.19		
8	MT77101605	Q+Ka	0.8	3.1	2.13	0.2804	367		200		6.54	1.55		
9	MT77101901	Q+Ka	1.4	9.3	0.14	0.2318	77		111		2.99	0.70		
10	PH79082407	Q	3.0	1.3	0.22	0.2047	63		143		2.15	0.50		

(Chemical analysis: Wet process by Mitsubishi Metal Research Institute)

*1 Total radiation dose are calculated as the alpha radiation dose equals to 10% of total alpha dose.

*2 Age A is obtained from the procedure explained in the text.

Table 13 Summary of TL dating of Izu alteration zones.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	IS73N1102	Q+Seri	0.2	1.0	4.31	0.4086	329		105		7.67	1.81		
2	IS73N1103	Q+Seri	0.2	0.9	1.42	0.1508	1036		388		17.71	(4.11)		
3	IS73N2354	Q+Seri	1.0	1.4	3.13	0.3541	1501		596		7.11	1.68		
4	IS73N0206	Q+KF	0.8	1.9	7.56	0.7438	645		502		1.73	0.41		
5	NI4325	Q	1.0	0.5	0.05	0.0672	65		565		1.71	0.40		
6	NI4374	Q+Seri	1.2	0.8	3.87	0.4216	313		396		1.87	0.44		

(Chemical analysis: Wet process by Mitsubishi Metal Research Institute)

*1 Total radiation dose are calculated as the alpha radiation dose equals to 10% of total alpha dose.

*2 Age A is obtained from the procedure explained in the text.

tion. This figure is the standard value for TL dating of fine grained samples (HAMADA, 1967). There were no age standard among these samples and the reference curve of Tamagawa Welded Tuff could not be used because the conditions of artificial radiation were different. Therefore, the age of 0.45 Ma for MZ78101408 which was obtained by the same procedure as secondary quartz measurement described in section III. 3 was used. The ages of other samples were obtained by referring to this age and specific TL value which started at zero and proportionally increased to 1.93 at the age of 0.45 Ma.

III. 5 Discussion on the results

The purposes of this section are limited on the short discussion on the validity of TL ages obtained from 4 kind of samples described in sections III. 1 to III. 4 and some short comments on the gological or geothermal problems. More detailed discussions are carried out for the Hachimantai and Kuju areas in the next chapter as case studies.

III. 5. 1 Quartz phenocryst

The relationship between FT ages and specific TL intensity of Tamagawa Welded Tuff is not so good. The probable range of error for a Sample which has the specific TL intensity equivalent to 1.0 Ma is about ± 0.3 Ma by the line of Figure 26. However, this is drawn by a very few number of samples and only one measurement for each sample. Accordingly, by adding new data to Figure 26, the range of error will be reduced. As it is easy to sample and measure in the TL method, it is feasible to dating many grains from different parts of age known strata in order to obtain reliable data.

There are no reference data for comparing the TL ages of Kurofuji volcanic rocks which are obtained by the reference line of Figure 26. The ages of some samples which are in parenthesis (Table 5) show disagreement with the stratigraphy. The reason of this discrepancy is unknown but, it will be reduced if large number of TL ages of each formation are obtained.

The duration of about 400,000 years for six stage activities in Kurofuji volcanic group (1.05 to 0.62 Ma in Table 5) is reasonable value for medium scale volcanic group which erupted about 32.5 km^3 of lavas and pyroclastics (MIMURA, 1967).

III. 5. 2 Plagioclase phenocryst

The most important point of TL dating of plagioclases is saturation. For clarifying this point, the natural sample is radiated by gamma rays and the increased portion of TL glow is compared with artificial one.

As shown in Table 9, increment of glow by gamma ray radiation of 10.35 k rad is small compared to natural TL glow itself. Accordingly, much larger error will have existed in saturation test and it can be used only for rough estimation. The ages are obtained by the reference line A of Figure 29 which is drawn by the data of Tamagawa Welded Tuff. There are many formations whose ages are known and are in the same stratigraphic horizon as the measured samples. Therefore, M–4 (MZ 78110401) is assigned to the mean value of FT and K–Ar ages of Haneyama lava. Then the TL ages were refined by figures B in Table 9 based on the line B in Figure 29.

The ages A which were obtained by line A are smaller than those of B. Based on the principles of TL dating, ages B are considered to be closer to actual ages of volcanic rocks of the Noya area. The difference between the above two may be attributed to few saturation in plagioclase.

As a conclusion, plagioclases can be used for TL dating of rocks younger than 0.5 Ma and even older rocks if all conditions are satisfactory well.

III. 5. 3 Secondary quartz

Alteration ages were calculated by the reference line of Tamagawa Welded Tuff and shown as ages A in Tables 10 and 11. There are no data for checking these results but ages of two or three samples taken from the same unit of alteration halo show very good agreement. This is the one evidence to support the reliability of results of TL dating of altered rocks. Also the ages of the secondary and phenocrystic quartz in MR–510 sample (MR–510 and MR–510Q) coincide with each other within the error of 10%. Of course, alteration ages never exceed those of the original rocks. However, there are very few data on Quaternary formations which can be compared to alteration ages obtained by TL method. Only two age data have been reported from Azuma area and no data from Kurikoma area in the case of Quaternary volcanic rocks. The ages of original rocks in Azuma area are 30,600 years for KR–130 by ^{14}C method (TOGASHI, 1969) and 0.34 Ma for HR–387 and MR–467 by FT method (TOGASHI *et al.*, 1978). For the Tertiary samples, it is enough to check that the TL ages do not exceed 2.0 Ma. Based on this judgement, only two age data for YR–227 and KR–130 were discarded. The reason of this discrepancy is not clear, but in general, the data of alteration ages are considered to be reliable.

The texture of altered rocks is quite different from that of Tamagawa Welded Tuff which is the standard for alteration ages of the above two areas. The difference of texture causes difference of annual dose evaluation. For this reason, it is better to use the same rock type for age references although there is no such standard at present time.

One of the predominant features defined by TL dating in Azuma area is the successive change of hydrothermal activities. As shown in Figure 31, alteration ages changed successively from old in western part to young in eastern part. That direction is in accordance with the volcanic activities of Azuma group which also changed from west to east (TAMIYA *et al.*, 1970).

III. 5. 4 Mixture of alteration minerals

The determination of alteration ages by use of non-treated altered rocks is the simplest way in TL dating. The data obtained by this method are shown in Tables 12 and 13. These ages did not contradict to the stratigraphcal evidences except for one sample (PH79082305 in Kuju area).

In the Kuju area, alteration ages determined by TL method are close to the ages of eruptions of the neighboring volcanoes. In the Izu area, the alteration ages of three samples from the southern part were older than those of the northern samples. This is also in good accordance with the distribution of Quaternary volcanoes in the area. The southern part is mainly composed of Tertiary formations whereas many Quaternary volcanoes exist in northern part. The samples showing young alteration ages of 0.40 to 0.43 Ma are closely related to high temperature Yatsu hot springs (IS73-N0206) and Quaternary volcanoes (NI4325 and NI4374). The latter two are considered as the samples belong to the same group of Ugusu alteration area where the alteration age is believed to be some time in Quaternary (IIJIMA and IWAO, 1970).

It is, therefore, concluded that TL dating of non-separated alteration minerals is effective for most alteration zones. However, better results can be obtained by using secondary quartz because of the low TL sensitivity and difficulty in annual dose evaluation for the fine grained mixture of alteration minerals. In addition, it is necessary to compare the data of gamma ray radiated samples with those of X-ray radiated samples because the reliability

Table 14 Variation and errors in TL measurements and chemical analysis (After TAKASHIMA, 1979).

No.	Sample No.	F. T. Age(m.y.)	Sample Locality	TL Peak Height (cm)				U (ppm)	Th (ppm)	K_2O (%)
				1	2	3	(A) Mean			
1	TM- 1	1.1	Hashiba	11.7	12.5	11.7	11.97	1.2±0.1	4.0±0.2	1.48±0.03
2	TM- 2	1.2	Kamihinokinai	13.2	13.6	13.3	13.37	2.2±0.1	6.8±0.3	2.37±0.03
3	TK- 4	1.2	Yanagisawa-rindo	6.5	6.5	6.3	6.43	0.8±0.1	2.7±0.2	1.11±0.03
4	TM- 3	1.7	Obonai	10.6	10.9	10.5	10.67	1.2±0.1	4.8±0.2	1.62±0.03
5	TM- 4	1.7	Bunamori-rindo	14.0	13.0	14.6	13.87	1.4±0.1	4.7±0.2	1.48±0.03
6	TM- 5	1.8	Komatakyo	11.5	11.6	12.0	11.70	1.3±0.1	4.4±0.2	1.55±0.03
7	TM- 6	2.0	Gojumagari	4.5	4.2	4.3	4.33	1.3±0.1	4.0±0.2	2.13±0.03
8	TK- 8	—	Akagawaonsen	2.2	2.0	2.2	2.13	1.5±0.1	5.6±0.2	4.46±0.03
9	TK-12	—	Yunomata-zawa	6.6	6.6	6.1	6.43	2.0±0.1	7.1±0.3	4.21±0.03

(Chemical analysis: Gamma ray spectrometry by H. KANAYA) of latter ones is not so good.

III. 6 Errors and applicability

As described before, there are many factors cause for error in TL dating. Some of them can be evaluated mathematically but impossible for many other factors. Therefore, it is reasonable to estimate the errors as total

For the TL dating of quartz phenocrysts in Tamagawa Welded Tuff, the errors of TL measurement and chemical analysis are the only items that can evaluate mathematically. The errors of above two are about $\pm5\%$ as shown in Table 14. The errors in artificial radiation of ^{60}Co are also smaller than $\pm5\%$. It is very difficult to evaluate another factors numerically. However, the total errors are roughly estimated as $\pm30\%$ based on the comparison with existing age data or other geologic data.

The TL dating of plagioclase phenocrysts are almost same as quartz but worse than that because the items of cause for errors are increased. Examples of them are saturation of TL, impurity of chemical composition in the crystal and low TL sensitivity.

For the alteration age determination, residual quartz phenocrysts are the best because of the reasons described in the experiment of Tamagawa Welded Tuff. Only one problem about alteration age dating by use of quartz phenocrysts is the evaluation of temperature that the quartz was suffered. Based on the data of some areas, secondary quartz in silisified zone is usable for alteration age determination. Errors of alteration ages determined by residual quartz phenocrysts and those of secondary quartz are in the same order as that of volcanic rocks because the factors are same. However, it is very difficult to check because there are no reference data for alteration ages.

In the case of mixture of alteration minerals, most of obtained ages were not contradict to geologic evidences although futher study is needed for checking the reliability of X-ray radiation.

As a conclusion, following order is recommendable for TL dating of volcanic rocks.

(1) Quartz phenocryst
(2) Plagioclase phenocryst

For the alteration samples, the order is as follows.

(1) Residual quartz phenocryst
(2) Secondary quartz
(3) Mixture of alteation minerals

The accuracy of the results are decrease with that order. Therefore, the sample selection must be important.

IV. Case study

IV. 1 Case study at the Hachimantai geothermal field

IV. 1. 1 Geology and geothermal activities

Hachimantai is one of the biggest geothermal field in Japan. Within this Hachimantai field, three out of seven Japanese geothermal power plants (Matsukawa, Onuma and Kakkonda) are installed and many geothermal areas are distributed such as Goshyogake, Sumikawa, Yakeyama, Tamagawa, Nyuto, Komagatake, Kakkonda and so on.

Geology is also very intersting from the viewpoint of geothermal study. Outline of stratigraphy of Hachimantai field is shown in Table 15 (Kawano and Uemura, 1964). In this area, Tamagawa Welded Tuff of latest Pliocene to middle Pleistocene (2.5 to 1.2 Ma by the work of Tamanyu and Suto, 1978) are widely distributed. This formation is considered as the cap rock for geothermal reservoirs. It is big problem for evaluation of stored heat of original magma of Tamagawa Welded Tuff because their ages are not so old and the volume of magma reservoir is considered as large as 500 km^3 which is same order of total eruption products (Satoh *et al.*, 1976).

Figure 38 shows the one example of geologic section of geothermal area (Nakamura and Sumi, 1981). The altered volcanic rocks so-called "green tuff formation" in Tertiary age have the suitable characters for the reservoirs and actually become main reservoirs at Matsukawa, Onuma and Kakkonda geothermal areas.

IV. 1. 2 Hydrothermal alteration

Heighly fractured strata and large amount of precipitation are apt to form alteration halos.

Table 15 Outline of stratigraphy at the Hachimantai area (After KAWANO and UEMURA, 1964).

Geological Age		Stratigraphy	
Quaternary	Recent	Alluvium	Yakeyama volcano Hachimantai volcano Kayodake volcano Iwate volcano
	Pleistocene	Terrace deposits	
		Tamagawa welded tuff	
Neogene Tertiary	Pliocene	Kitamatagawa formation	
	Miocene	?	
		Koshitomae formation	
		?	
		Kumazawagawa formation	
Pre-Neogene		Granodiorites	Quartz diorite porphyrys
		Paleozoic formation	

These alteration halos preserved well and act as the fossil of geothermal activities. From careful analysis of them, information about geothermal activities and their historical changes are obtained.

In the Hachimantai field, intensive studies of surface alteration halos were carried out. First of them are the works on Matsukawa (NAKAMURA and SUMI, 1961; SUMI, 1966). Then the survey was carried out as a part of major work of national wide geothermal resources evaluation. The areas included above survey are Nyuto, Kuroishi and Komagatake (GEOLOGICAL SURVEY of JAPAN, 1976) and Goshyogake, Yudamata, Fukenoyu, Sumikawa and Yakeyama (TAKASHIMA *et al.*, 1978a). In addition, distribution of alteration halos are described in the reports of sulphur exploration survey (HAYAKAWA, 1952; KAWANO and UEMURA, 1954).

Surface alteration zones are divided into two categories. First one is the white colored alteration zone which was formed by the reaction with acid hot water and mainly formed near surface zones. Most of surface alteration studies include above works are aiming to clearify the characters of that white colored zones. Another one is the green colored

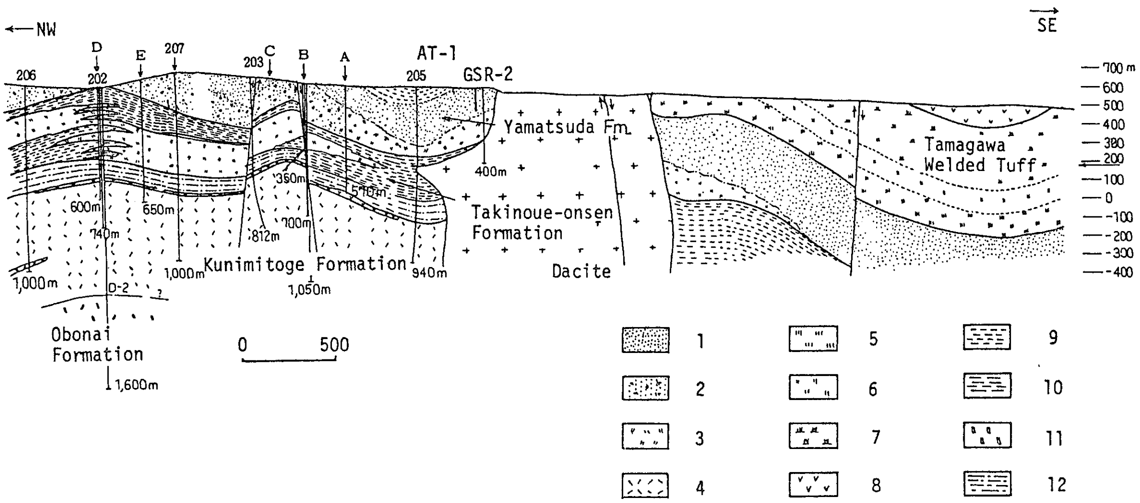


Fig. 38 Schematic geologic section along the Kakkonda River in Takinoue area (After NAKAMURA and SUMI, 1981). (1) Sandstone (2) Tuffaceous conglomerate (3) Dacitic tuff (4) Andesitic tuff and shale (5) Dacitic tuff (6) Pumiceous tuff (7) Pumiceous tuff breccia (8) Andesite (9) Siltstone (10) Shale (11) Rhyolitic tuff (12) Sandy shale

alteration halo which was formed by the reaction with neutral or alkaline hot water and mainly formed at slightly deeper zones. This alteration halo can be observed after some erosion and normally wide distribution than white colored alteration zones.

This kind of alteration has been studied by Kimbara *et al.*, (1979, 1982) for underground heat evaluation and reservoir prospecting. Figure 39 is the compiled distribution map of alteration halos in this field based on the above works and actual field survey.

Mineral assembleage of these alteration halos are shown in Table 16. Major alteration minerals in white colored alteration halos are pyrophyllite, sericite, dickite and kaolinite

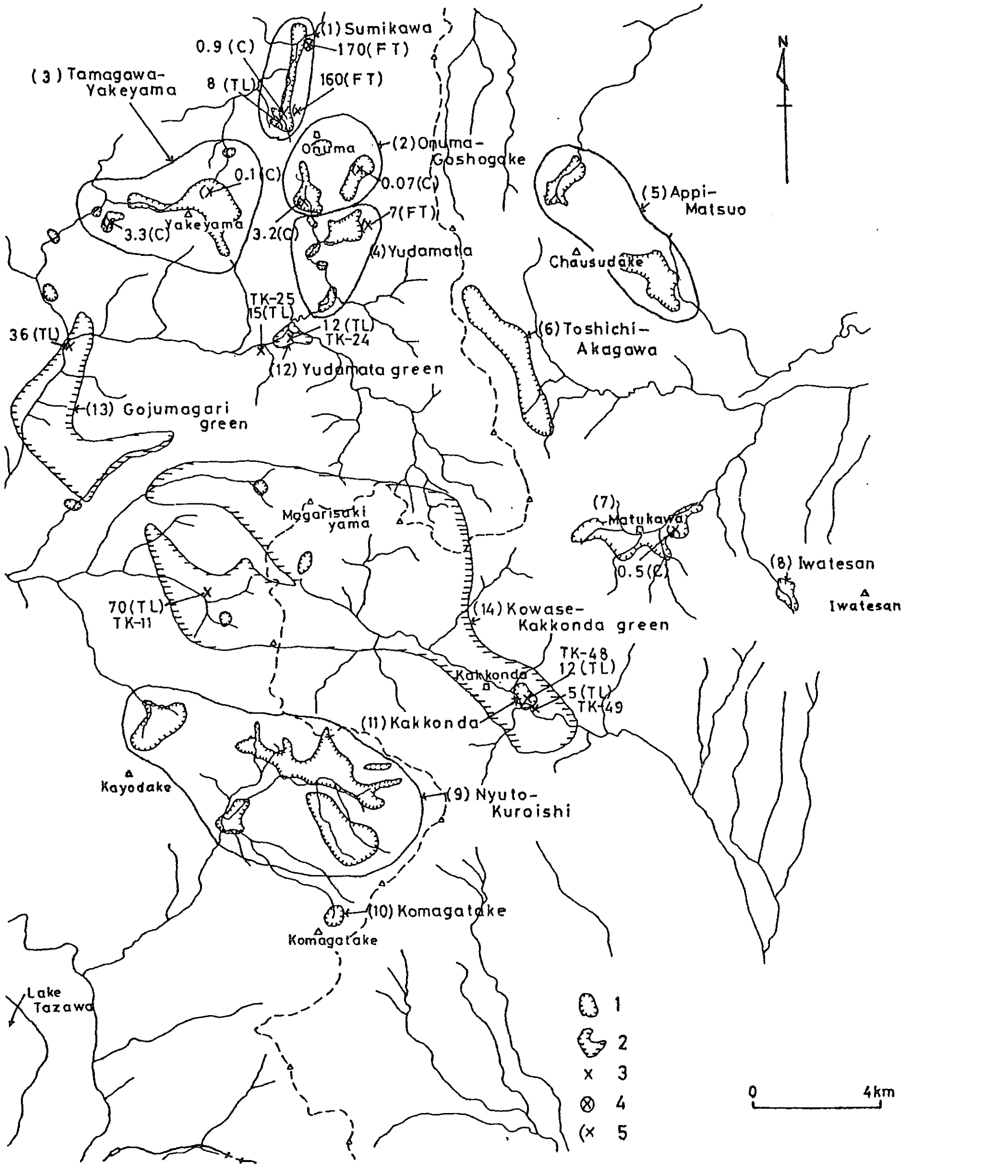


Fig. 39 The distribution of alteration zones and dating results in Hachimantai area.
1: Alteration zone (White) 2: Alteration zone (Green) 3: Alteration age 4: Age of host rock for alteration 5: Age of upper or lower formation of alteration zone FT: Fission-track K: K–Ar C: C–14 Unit of age: 10^4 years

Table 16 Alteration minerals of Hachimantai area.

Area	Alteration Minerals					Surfacee manifestation	References
	Silica	Clay	Zeol.	Sulfate	Others		
(1) Sumikawa	Q, Cr	Ser, Hall K, Mt	Lm, St	Al	Pr	Steam (95°C)	Takashima et al. (1978)
(2) Onuma-Goshiogake	Q, Cr Tr, Op	K, Mt		Al		Steam (95°C)	
(3) Tamagawa-Yakeyama	Q, Cr Tr, Op	Ser		*	Pr, Ht	Steam (95°C)	Sumi and Takashima (1972)
(4) Yudamata	Q, Cr Tr,	K, Mt Hall	St	Al	S	Steam (91°C)	Takashima et al. (1978)
(7) Matsukawa	Q, Cr	Pyro,Ser,K Mt, Sap		Al	Dp		Sumi (1968)
(9) NyUto-Kuroishi	Q, Cr Tr,	Pyro,Dc,K Ser, Mt		Al	Pr, Mc Gt	Steam (93°C)	
(11) Kakkonda	Q, Cr Tr, O	Pyro,K Ser/Mt,Mt		Al		Steam	
(12) Yudamata green		Chl, Mt	Lm			76°C	Kimbara et al. (1982)
(13) Gojumagari green	·	Chl, Mt Ser/Mt,Chl/Mt	St, Y Lm, W			59°C	
(14) Kowase-Kakkonda green		Chl, Mt Ser/Mt,Chl/Mt	Lm,W				

Q: Quartz Cr: Cristobalite Tr: Tridymite O: Opal Pyro: Pyrophyllite K: Kaolin Mt: Montmorillonite Hall: Halloysite Sap: Saponite Chl/Mt: Mixed layer W: Wairakite Lm: Laumontite Y: Yugawaralite Al: Alunite Jaro: Jarosite Pr: Pyrite S: Sulfer Dp: Diaspore Gt: Goethite Ht: Hematite Ma: Marcasite Ser: Sericite Dc: Dickite Chl: Chlorite Ser/Mt: Mixed layer Md: Mordenite St: Stilbite

with few zeolites, and those of green colored alteration halos are chlorite and mixed layed clay minerals of sericite-montmorillonite with large amount of zeolites.

Based on the careful study of mineral paragenesis, successessive story of hydrothermal activities are identified (SUMI, 1968; TOGASHI, 1977). However, it is need to determine the age of alteration for evaluating the residual heat beneath the alteration halos.

IV. 1. 3 Historical changes of geothermal activities

The ages of alteration minerals, volcanic rocks and carbonaceous materials in sediments of altered formations are also shown in Figure 39. The methods for dating are ^{14}C, K–Ar, FT and TL which are depend on the samples.

In case of alteration age determination, TL and ^{14}C methods are the best way. Preliminary assessment of alteration ages were carried out for Kowase-Gojumagari area (TAKASHIMA, 1979). On that paper, only TL peak height of quartz separated from altered Tamagawa Welded Tuff are plotted. Even that simple procedure, the areas with young alteration zones are inferred. The points showing young alteration ages appear in limited areas where hot springs are occurred or high temperature alteration minerals such as wairakite and sericite are formed.

The precise TL data of this area are shown in Table 17. From these TL data and existing ^{14}C and FT ages, the history of hydrothermal activity for each geothermal area is presumed (Table 18). As shown in this table, TL ages directly indicate the age of alteration whereas data of ^{14}C and FT methods show only upper or lower limit of alteration age.

From the age data of this area, historical changes of geothermal activity of relatively wide area is inferred. Figure 40 is the schematic model of hydrothermal history from early to late Pleistocene. From this model, following features are pointed out.

(1) After huge eruptions of acidic magma (Stage 1), large scale hydrothermal activities were occurred and continue to about 700,000 years B. P. This activity was characterized by the formation of green colored alteration (Stage 2).

(2) After that, another small scale hydrothermal activities arisen in many places, which

Table 17 Summary of TL dating of altered Tamagawa Welded Tuff.

No.	Sample No.	Mineral	U (ppm)	Th (ppm)	K_2O (%)	(T) Total*1 Radiation Dose (rad/y)	TL glow intensity (Average)			C/(B−A)	Specific TL A/C/T	Age*2 (Ma)		Comments
							(A) Original	(B) γ-assist	(C) Artificial			A	B	
1	TM- 6	Quartz	1.3	4.0	2.13	0.2560	468.6		214.4		8.54	0.38		
2	TK- 8	〃	1.5	5.6	4.46	0.4808	297.5		576.0		1.07			
3	TK-11	〃	0.9	2.5	0.80	0.1189	238.2		120.0		16.69	0.70		
4	TK-12	〃	2.0	7.1	4.21	0.4841	953.7		665.7		2.96			
5	TK-24	〃	1.9	6.3	2.39	0.3137	97.6		122.8		2.53	0.11		
6	TK-25	〃	1.8	5.3	2.15	0.2817	60.7		64.4		3.28	0.14		
7	TK-48	〃	0.5	1.8	1.77	0.1849	36.3		70.0		2.80	0.12		
8	TK-49	〃	0.6	2.2	0.95	0.1181	23.5		155.4		1.28	0.05		

(Chemical analysis: Gamma ray spectrometry by H. KANAYA)

*1 Total radiation dose are calculated as the alpha radiation dose equals to zero.

*2 Age A is obtained by the reference curve of Fig. 26. TL ages of TK–8 and TK–12 are not adopted because of big difference in TL patterns between natural and artificially radiated samples.

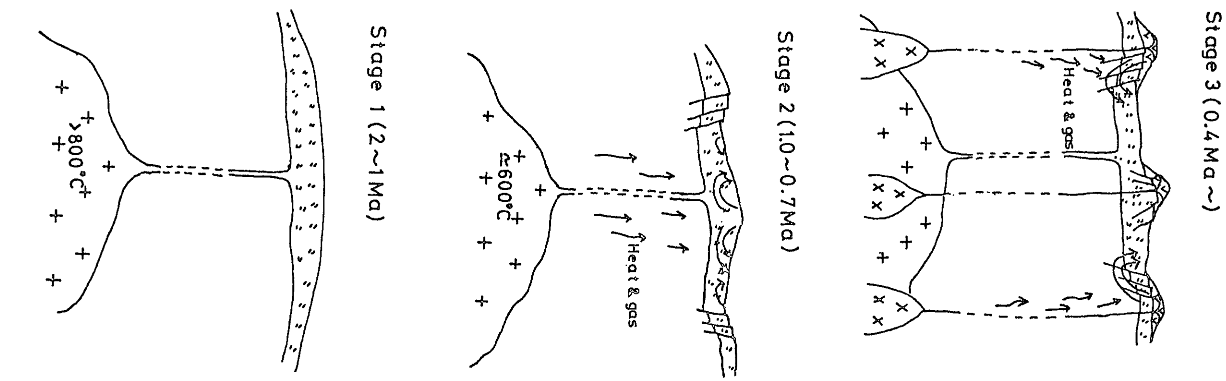
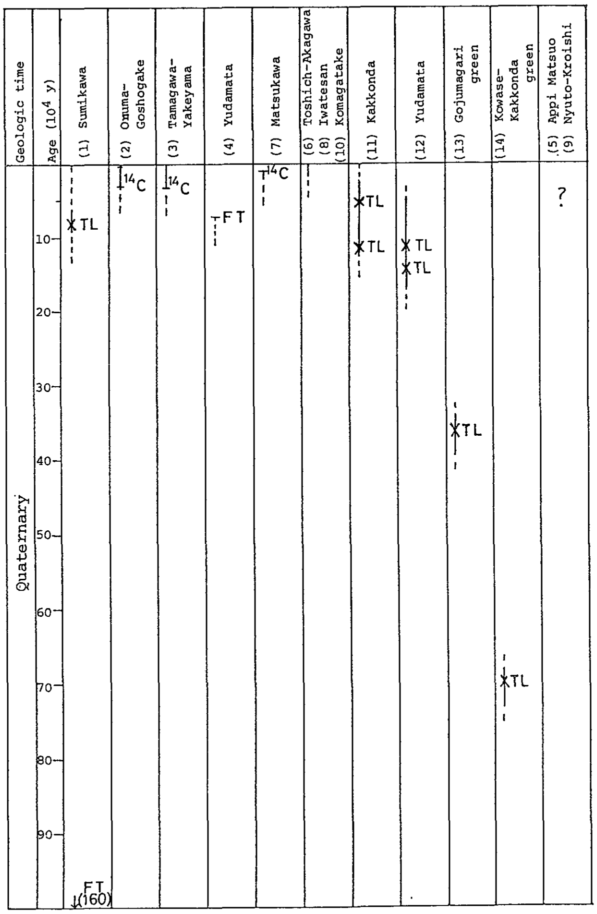


Fig. 40 Schematic model for historical changes of hydrothermal activities from early Quaternary to present.

Table 18 Summary of alteration ages in the Hachimantai area.



were accompany with relatively small and separate andesitic magmas. The start of these activities was considered at about 400,000 years B. P. (Stage 3).

(3) At present, most of hydrothermal activities have a close relation to late Quaternary andesite volcanoes.

Above assumptions must be confirmed by more detailed dating data for all altered zones in Hachimantai field. However, even limited data can provide useful information. For example, the huge acidic magma which was active in early Pleistocene may not provide the substantial heat for this area, because the hydrothermal activities caused by that magma were ended by 700,000 years B. P. although no comparable data for supporting above conclusion are exist. As this is the first work of stored heat evaluation by alteration age dating, final answer will be obtained by the deep drilling at the center of eruption of Tamagawa Welded Tuff.

IV. 2 Case study at the Kuju geothermal field

IV. 2. 1 Geology and geothermal activities

Same as Hachimantai, Kuju field is another large geothermal field in Japan where two geothermal power plants (Otake and Hatchobaru) are installed. Besides above two areas, steaming ground is found at Takenoyu, about 5 km northwest of Otake. Another one is the fumarolic activity in explosive crater of Kuju-iwoyama. The highest temperature observed in this crater was 480°C (Iwasaki *et al.*, 1962). Many other high temperature (over 90°C) hot springs such as Amagase, Noya, Tsuetate, Kurokawa, Sujiyu and Makinoto are distributed in this area as shown in Figure 41.

The stratigraphy of this field is shown in Table 19. Recently, stratigraphy and history of volcanism were revised by the new data from geothermal exploration. Table 20 is one example of them (Tamanyu, 1981). This field is situated in the large graven structure which is streching from Oita to Kumamoto-Unzen. Pre-Tertiary basement rocks are found in a deep drill hole for geothermal exploration at Hatchobaru geothermal area (Tanaka and Ejima, 1982). The altered volcanic rocks in both Tertiary and Quaternary ages are the main reservoirs for Otake and Hatchobaru geothermal power plants.

Volcanisms in Quaternary age are roughly divided into four stages such as Hohi, Bungo, old Kuju and young Kuju from old to young (Matsumoto, 1963, 1977). Among them, young Kuju is actually become heat source and Hohi is too old to supply heat to this area. Therefore, the estimation of residual heat beneath the old Kuju and Bungo volcanos are main problem in this field.

IV. 2. 2 Hydrothermal alteration

The alteration halos in this field are divided into two types same as Hachimantai field.

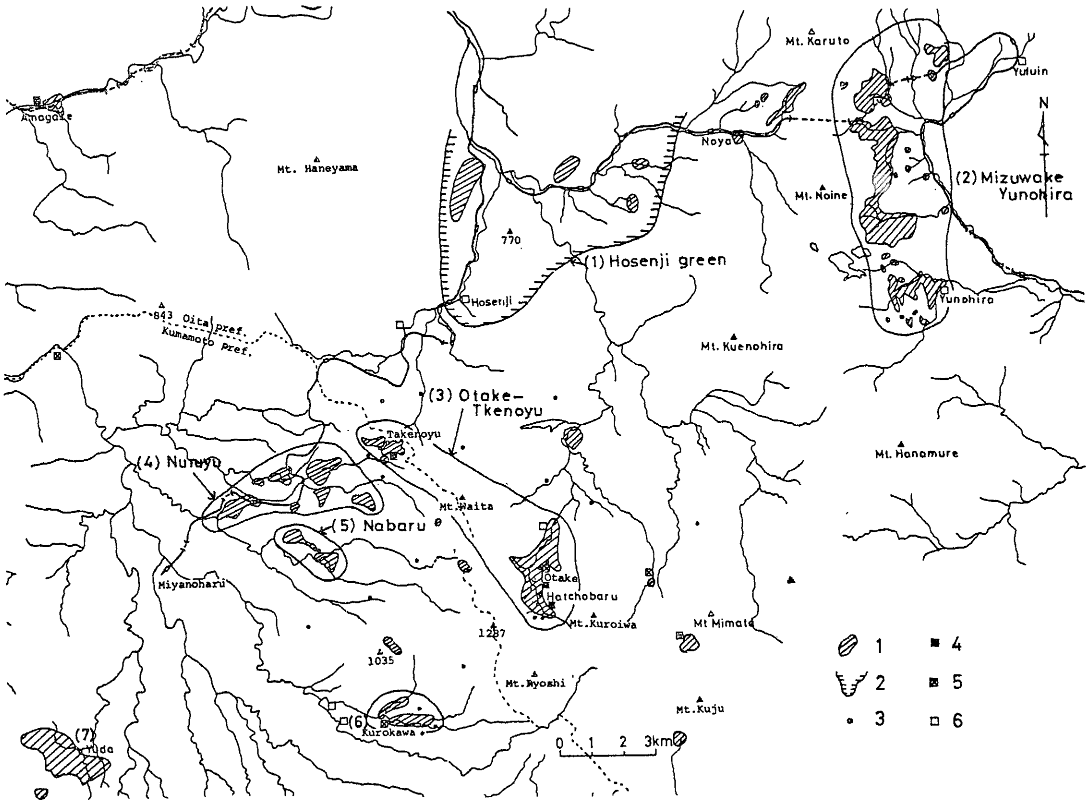
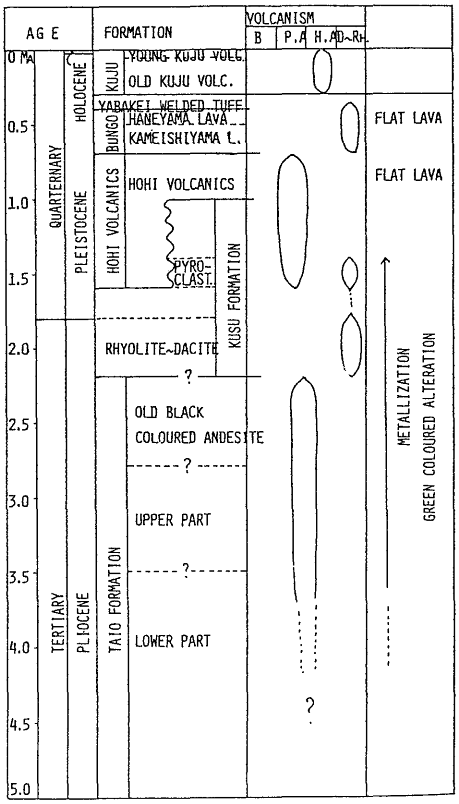


Fig. 41 Distribution of alteration zones in Kuju and Noya areas.
1: Alteration zone (white) 2: Alteration zone (green) 3: Research drilling 4: Fumarole or steaming ground
5: Hot spring (above 90°C) 6: Hot spring (60 to 90°C)

Table 19 Stratigraphic sequence of Kuju and Noya areas (After IKEDA, 1979).

Holocene		alluvium, talus, volcanic fans Pyroxene andesites belonging to Ryukyu volcanic series	activities of Ryukyu volcanic series
late-Pleistocene	Kuju group	Younger hornblende andesites belonging to San'in volcanic series Aso pyroclastic flow (Aso-4) Older hornblende andesites belonging to San'in volcanic series	activities of San'in volcanic series
	Oita group	Yabakei pyroclastic flow Haneyama lavas (rhyolite) Yoshibu-Kameishiyama volcanics (hornblende andesite)	
early-Pleistocene		Tsukushi lavas (pyroxene andesite) Hita, Yabakei, and Takio formations	Hohi volcanic activity
Pliocene		"Kusu-gawa unconformity"	
Miocene	Sekinan group (Kusu group)	Handa, Higashiwasada, Nogami, and Hosenji formations, and volcanic rocks	activities of Setouchi volcanic series
	Usa group	propylites and green-tuffs	
pre-Miocene		sedimentary, metamorphic and intrusive rocks	

Table 20 Revised stratigraphy and volcanism of Kuju (Hohi) field (After TAMANYU, 1981).



VOLCANISM
B: Basalt
PA: Pyroxcene andesite
HA: Hornblende andesite
D-Rh: Dacite to rhyolite

First one is green colored alteration halo which is formed by neutral or alkaline conditions. Another one is white colored alteration halos which are formed by acidic conditions. They are distributed all over the field but the size of them are not so large (Fig. 41). The mineral assembleage of these alteration halos are already reported by many authors (YAMASAKI *et al.*, 1970; HAYASHI, 1973; TAKASHIMA, 1972, 1980b).

Surface alteration of this field are first studied as an exploration technique for Otake (NAKAMURA and ANDO, 1954; YAMASAKI *et al.*, 1970) and Takenoyu (TAKASHIMA, 1972). Then the survey was carried out as a major work of national wide geothermal resources evaluation same as Hachimantai field. The areas included above survey are Takenoyu, Kurokawa, Noya, Mizuwake, Yunohira etc. The distribution of above alteration halos are also shown in Figure 41 which is drawn by above data and actual field survey (TAKASHIMA *et al.*, 1981).

Table 21 is the outline of mineral assembleage of alteration halos in this field. In general, high temperature minerals such as pyrophyllite and sericite are distributed at the far away areas from presently active Otake and Takenoyu areas. The difference of mineral composition and distribution patterns may express the difference in time of hydrothermal alteration. In other word, high temperature minerals were formed at deeper part of the area and appear now as high temperature alteration halo after the long time of erosion.

IV. 2. 3 Historical changes of geothermal activities

Historical changes of geothermal activities are one of the important factors in exploration. They are traced by the datings of alteration minerals and volcanic rocks.

As shown in Table 12 (Chapter III), nine alteration ages were obtained by TL dating of alteration minerals in the Kuju field. These ages are indicated in Figure 42 in which other dating results, distribution of alteration halos, gravity data and lineament patterns are added. The most of above information are taken from compiled geologic map of Hohi geothermal field (GEOLOGICAL SURVEY of JAPAN, 1982) and large scale lineament are drawn by the LANDSAT images. From these data, following geothermal history is assumed.

(1) Hydrothermal activities occurred in southwest part of the area at late Tertiary or early Quaternary age.

(2) Hydrothermal activities occurred in northwest part of the area which related to the volcanic eruptions of Haneyama and adjacent volcanoes. The duration of these activities is considered to be 500,000 to 400,000 years B. P.

(3) Hydrothermal activities occurred in the northeast part of the area which related to the volcanic eruptions of old Kuju volcanic qroups. The duration of these activities is considered to be 400,000 to 300,000 years

Table 21 Alteration minerals of Kuju and Noya areas (Abbreviations are same as Table 16).

Area	Alteration Minerals					Surface manifestation	References
	Silica min.	Clay min.	Zeol. min.	Sulfate min.	Others		
(1) Hosenji green	Q, Cr	Chl, Mt Ser/Mt	H				
(2) Mizuwake-Yunohira	Q, Cr T	Pyro, K Mt, Hall		Al	Pr	85°C	Takashima (1980b) Takashima and Muraoka (1980)
(3) Otake-Takenoyu	Q, Tr Cr	K, Mt Ser	St, Md	Al	S	Steam (99°C)	Hayashi (1973) Takashima (1972)
(4) Nuruyu	Q, Cr Tr	K, Mt Hall	Md	Al	Pr, S	32°C	
(5) Nabaru	Q, Cr Tr	K, Nt Hall		Al	Pr,	43°C	
(6) Kurokawa	Q, Cr Tr	K, Mt Hall		Al, Jaro		98°C	
(7) Yuda	Q, Cr Tr	Pyro, K Mt, Ser				32°C	

B. P.

(4) The hydrothermal activities of presently active areas (Otake, Hatchobaru and Takenoyu) were started about 200,000 years ago. It is considered that the age of this order can supply substantial heat to the appropriate depth although many factors affect this evaluation.

The predominant geologic structure of this area is the graven of ENE–WSW trend where many active volcanoes are arranged. Actually, many lineaments are found in this field by the aerophotograph analysis that drawn in Figure 42. The formation of this graven structure is estimated to have begun during the period of 800,000 years B. P. by the analysis of active faults (IKEDA, 1979).

However, most of geothermal activities and the arrangements of large scale alteration halos which formed at older times seem to be related to NEN–SWS lineaments drawn from LANDSAT images. This is the same direction of linear arrangement of volcanoes (OIDE, 1974) and some parts of alteration halos (Fig. 41).

V. Concluding remarks

Thermoluminescence dating have many advantages described before. In this paper, techniques, errors and data analyses of many kind of samples were carried out. The aims of that method are concentrated for the geothermal subject such as reservoir estimation, heat evaluation and exprolation. However, TL dating can be applied to many other geological fields. The best application of it is the determination of age of middle to late Quaternary volcanoes, which are difficult to obtain their ages by other methods. Another interesting subject of application is the analysis of geological stress field by the dating of intrusive rocks or alteration zones which have the directional arrangements.

Although many applications are expected, there are many unknown factors are remined in TL dating described in this paper. At present, very few works are done for this method although commonly used and technically established in archeological field. It is desireble to study more because this method is easy for experiment and no need to have expensive instruments.

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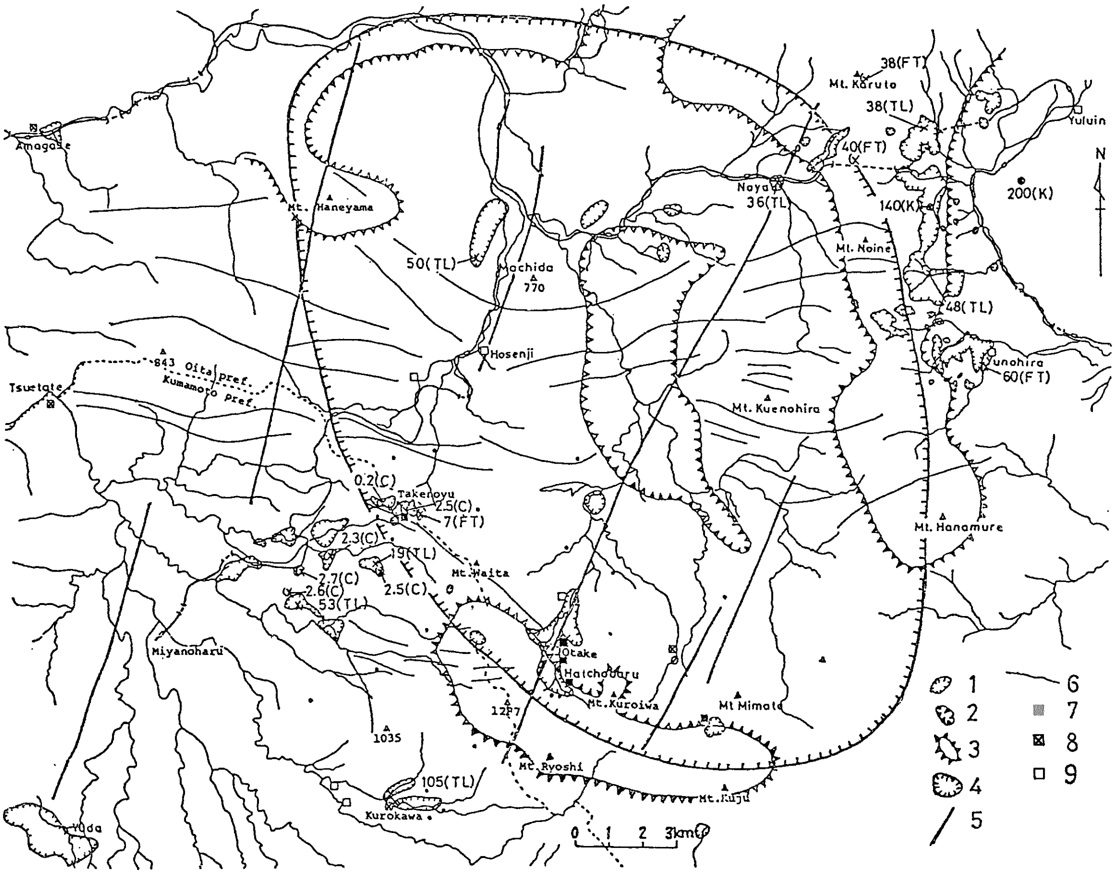

Fig. 42 Summary of the geologic structure, alteration and dating results.
1: Alteration zone 2: Gravity low area 3: Gravity high area 4: Caldera or volcanic depression 5: Linearment from LANDSAT 6: Linearment from aerophotograph 7: Fumarole or steaming ground 8: Hot spring (above 90 °C) 9: Hot spring (60 to 90 °C) FT: Fission-track K: K–Ar C: C–14 Unit of ages: 10^4 years

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熱ルミネッセンス法による火山岩と変質岩の年代測定とその地熱活動史研究への応用

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要　旨

熱ルミネッセンス（Thermoluminescence, 以下 TL と記す）法により第四紀の火山岩及び地熱変質岩の年代測定を行い，その結果から，東北地方の八幡平及び九州の九重という日本の代表的地熱地域の地熱活動史を求めた．地熱資源は熱を主要な対象としているため，火山の年代，特に第四紀後半の数10万-数万という年代の決定が重要な意味を持っている．しかし，この範囲の年代は従来の K-Ar, フィッショントラック，^{14}C 法などの通常の適用困難な領域である．これに対して TL 年代測定は第四紀後半が対象年代であり，地熱の熱源評価に最も適している．さらに，同法は熱水変質帯の年代を求めることが可能であり，地熱研究には欠くことのできないものであるが，方法そのものに不確実な要素が残されているため，これまで地熱地域に実際に適用された例はなかった．筆者は地熱研究に対する TL 年代測定の有用性を確めるため，東北，中部，九州の7地点の試料について測定を行った．火山岩の年代については斑晶石英及び長石を用いて測定を行い，前者については40-200万年，後者については20-70万年の範囲の年代が誤差±30%で得られた．なお，本研究ではすべての TL 年代は既知の試料との対比により相対的に求めており，誤差についても，それら年代標準との差として求められている．変質岩については，加熱実験により200℃以上の温度でそれまでに蓄積された TL が放出されることを確認した後，残留斑晶石英，二次生成石英，変質鉱物集合体の三種について測定を行った．得られた年代は各々5-70, 5-100, 20-170万年であるが，誤差については基準となる年代既知試料が無いことから明確に求めることは困難である．しかし，残留斑晶石英は火山岩と同じ条件下にあり，誤差としても同程度の±30%程度が見込まれる．他の二者についても，得られた年代は少数の例外を除き周辺火山の年代，火山層序と矛盾しないことから，ほぼ同程度かやや劣る精度を持つものと思われる．実際の適用に当っては，鉱物の安定性その他から火山岩では斑晶石英，変質岩では残留斑晶石英又は二次石英を利用するのが望ましい．TL 年代測定結果から前記二地熱地域の地熱活動の歴史が求められ，火山活動の場の変遷とそれに伴なう熱水活動の移動が明らかになった．この結果は最も有望な地熱開発候補地の同定及び地下残存熱量評価など，地熱探査研究上有効な情報として広く利用できる．

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