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Thermoluminescence dating of volcanic and altered rocks in the Bajawa geothermal area, central Flores Island, Indonesia

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Isao TAKASHIMA, Asnawir NASUTION and Hirofumi MURAOKA (2002) Thermoluminescence dating of volcanic and altered rocks in the Bajawa geothermal area, central Flores Island, Indonesia. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 139-146, 8 figs., 2 tables.

Abstract: Ages of volcanic and altered rocks distributed in the Bajawa geothermal area were determined by thermoluminescence (TL) dating. All volcanic rock samples are collected from formations younger than 0.15 Ma by K-Ar dating but their fixed ages have not been determined. Separated quartz and plagioclase are used for dating. Ages for eight volcanic rocks range from 32-160 ka. The youngest age of 32 ka is obtained for Mt. Keli Inerie, a large active stratovolcano. Ages of 72-160 ka are first reported for small stratovolcanos that are characterized by clear craters at the summits and linearly arranged. Most acidic white colored alteration halos have been formed at low temperatures, generating no quartz. Only Nage, Mataloko and Rakalaba alteration zones have yielded samples for TL dating using quartz. The obtained TL alteration age range are 12-54 ka, 28-33 ka and 44 ka for Nage, Mataloko and Rakalaba, respectively. Ages of volcanic rocks are expected for a heat source in most geothermal fields in the Bajawa geothermal area. Young alteration ages also suggest the existence of reservoirs beneath this area.

1. Introduction

Many geothermal fields are recognized in Indonesia along a volcanic arc. Among these fields, the Bajawa area, central Flores Island has been studied by "Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia" (Muraoka *et al.,* 1998).

This area is characterized by two major active volcanoes, Keli Inerie and Wolo Inerika, and also chains of volcanic craters were clearly identified by a satellite image (Urai *et al.,* 1998) associated with many fumaroles and hot springs. A pre-feasibility survey was carried out for this area (Muraoka *et al.,* 1998), and the Mataloko was selected for further study and intense exploration including drilling.

This project includes almost all exploration techniques of geology, geophysics and geochemistry. Some research data have been published and provided a better understanding of the geothermal system in this area (e.g. Nasution *et al.,* 1999; Urai *et al.,* 2000; Takahashi, M. *et al.,* 2000; Tagomori *et al.,* 2000; Koseki *et al.*, 2000). Although intense geological studies have been carried out (e.g. Nasution *et al.,* 1999; Muraoka *et al.,* 2000; Takahashi, H. *et al.,* 2000), a detailed volcanic succession is still unknown.

Our research work was focused on the age determination of the youngest volcanic rocks and alteration products by a thermoluminescence (TL) method. Ages in this report can be used for heat source and thermal potential evaluation beneath the alteration zone. Figure 1 shows the locality of the study area.

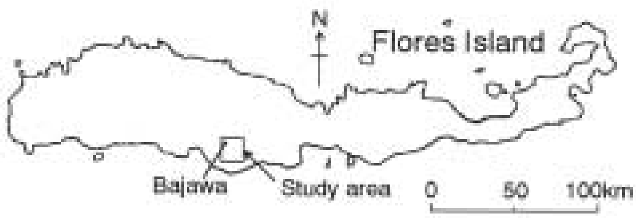

Fig. 1 Locality of study area.

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2. Outline of geology, chronology and geothermal features

The only published geologic map concerning the study area is by Koesoemadinata *et al.* (1994) on a scale of 1:250,000. The geology of this area is described as Quaternary volcanic rocks and Mt. Inerie and Mt. Inerika lavas. Through this cooperation research project, detailed geologic succession and structure have been proposed. Muraoka *et al.* (2000) classified Pliocene into six formations and Pleistocene into seven formations for an area wider than the study area in this paper. All formations are of volcanic origin such as lava and pyroclastic, lacustrine and lahar deposits. Most of them have the composition of basalt or basaltic andesite with a few exceptions of rhyolitic lava and pumice. The formations distributed in our study area are Waebela Basalt (K-Ar ages: 2.40 Ma and 1.61 Ma), Wolo Sasa Andesite, Aimere Scoria Flow Deposits (K-Ar ages: younger than 0.15 Ma for two samples), Mataloko Andesite, Wolo Bobo Andesite, Inerika Andesite and Inerie Basalt in ascending order. Paleomagnetic data shows that the age of Wolo Sasa Andesite is older than 0.73 Ma.

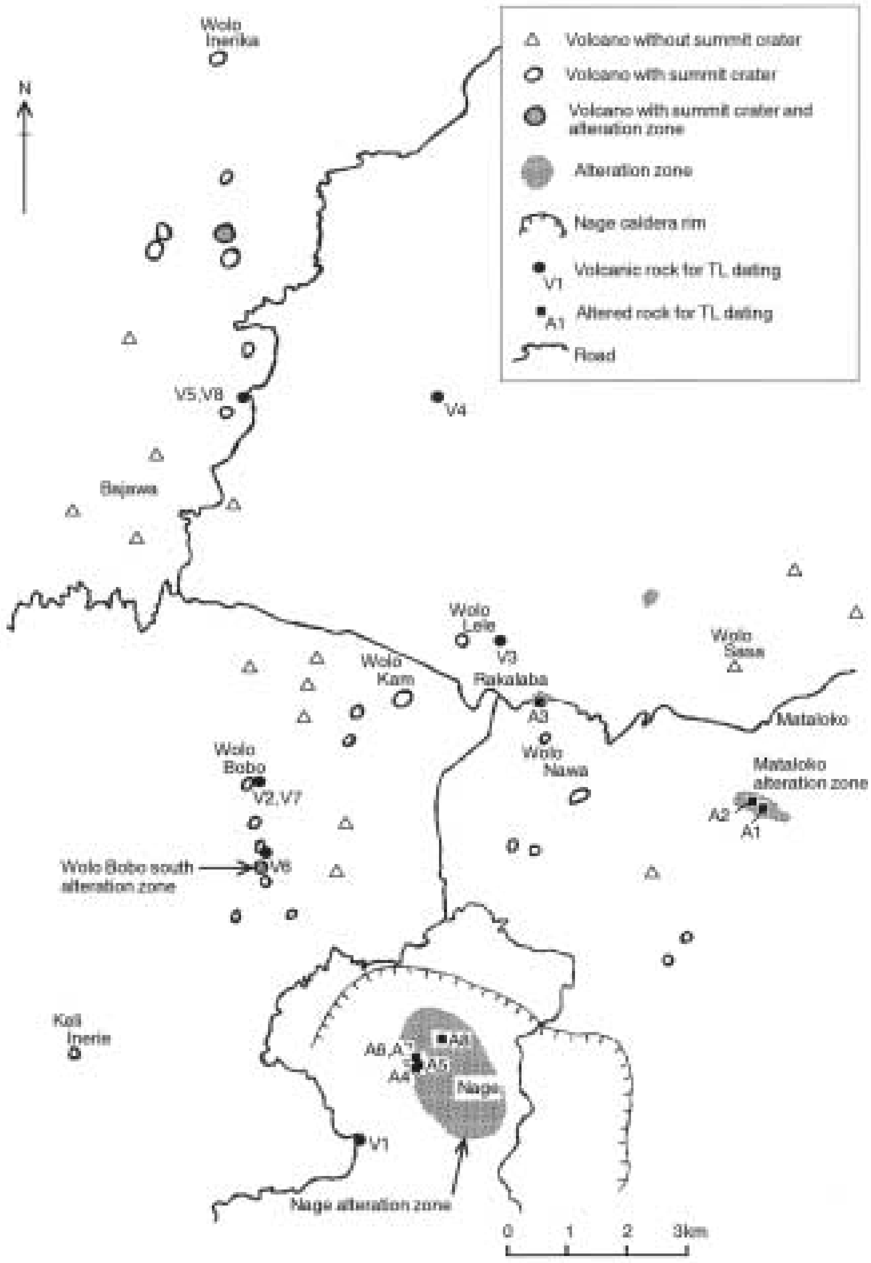

Fig. 2 Distribution of volcanic centers by observation of the satellite image, sample localities and geology/geothermal features.

Takahashi, H. *et al.* (2000) studied a smaller area than Muraoka *et al.* (2000) and divided the volcanic products into four units based on analyses of satellite image and field survey. They are Old Volcanics (K-Ar ages: 1.1 Ma and 1.6 Ma), Bajawa Caldera Volcanics (K-Ar age: younger than 0.15 Ma), Cone Volcanics (K-Ar age: yonger than 0.15 Ma) and Inerie Volcanics in ascending order. They identified the Nage caldera which surrounds the Nage geothermal field.

Since there is no location data and different geological criteria in both studies, it prevents a detailed chronological discussion.

Alteration halos are shown in Fig. 2. White altered lands are sporadically distributed. Three of them, Mataloko, Nage and South of Wolo Bobo, have fumaroles and hot springs. Mineral composition and hot spring data are summarized by Takahashi, H. *et al.* (2000) and chemistry of hot springs are reported by Takahashi, M. *et al.* (2000).

3. Samples and method of thermoluminescence dating

We selected five quartz bearing volcanic rocks and eight altered rock samples for TL dating by X-ray diffraction because reliable TL age can be obtained by the measurement of quartz. Except for the Nage geothermal field, silica minerals identified from altered rocks were mainly α-cristobalite, and only eight samples were selected for TL age determination. We tried to measure the TL age from plagioclase in volcanic rocks. From the 10 plagioclase samples, final results were obtained for only three samples. Locations of the samples are shown in Fig. 2. Volcanic rock samples for TL dating were selected based on the geologic map by Muraoka *et al.* (2000) with formations younger than Wolo Sasa Andesite.

The procedure of TL dating is almost the same as Takashima and Watanabe (1994). The sample is crushed smaller than 0.84 mm for γ-ray spectrometry. Another fraction is crushed to 0.077-0.25 mm for quartz or plagioclase separation by a magnetic separator and chemical treatments of HF and HCl.

Annual dose (AD) was calculated from contents of U, Th and K obtained by γ-ray spectrometry. In this calculation, the contribution of an α-ray was counted for altered samples because secondary quartz in altered rock is small enough to interact with an α-ray. Correction factor of a γ-ray is 0.1 based on the suggestion of Aitken (1985). Cosmic ray contribution is also considered. The average contribution of a cosmic ray is 0.2-0.3 mGy/y. However, samples collected for dating had been kept in depth for a long geologic time and appear on the surface at present. Figure 3 is a schematic model for such process in case of the initial burial depth was 10 m. Accordingly, we must count the cosmic ray contribution by analyzing the topography of sampling site.

Paleodose (PD) or accumulate dose was obtained by measurement of light emission of separated quartz or plagioclase. In this process, natural and artificially irradiated mineral grains were measured. Glow curves of quartz and growth curve for PD evaluation are shown in Figs. 4 and 5, and those for plagioclase are shown in Figs. 6 and 7. The growth curve method (Takashima and Honda, 1989) is used for quartz. However, plagioclase is drown by the additive dose method because plagioclase tends to change the TL sensitivity by the preheat (320 ℃) treatment.

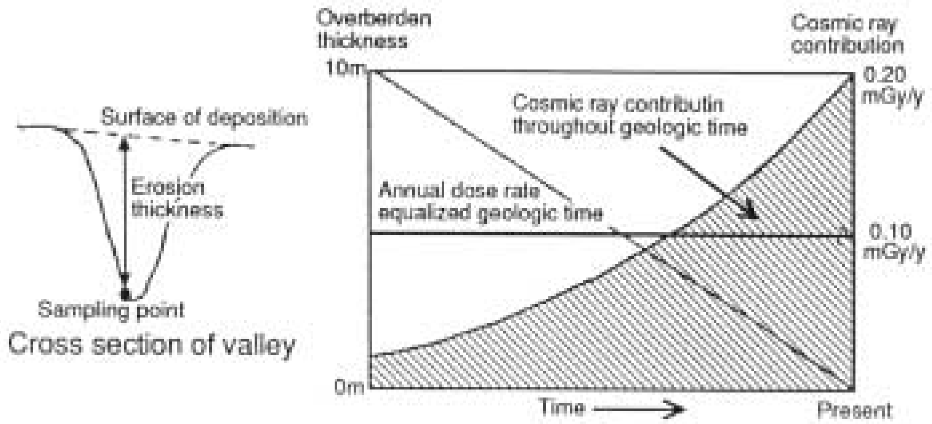

Fig. 3 Model of cosmic dose rate with erosion.

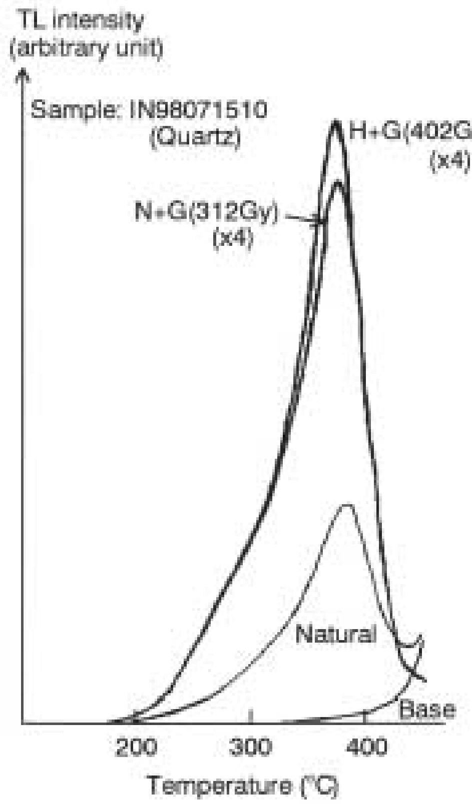

Fig. 4 TL glow curves of quartz separated from altered rock. Increment of TL glow is caused by γ-ray (^{60}Co) irradiation to natural (N+G dose, Gy) and preheated (H+G dose, Gy) samples.

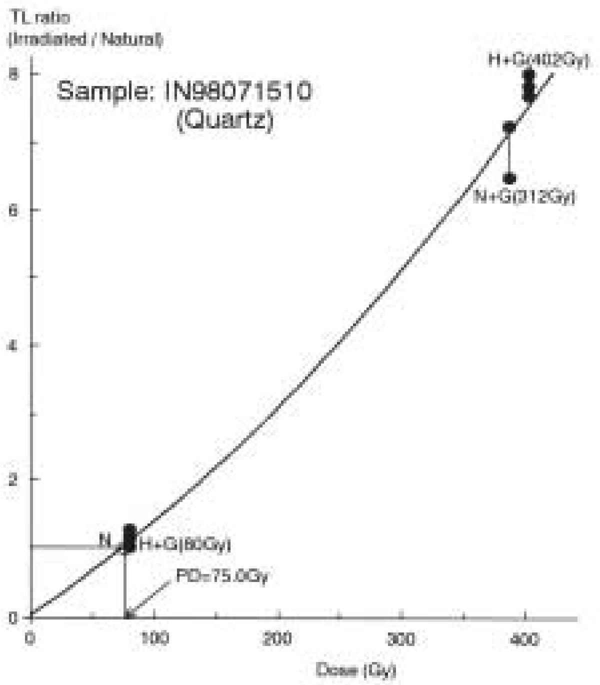

Fig. 5 TL growth curve of the same sample as Fig.4. Paleodose (PD) is obtained from the data of TL peak height ratios of γ-ray irradiated/ natural shown in Fig. 4.

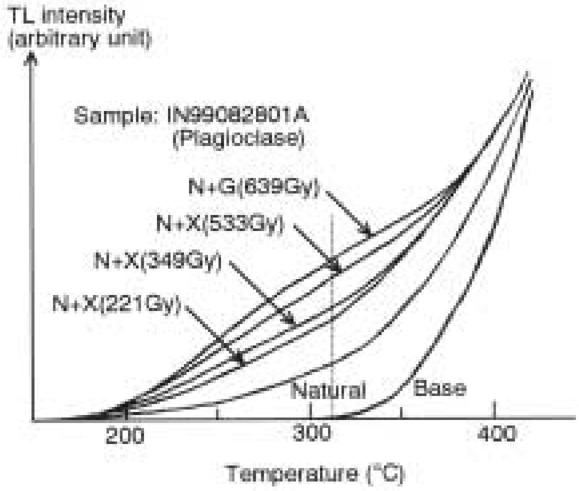

Fig. 6 TL glow curves of plagioclase separated from volcanic rock. Explanation is same as Fig. 4, but X-ray is added for irradiation. The identified temperature for intensity is shown by dotted line.

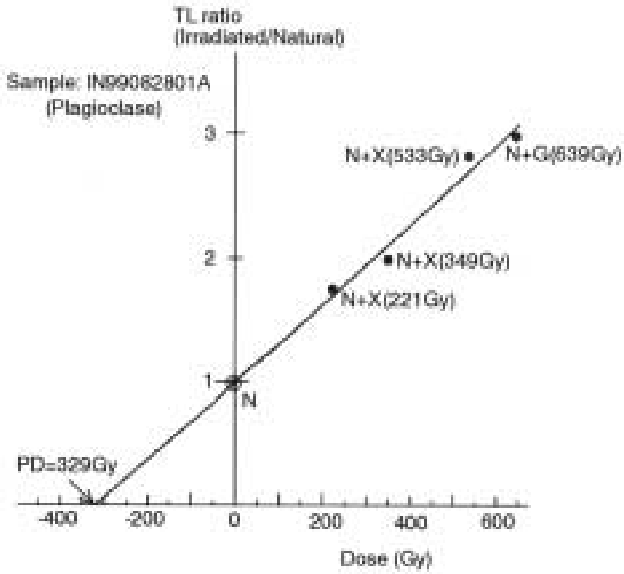

Fig. 7 Paleodose (PD) evaluation by the additive dose method. PD is obtained data only (N+G/X dose, Gy) data. Other explanations are same as Fig. 4.

4. Ages and description of volcanic rocks

Ages of eight volcanic rocks range from 32 ka to 160 ka (Table 1). The errors are not specified but roughly estimated values are about 15-30 %. The description of the measured samples is as follows. Formations shown in Table 1 are from Muraoka *et al.* (2000).

V1 (32 ka): Fresh andesite rock fragment; basaltic pyroclastic flow deposit.

V2 (82 ka): Fresh andesite rock fragment; phreato-magmatic deposit.

V3 (160 ka): Fresh andesite rock fragment; pyroclastic flow deposit.

V4 (98 ka): Fresh andesite lava; lava flow thickness over 30 m in outcrop.

V5 (105 ka): Fresh andesite rock fragment; phreato-magmatic deposit.

V6 (147 ka): Fresh andesite rock fragment; phreato-magmatic deposit.

V7 (72 ka): Fresh andesite rock fragment; phreato-magmatic deposit; same outcrop as V2 but about 5 m in the upper horizon.

V8 (128 ka): Fresh andesite rock fragment; phreato-magmatic deposit; same outcrop as V5.

Table 1 TL ages of volcanic rocks in the Bajawa area.

Locality No.	Sample No.	U (ppm)	Th (ppm)	K_2O (%)	Annual dose (mGy/a)	Paleodose (Gy)	TL age (ka)	Formation (Muraoka et al., 2000)
	(Quartz)							
V1	IN98071607	2.01	8.93	1.77	2.46	77.4	32	Inerie Basalt
V2	IN98071701A	2.09	10.13	1.59	2.42	199	82	Wolo Bobo Andesite
V3	IN98071702B	1.79	7.28	1.34	1.96	313	160	Mataloko Andesite
V4	IN98071703C	1.49	7.20	1.13	1.72	169	98	Inerika Andesite
V5	IN99083001B	1.60	7.86	1.27	2.03	213	105	Inerika Andesite
	(Plagioclase)							
V6	IN99082801A	2.49	9.55	1.51	2.18	321	147	Wolo Bobo Andesite
V7	IN99082802	2.00	8.17	1.39	1.91	137	72	Wolo Bobo Andesite
V8	IN99083001A	1.91	8.27	1.23	1.79	229	128	Inerika Andesite

Table 2 TL ages of altered rocks of Mataloko, Nage and Rakalaba zones.

Locality No.	Sample No.	U (ppm)	Th (ppm)	K_2O (%)	Annual dose (mGy/a)	Paleodose (Gy)	TL age (ka)	Location
	(Altered rocks)							
A1	IN98071301	0.51	1.80	0.08	0.875	20.0	20	Mataloko
A2	IN98071503A	0.34	2.66	0.08	1.92	62.8	33	Mataloko
A3	IN98071510	0.49	4.83	0.20	1.71	75.0	44	Rakalaba
A4	IN98071601A	1.24	3.44	0.09	1.91	103	54	Nage
A5	IN98071602	0.33	0.77	0.09	0.569	6.8	12	Nage
A6	IN98071603A	2.23	5.20	0.09	3.10	166	54	Nage
A7	IN98071603B	2.50	7.17	0.06	3.74	89.2	24	Nage
A8	IN98071605D	4.52	19.43	2.86	10.5	415	40	Nage

5. Ages and description of altered rocks

Ages of eight altered rocks from three alteration zones (Mataloko, Rakaraba and Nage) range from 12 ka to 54 ka (Table 2). The errors are almost same as volcanic rocks (15-30 %). The description of the measured samples is as follows.

A1 (28 ka): White silicified rock; minerals identified in this sample are α-cristobalite and quartz.

A2 (33 ka): White acidic alteration rock; minerals identified in this sample are α-cristobalite, quartz and kaolinite.

A3 (44 ka): Secondary lacustrine deposit of silicified alteration products; minerals identified in this sample are α-cristobalite and quartz.

A4 (54 ka): Silicified rock; mineral identified in this sample is only quartz; host rock is lacustrine deposits because clear bedding is observed.

A5 (12 ka): Silicified rock; mineral identified in this sample is only quartz.

A6 (54 ka): Silicified rock; mineral identified in this sample is only quartz.

A7 (24 ka): Silicified rock; mineral identified in this sample is only quartz.

A8 (40 ka): Silicified rock; mineral identified in this sample is only quartz.

6. Discussion and conclusions

All samples are too young to obtain the K-Ar age. The ages of <0.15 Ma have been reported (Muraoka *et al.,* 2000; Takahashi, H. *et al.,* 2000). The TL ages give an idea of the eruption history for the youngest volcanic group. Figure 8 is the plot of age data to stratigraphic data of Muraoka *et al.* (2000). The small stratovolcanos (Formations of Mataloko Andesite, Wolo Bobo Andesite and Inerika Andesite) in this area are younger than 0.16 Ma and an eruption age of 0.032 Ma was obtained for Inerie Volcano.

The age of small stratovolcanos is young enough to become heat source. The magma type of these volcanic rocks are calc-alkaline, which is suitable for the formation of geothermal systems (Muraoka *et al.,* 2000).

The age data of altered rocks are also limited but show very young. We did not find a quantitative relation between the surface alteration age and underground reservoir temperature. However, a wide and young alteration halo is a good indicator for reservoir evaluation. A direct relationship between eruption of volcanoes and hydrothermal activities is not clear. However, there is some possibility to feed a hydrothermal system by heat from magma of the small stratovolcanic group.

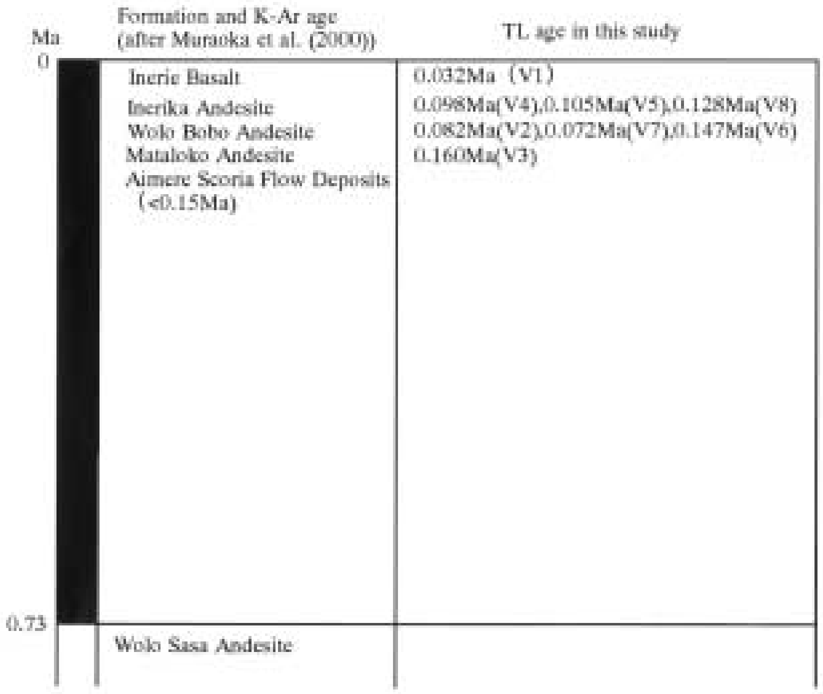

Fig. 8 Schematic diagram plotting TL ages of volcanic rocks to paleomagnetic ages of Mankinen and Darlymple (1979). Stratigraphic sequence follows Muraoka *et al.* (2000).

The TL dating is very useful for age determination of young volcanic rocks and gives new data in the Bajawa area. The TL dating of alteration rocks also gives a rough idea of the hydrothermal activity.

The TL dating is a powerful tool for geothermal exploration. However, there are not enough measured sample to discuss the detailed volcanic history and reservoir evaluation. Further studies are need for plagioclase dating. We also need methods to do a quantitative evaluation of the heat source and reservoir characteristics from the ages of volcanic and altered rocks.

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インドネシア・フローレス島中部バジャワ地熱地域の火山岩及び変質岩の熱ルミネッセンス年代

高島 勲・Asnawir NASUTION・村岡洋文

要　旨

インドネシア・フローレス島のバジャワ地熱地域周辺の火山岩と変質岩の熱ルミネッセンス年代測定を行った．火山岩は，中心部の新期成層火山群を対象に 8 個測定し，最も新しいイネリエ火山噴出物が 32 ka，それ以外の小成層火山が 72-160 ka となった．この年代は，本地域についての初めての報告であり，地熱開発の点では十分熱源になり得るものである．変質岩についても 8 個の測定を行い，マタロコ変質帯では 33 ka，ナゲ変質帯では 54 ka より若く，ともに地下に貯留層が期待される．