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Thermoluminescence Techniques for Geothermal Exploration and Reservoir Evaluation

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ABSTRACT

Thermoluminescence (TL) phenomena of minerals was affected by natural annealing which was caused by geothermal activity and hydrothermal alteration. We applied TL of mineral to geothermal exploration. Quartz is usually used as a mineral for TL dating because of stability of crystal structure and impurity in crystal, and TL of quartz is good indicator to evaluate thermal effect of geothermal activity. We applied TL of quartz in siliceous pyroclastics and intrusive rocks for evaluation of geothermal activities. We present some case studies for applying TL geothermal exploration by using quartz in Japan. Coupled with kinetic equation of TL of quartz and heat transfer in geothermal reservoir, we could propose novel methodology for geothermal reservoir evaluation. We estimate reservoir lifetime, potential and evaluation of sustainable development by TL techniques.

1. INTRODUCTION

Thermoluminescence (TL) is a phenomenon whereby a material (e.g. quartz, feldspar and calcite) emits light when heated. Certain materials accumulate energy as a consequence of their exposure to natural ionising radiation (McKeever, 1985), so that measurement of the “natural TL” (or NTL) emitted by them may be used to estimate their relative ages. Indeed, TL dating is now widely used to date archaeological materials (Aitken, 1985), as well as having applications to geothermal exploration and resource evaluation (Tsuchiya et al., 2000).

The quantity of NTL is strongly affected by natural annealing, which is a limiting factor for dating some archaeological materials, but advantageous for deducing thermal processes within active hydrothermal systems. Quartz and feldspar, in particular, are common primary minerals of many rocks, so their study (from surface or drillhole samples) may provide important information about the physical and/or chemical conditions within a geothermal system (Nambu et al., 1996; Tsuchiya et al., 2000; Saito et al., 2017, 2019; Yamamoto and Tsuchiya, 2006). Since the NTL of these minerals is strongly affected by thermal stimulation, it has the potential to delineate the lateral extent of a geothermal field and relative intensity in different parts of a prospect (as a form of “TL-geothermometer”), and the evolution of the geothermal system (Tsuchiya, et al., 2000).

In this paper, we focus on the NTL signature of primary quartz crystals in tuff, ignimbrite and other pyroclastic rocks collected from active geothermal field. We describe relationship between TL phenomena and hydrothermal alteration of rocks in fossil geothermal field which had activated in Pliocene and Pleistocene. TL exploration techniques can be applied to fossil geothermal area to realize current geothermal activity. TL is also kinetic phenomena which reflects time and temperature relations. We applied kinetic behavior of TL coupled with heat transfer in geothermal field to reveal geothermal reservoir performance.

2. TL MEASUREMENT

2.1 Equipment

We developed two types of TL measurement system. One is portable and the other is desktop type (Fig. 1). The newly developed TL measurement system is divided into three units which are heating, photon-detecting, and control/recording (PC). The photon-detecting unit is composed of photomultiplier (PMT, Hamamatsu Photonics) and HV (high voltage) source (Hamamatsu Photonics).The data logger and heat controller (Temperature control unit) are controlled by PC. Figure 1 shows an overview of the equipment and its schematic diagram. The equipment can be powered by an ordinary electric current source (usually 100V and around 220V available attached with transformer), and all of the items can be packed in a carrying case for transportation. This instrument is manufactured based on the Japanese Patent No.5995021 (Thermoluminescence Measurement System and Method) for geothermal resource exploration. The equipment requires only 20mg sample (quartz), and measurement procedure is automatic sequence for the warm-up and TL measurement by PC. Preparation of samples and measurement procedure were already summarized in Tsuchiya et al (2016).

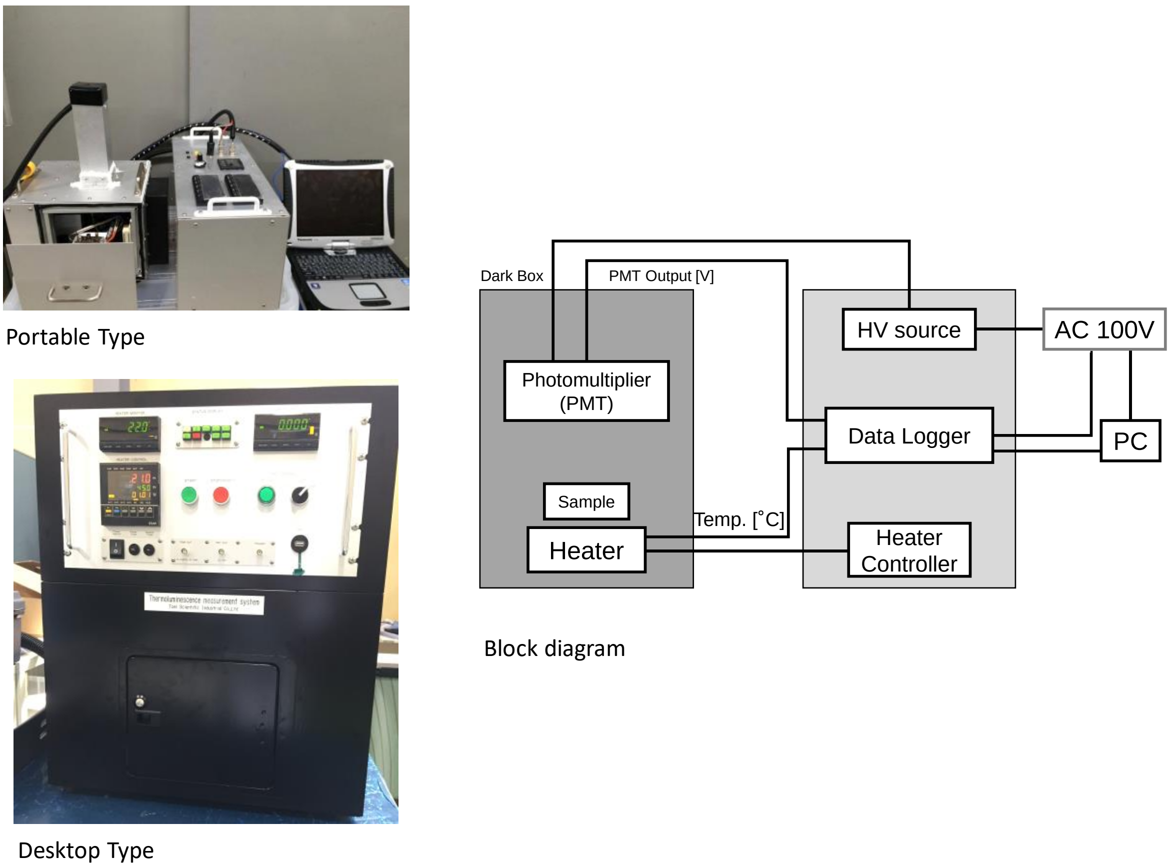

Figure 1: Thermoluminescence measurement system (Portable type (left up) and desktop type (left down).

2.2 Measurement Procedure

First, a specific mineral (quartz) was separated from a whole rock. After cleaning by ultrasonic cleaner, the grain sample was crushed by an agate mortar, and 100-250 µm fraction was obtained by sieving. After accurate weighting, the sample was put in an aluminum pan and placed on the heating element. The sample was heated from an ambient temperature to 400°C for detecting TL emission, and then air-cooled to 50°C. After achieving 50°C, the sample was re-heated to 400°C for measurement of background luminescence (Fig. 2). Heating rates for both cases (TL emission and background) were 1°C/s or 0.5°C/s. TL glow curve were obtained by subtracting the background luminescence (Fig. 2). The continuous procedure was controlled by dedicated software installed in the control PC. TL intensity was described as an arbitrary unit (a.u.), which is actually in a unit of output voltage of the photomultiplier tube divided by the sample weight (V/g).

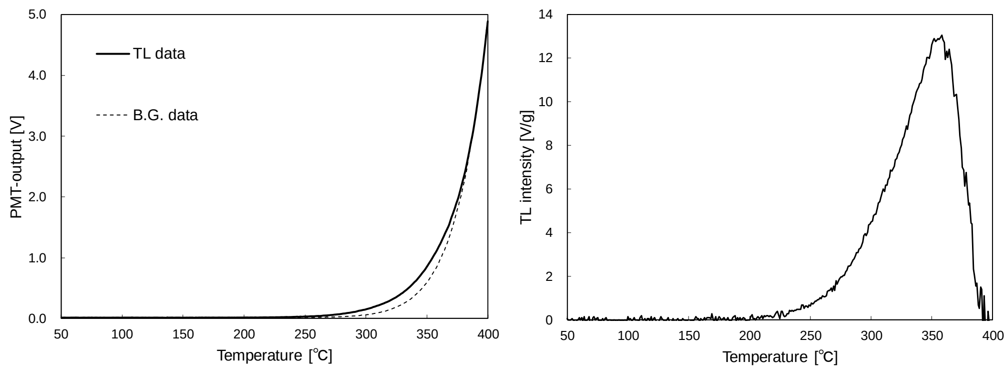

Figure 2: TL glow curve.

3. GEOTHERMAL EXPLORATION

3.1 Shirasawa Caldera

Figure. 3a shows location of the Shirasawa Caldera, west Sendai, Tohoku District Japan. Geological age of the caldera was Pliocene (5 -7 Ma). Diameter of the caldera was ca. 15 km, and the caldera was filled by mainly tuffs rocks and lake sediments. Here is suburban area and many people live in the caldera. Current manifestation of geothermal activity is weak, however, the caldera fill formation was hydrothermally altered due to paleo geothermal activity. Fig. 3b shows TL intensity of quartz collected from the caldera fill sediments. Geological ages of the caldera fill sediments were almost same (5 to 7 Ma). However wide variation of TL intensities (normalized relative intensity between 0.0 and 1.0) was recognized. Low intensity zones (reddish color in Fig. 3b), which indicates strong thermal effect, were distributed along Hirose River in south part and center of the caldera. In the center of the caldera, there is hydraulic dam, shown gray color in Fig. 3b, and the hydraulic dam wall was constructed by using intrusive dike (andesite). High intensity zones (blueish color in Fig. 3b), which suggests weak thermal effect, were in the center of the caldera. Those results indicate that thermal effects are realized along the Hirose river in the south part and around dam in the center. The Shirasawa caldera has been already non-active volcanic caldera and any obvious thermal manifestation was not observed on the surface except hot spring besides Hirose River of which temperature is less than 40℃. Hirose River maybe flow along weak zone by fault and/or lineament, and dike zone around the hydraulic dam was considered to be connected to a magma chamber where was fracture zone due to intrusion of dike. Here is also weak zone and it is a candidate of upwelling zone of geothermal fluid. TL is sensitive sensor to realize upwelling of geothermal fluid. TL can suggest upwelling zone even in fossil geothermal field.

Saito et al (2019) described thermal effect of hot springs in Tsunagi hot spring (Iwate Pref. Northeast Japan). Coupled with 1 m temperature profile, hydrothermal alteration and TL intensity, they mentioned possibility of TL phenomena can realize activities of geothermal and hot spring without surface manifestation.

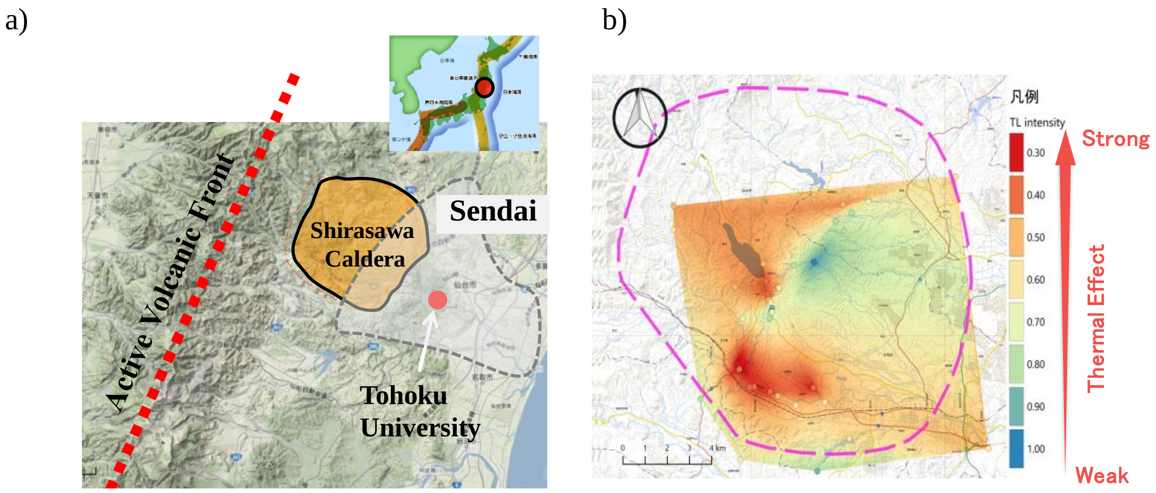

Figure 3: Shirasawa caldera, and TL intensity of quartz in caldera fill sediments (Saito et al., 2017)

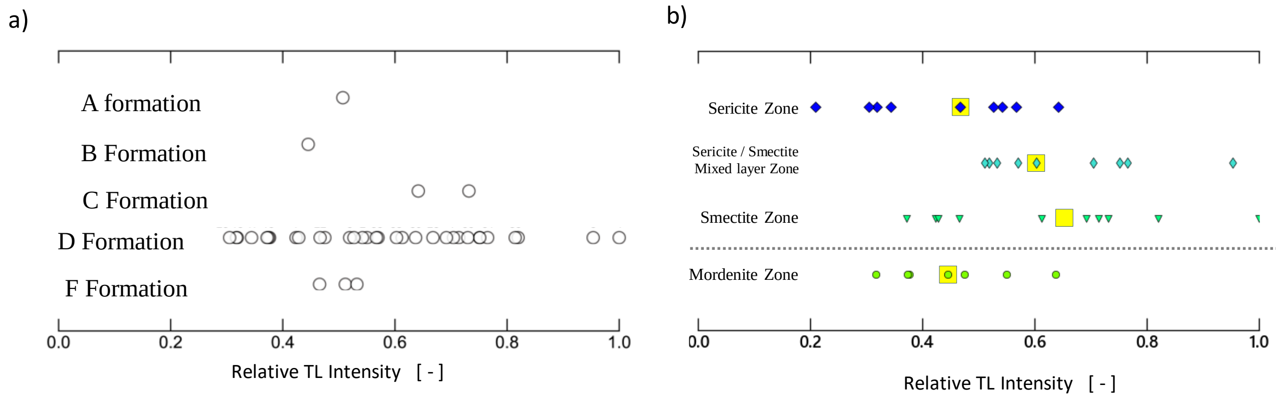

Figure 4: a) TL intensity of geological formation. b) relationship between hydrothermal alteration and TL intensity. Yellow squares indicate arithmetic mean of TL intensity of each hydrothermal alteration zone (Saito et al., 2017).

Figure 4a shows variation of TL intensity (integrated intensity of glow curve normalized by the maximum intensity) of each formation. If TL phenomena could be applied as dating method, TL intensity of the same formation showed the same TL intensity. For instance, TL intensity of D formation (Shirasawa formation which is the main caldera fill sediments) show very wide range from 0.31 to 1.0 (the maximum value) of TL intensity. TL intensities of Formation C and F didn't show single value. Those results suggest that TL intensity could not apply to dating methods in this area, it indicates thermal effect caused by local geothermal activity.

Figure 4b shows relationship between TL intensity and hydrothermal alteration minerals (sericite, sericite/smectite mixed layer mineral, smectite and mordenite). Yellow squares in Fig. 4b indicate arithmetic mean value of TL intensity of each mineral zone. The mean value of TL intensity in the sericite zone (relatively higher hydrothermal alteration temperature) is the minimum and that of smectite zone (relatively lower hydrothermal temperature) was the maximum. Those results suggest that TL intensity was strongly affected by hydrothermal activities, and TL intensity indicates strength of thermal effect of the rock specimen. Relationship between hydrothermal alteration temperatures of clay and zeolite minerals was uncertainly, and it is difficult to compare each other due to variation of chemical composition of rocks and fluid. TL intensity could compare thermal effect in mordenite and clay mineral zones, because TL intensity was represented by arithmetic value. It is possible to compare each other. Variation range of TL intensities and mean values in mordenite and sericite zones were almost same in Fig. 4b, those facts indicate that thermal activity in mordenite zone was almost similar to sericite zone. Hydrothermal mineralization was well recognized as an indicator of geothermal activity, and mineral assemblage of hydrothermal alteration mineral indicate relative paleo-temperature. TL intensity suggests not only paleo-temperature and its duration, and it is possible to compare by using quantitative value of TL intensity.

3.2 Reservoir simulation

TL behavior was kinetic phenomena which was a function of time and temperature. Based on kinetic experiment (isothermal decay experiment), we can obtain kinetic equation of TL phenomena. Heat conduction model was also described as a function of time and position, If we assumed physical conditions of heat source such as temperature, shape, size and thermal conductivity of reservoir rocks, we can calculate heat transfer from the heat source to surface. We already know distribution of TL intensity on surface. Coupling with equations of TL kinetics and heat transfer, we can obtain simultaneous equations to realize relationship among time-temperature-TL intensity for a given position. According to the procedure, we can obtain reasonable heat source model which adapted to TL distribution on the surface, and then we calculated fluid flow model in the geothermal reservoir using HYDROTHERM. This is evaluation methodology of geothermal reservoir performance coupled with TL behavior, heat source model and fluid flow. The procedure is schematically shown in Fig. 5. First Step: TL intensity distribution and kinetic equation of TL intensity, Second Step: Heat Conduction obeyed by Fournier's equation, Third Step: Coupling with TL kinetics and heat conduction, Fourth Step: Coupling with het source model and fluid flow by HYDROTHERM, Fifth Step: Validation with TL distribution. We need several assumptions to apply the methodology for reservoir performance, for instance, heat transfer was only heat conduction, thermal conductivity is homogeneous within the geothermal reservoir and so on. TL phenomena can be applied to not only evaluation of thermal effects but also estimation of lifetime, potential and sustainable development of geothermal reservoir. We tried to simulate potential and sustainable development of geothermal reservoir of Kakkonda geothermal field, Northeast Japan. Based on TL intensity data on surface and boreholes, we could simulate and validate heat transfer as a function of time and depth, and then we could obtain thermal history of geothermal heat source and reservoir.

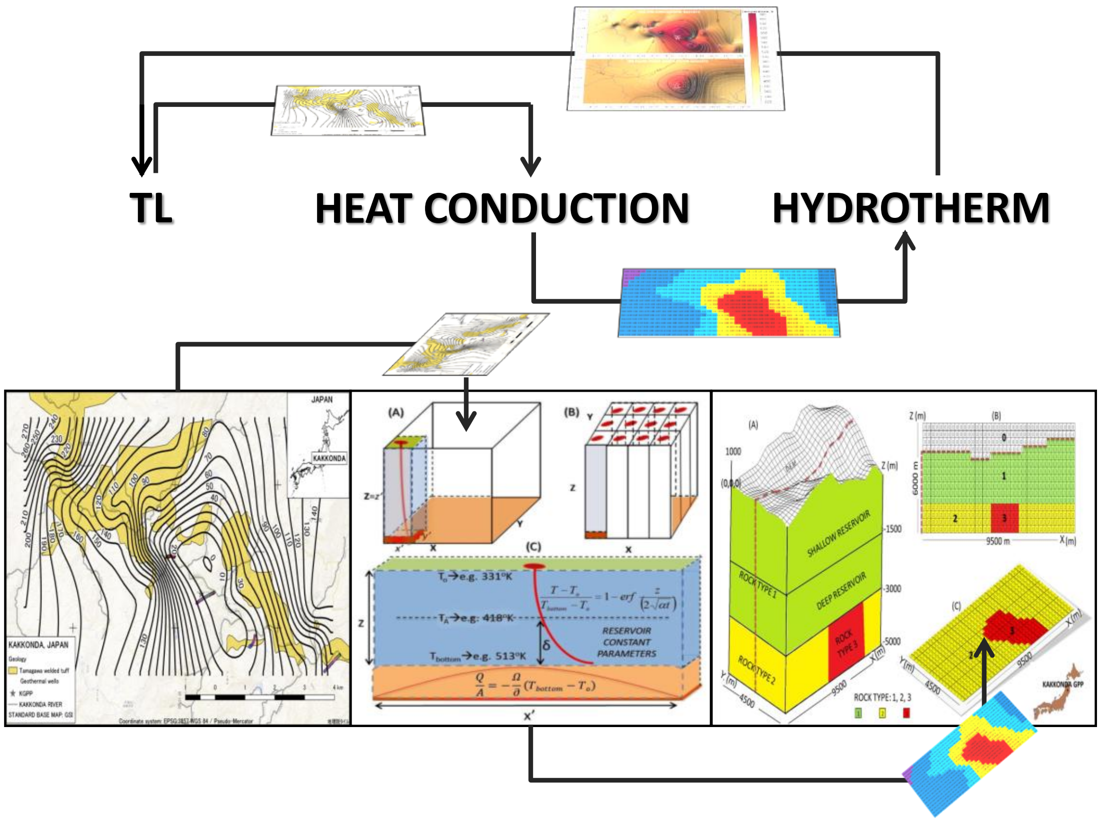

Figure 5: Coupled model of TL, heat conduction and fluid flow.

4. CONCLUSION

Thermoluminescence (TL) phenomena of minerals was affected by natural annealing which was caused by geothermal activity and hydrothermal alteration. TL behaviors of minerals in active and fossil geothermal areas suggest strength of geothermal activities, and we can estimate thermal effect of geothermal activity as well as hydrothermal alteration minerals. We could numerically evaluate geothermal activities using TL intensity of quartz, it is applicable as geothermal exploration techniques. Coupled with kinetic equation of TL of quartz and heat transfer in geothermal reservoir, we could propose evaluation protocol of geothermal reservoir performance such as reservoir lifetime, potential and evaluation of sustainable development, by using TL techniques.

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REFERENCES

Aitken M.J. : Thermoluminescence dating. *Academic Press.* (1985), 359p.

McKeever, S.W.S.: Thermoluminescence of solids. Cambridge University Press,. (1985), 376p.

Nambu, M. et al.: Thermoluminescence of Quartz in the Borehole Cores from the Minase Geothermal Area, Akita Prefecture, Japan. *Journal of the Geothermal Research Society of Japan*, **18**(1996), 39-49. *In Japanese with English abstract*

Tsuchiya, N. et al.:Development of portable thermoluminescence measurement equipment for geothermal exploration, *Journal of the Geothermal Research Society of Japan*, **38**(2016), 127-131.

Tsuchiya, N. et al.: Thermoluminescence as a new research tool for the evaluation of geothermal activity of the Kakkonda geothermal system, northeast Japan. *Geothermics*. **29** (2000), 27-50.

Saito et al.: Thermoluminescence behaviors of quartz in the Miocene dacitic pyroclastics and geothermal exploration in Tsunagi-hot springs, Morioka, Northeast Japan, *Journal of the Geothermal Research Society of Japan*, 41(2019), 215-226. *In Japanese with English abstract*

Saito et al.: Thermoluminescence behaviors of quartz in caldera fill deposit and geothermal exploration in Shirasawa caldera, Sendai, Northeast Japan. *Journal of the Geothermal Research Society of Japan*, **39**(2017), 101-110. *In Japanese with English abstract*

Yamamoto, M., Tsuchiya, N.: Application of TL as a geochemical sensor, *Radiation Protection and Dosimetry*, **119** (2006), 119-123.