

## Novel Geothermal Exploration Techniques by Thermoluminescence of Minerals

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### ABSTRACT

Thermoluminescence (TL) of mineral is widely recognized as a dating technique for relatively young geomaterials that are younger than 1 Ma. However, TL phenomena of minerals are affected by natural annealing which is caused by geothermal activity and hydrothermal alteration. We applied TL of minerals 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 an indicator to evaluate thermal effects of geothermal activity. Andesite and basaltic rocks are widely distributed in geothermal field, and sometimes it is very hard to separate quartz and feldspar in hydrothermal altered rocks even though they have both of quartz and feldspar.

We measured TL phenomena of bulk rock sample without separating quartz, feldspar and other minerals. In the central zone of geothermal area (Hachimantai geothermal field, Northeast Japan), we could not observe any TL of rocks, which indicates geothermal activity is strong enough to reset of natural TL (NTL) of quartz and feldspar. However, after irradiation of cobalt-60, we could obtain TL of quartz and feldspar (ATL: Artificial TL), and integrated intensity of ATL is a relevant indicator to evaluate geothermal activities. NTL could not been observed in strong manifestation area in geothermal field, however ATL is the alternate indicator to evaluate geothermal activity in central zone of geothermal area. TL of minerals (quartz and feldspar) could be effective method to evaluate geothermal activity such as surface manifestations and subterranean heat flow.

### 1. INTRODUCTION

Thermoluminescence has been applied for dosimetry by using high sensitive artificial materials for radiation measurements and dating of geomaterials, which are younger than ca. 1 Ma, by using quartz in rocks. 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; Banerjee, 2001; and Murray-Wallace et al., 2002), 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; Bos, 2007), as well as having applications to geothermal exploration and resource evaluation (Nambu et al., 1996; Tsuchiya et al., 2000).

Although the NTL of minerals has been widely studied, far less attention has been paid to their “artificial TL” (or ATL; i.e. the TL of an artificially irradiated material, after annealing it in the laboratory), and applying the ATL phenomenon to resolving processes and conditions within active/fossil hydrothermal systems. Certainly, TL can vary in intensity and wavelength, due to lattice defects and impurities in a material caused by heating or degassing (Hashimoto et al., 1986, 1994, 2001). Yamamoto and Tsuchiya (2006) described different ATL phenomena in feldspars, in rocks from unaltered and hydrothermally altered zones, but the exact nature of ATL variability as a consequence of structural changes (e.g. distortion of the crystal lattice) resulting from hydrothermal activity is not known.

The quantity of natural TL is strongly affected by natural annealing, which is a limiting factor for dating some archaeological materials, but is 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 drill hole samples) may provide important information about the physical and/or chemical conditions within a geothermal system (Nambu et al., 1996; Tsuchiya et al., 2000; Yamamoto and Tsuchiya, 2004). Since the NTL of these minerals is strongly affected by thermal stimulation, it has a 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 and Nakatsuka, 2002).

In this paper, we focus on the ATL signature of cuttings of volcanics (andesite - basalt) and other pyroclastic rocks within the Hachimantai Geothermal Field, Japan. The Hachimantai area was selected, as it has been explored by drill holes (providing by NEDO and Geo-E) which intersected regionally extensive, quartz and feldspar-bearing units and formations, with a wide variation in style and intensity of hydrothermal alteration. Our study aimed to identify any applications of the phenomena for resolving the nature of geothermal activity within active volcanic-hydrothermal systems.

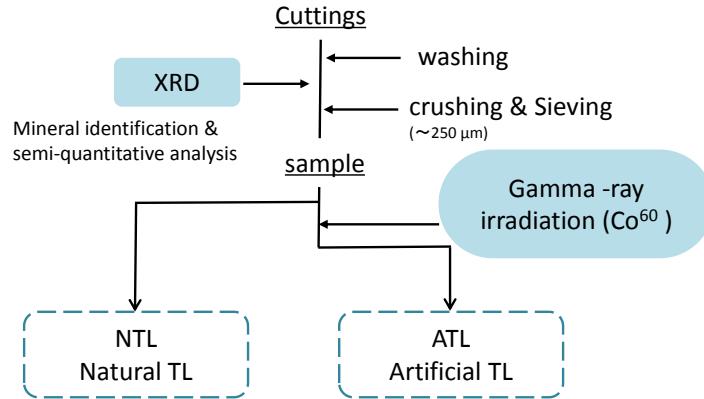
### 2. EXPERIMENTAL

#### 2.1 Field and sample

We collected cuttings of HA-1(1703 m depth, maximum temperature 301°C), 2 (1701 m depth, maximum temperature 277 °C) and 3 (952 m depth, maximum temperature 176 °C) boreholes in the Hachimantai geothermal field, Tohoku District, Northeast Japan. Stratigraphy of the Hachimantai geothermal field was divided into Quaternary volcanics, Tamagawa Welded Tuffs, Yamatsuda F., Koshitomae F. and Kunimitoge F. in ascending order. The area was hydrothermal altered and geothermal manifestation at surface was partly observed. Smectite and mixed layer hydrothermal alteration zone was recognized from surface

to ca. 550 m depth. Chlorite zone (550 m - 950 m depth) and sericite zone (950 m - 1700 m depth) were identified in deep depth. Cutting samples contained some amount of quartz and feldspar with additional accessory minerals which were mainly clay minerals. Semi-quantitative analysis of mineral was carried out by using XRD profiles. It is difficult to separate mineral due to cryptocrystalline texture, In this study, we used bulk cutting samples without liberation.

Figure 1 shows the procedure of sample preparation. After washing, cuttings were crushed and sieved through 250  $\mu\text{m}$ . The measurement samples were for NTL (natural TL) without irradiation and ATL (artificial TL) which was irradiated by using  $\text{Co}^{60}$  at Takasaki Advanced Radiation Research Institute (JAEA: Japan Atomic Energy Agency). Total dose was less than 3000 Gy. ATL showed fading after irradiation (Sanderson, 1988; Pinnioja et al., 1999). We measured ATL after 10 days from irradiation because ATL became stable.

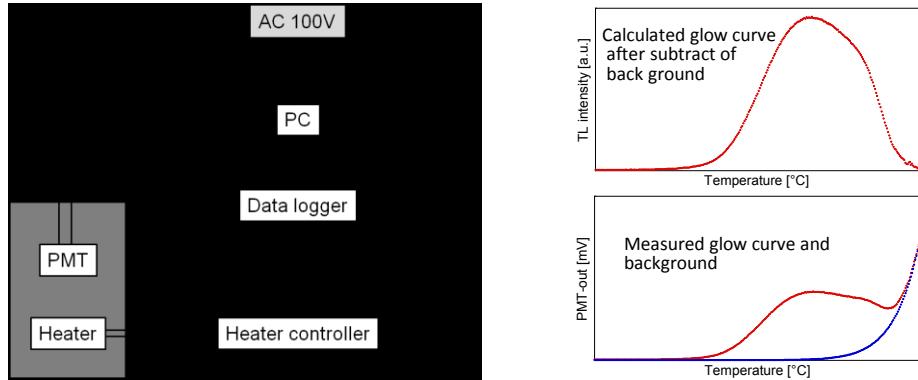


**Figure 1: Procedure of samples for TL measurements.**

## 2.2 TL measurement

A weight of the sample was around 30 mg, and sample was heated up to 400  $^{\circ}\text{C}$  (heating rate 1  $^{\circ}\text{C/sec}$ ). Integrated TL intensity from 325 to 850 nm was calculated in both cases of NTL and ATL. Figure 2 shows a block diagram of the measurement system. High voltage for photomultiplier tube (PMT: Hamamatsu Photonics R376) was ca. 1200 V.

TL emission was measured by PMT and background was increased above ca. 350  $^{\circ}\text{C}$  due to radiation of heater. After subtracting the background, we can obtain a calculated glow curve of the given material, which is schematically shown in Fig. 2.



**Figure 2: TL measurement system and schematic glow curves.**

## 3. RESULTS AND DISCUSSION

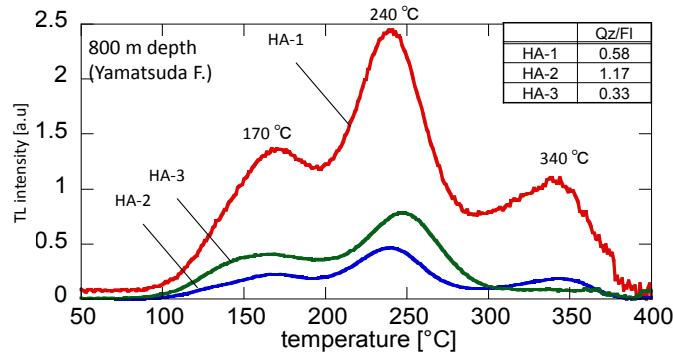
### 3.1 NTL

No NTL emission was observed in all of cutting samples from HA-1, 2, and 3, including very near surface samples. Those facts indicate that surface samples were thermally altered and that all of natural radiation energy has been already released by natural geothermal annealing. In other words, NTL could not indicate any differences of geothermal activity in this field.

### 3.2 ATL

Figure 3 shows examples of ATL glow curve of 800 m depth of the Yamatsuda F. Sample contained quartz and feldspar with additional clay mineral. Semi-quantitative ratio of quartz and feldspar determined by XRD were 0.58 for HA-1 (quartz < feldspar), 1.17 for HA-2 (quartz > feldspar), and 0.33 for HA-3 (quartz < feldspar), respectively. The highest peaks of the glow curves were recognized around 240  $^{\circ}\text{C}$ , and other several peaks were observed between 150  $^{\circ}\text{C}$  and 340  $^{\circ}\text{C}$ . Each peak could not be identified

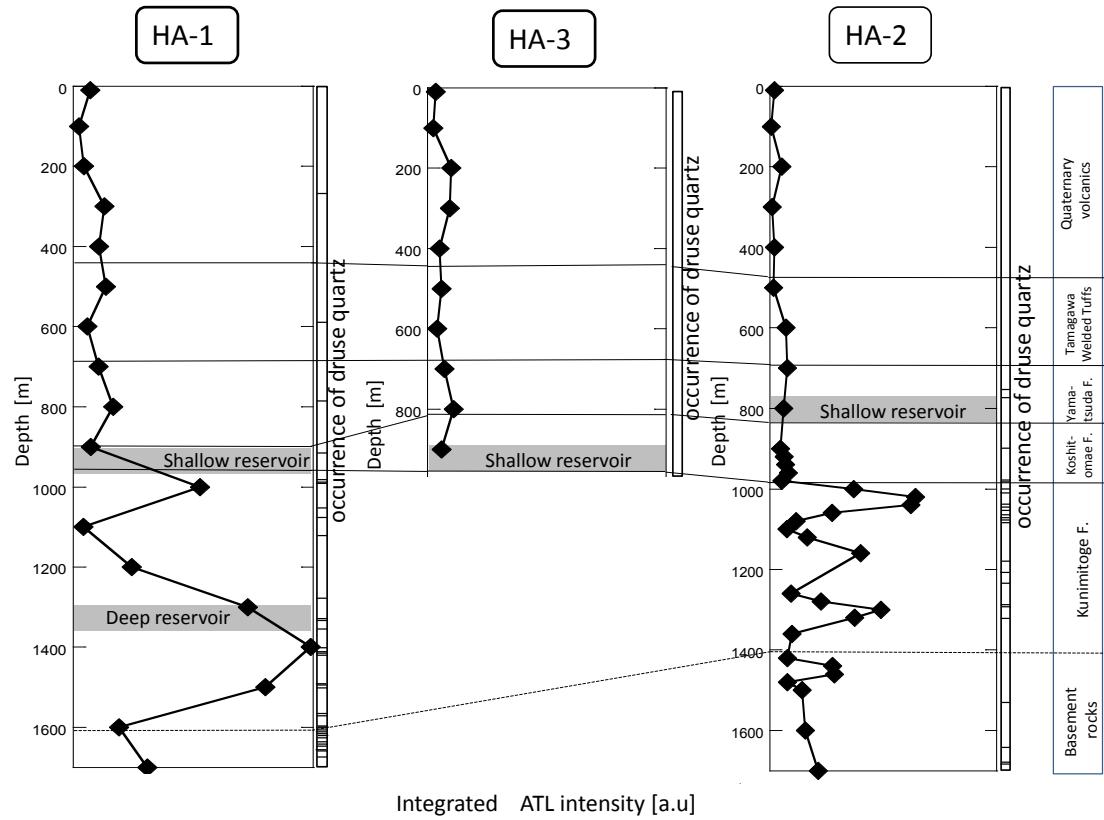
into each mineral due to mixed mineral sample of quartz and feldspar, so that ATL intensity per weight of sample was calculated as integrated intensity from 100 °C to 400 °C.



**Figure 3: ATL glow curves of pyroclastic sample which contains quartz and feldspar.**

Figure 4 shows depth profiles of the integrated ATL intensity. ATL intensities from surface to ca. 800 m depth (Quaternary volcanics, Tamagawa Welded Tuffs, and Yamatsuda Formation) were very weak in all boreholes. Lost circulation was occurred at 930 m (HA-1), 807 m (HA-2), and 906 m in depth (HA-3) (NEDO, 2011), which were recognized as a shallow hydrothermal reservoir. However, significant geological and petrological evidences of shallow hydrothermal reservoir were not so clear.

Several high intensity peaks were observed in deeper parts of HA-1 and HA-3. In case of HA-1, relatively high intensities were observed around 1000 m and 1400 m depth. In case of HA-2, high intensities were observed around 1000 m, 1200 m 1300 m and 1450 m depth. Occurrence of druse quartz which has high transparency with rock-crystal shape is also shown in Fig. 4. Occurrence of druse quartz suggests open fracture and evidences of fluid flow through rock fracture. High intensity of ATL was corresponded to occurrence of druse quartz. Hydrothermal quartz showed thermoluminescence around 470 and 560-580 nm (Rink et al., 1993; Topaksu et al., 2012), hence volcanic quartz has single peak around 630 nm. Quartz formed by hydrothermal environment such as druse quartz was considered to show high sensitivity for ATL. ATL intensities at 1600 m depth of HA-1 was not so high in spite of high density of occurrence of druse quartz. The reason was unclear, however, total amount of druse quartz might be relatively small compared with that of other depth, because host rock deeper than 1600 m in HA-1 was hornfels.



**Figure 4: Depth profiles of ATL intensity of HA-1, 2 and 3.**

#### 4. CONCLUSION

Natural thermoluminescence (NTL) had been decreased by geothermal annealing, which indicates strength and duration of geothermal activities and it could be applied to geothermal exploration techniques. No TL emission could be observed in the central area of geothermal field (Tsuchiya et al., 2000) due to strong geothermal activity. Thermoluminescence technique using NTL is effective method to identify a central zone of geothermal field, however, if surface geothermal manifestation was very strong and wide, it is very difficult to distinguish the most effective geothermal zone because of no NLT. Additionally, if host rock contains small amount of quartz and/or rock has no quartz, it is also difficult to obtain thermoluminescence of quartz. In Japan, high potential geothermal areas are located in and around volcanic area. Andesite and andesite-basalt are dominant volcanic rocks in those areas, which means feldspar is dominant rock-forming mineral compared with quartz. If we could use thermoluminescence of feldspar, TL techniques could be applied to many geothermal fields.

Natural thermoluminescence of feldspar had been considered as unsuitable mineral to determine geological age of rocks because NTL of feldspar is relatively unstable and weak compared with NTL of quartz. However, ATL of feldspar is very strong compared with NTL of feldspar and becomes stable after 10 days from irradiation. We could not separate each minerals but it is effective to use bulk samples which contains quartz and feldspar in the case of ATL measurement. We need further studies such as spectroscopic properties of ATLs of quartz and feldspar, however, ATL of volcanic rocks could be applied as a novel geothermal exploration technique to evaluate geothermal activity such as surface manifestations and subterranean heat flow.

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