Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DEVELOPMENT OF MICROCRACKS IN GRANITES CLARIFIED BY FLUID INCLUSION STUDY : EXAMPLES FROM THE QUATERNARY TAKIDANI PLUTON, JAPAN

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Key Words: fluid inclusion, microcrack, magmatic fluid, hydrothermal, granitoid rocks, Quaternary

ABSTRACT

The Takidani Granodiorite is the youngest exposed plutonic rock on Earth. Hydrothermal processes, and crack formation in the Takidani Granodiorite, characterized by analyzing fluid inclusions in primary quartz. Most of the fluid inclusions are secondary, and have been classified as liquid-rich inclusions, vapor-rich inclusions, and polyphase inclusions.

Homogenization temperatures of the fluid inclusions ranged from about 70°C to over 600°C, which of salinity varies from 1.2 to 73 NaCl eq wt.%. High salinity fluid inclusions occur in samples from the “core” of the zoned pluton. The origin of the high salinity fluid is interpreted to derive from a magmatic fluid which had not been diluted by low temperature, low salinity meteoric water, which prevailed during recent time.

The distribution of healed microcracks in a sample collected from Shiradashi-zawa (S1) show clear preferred orientations; comprising two N-S oriented microcracks dipping to west and east respectively, and E-W striking vertical cracks. These features correspond to the orientation of joints evident at an outcrop scale. Open cracks show one preferred orientation, in places corresponding to the orientation of healed cracks and joints. The homogenization temperature of secondary inclusions trapped along healed cracks from outcrop S1 are between 256°C and 340°C with high salinity (2.6-57 NaCl eq wt.%). The homogenization temperatures were pressure corrected to obtain actual trapping temperatures, assuming a lithostatic pressure obtained by PSHA techniques. Assuming that the generation of the cracks and trapping of fluid inclusions occurred simultaneously, then we infer that microcracks in the Takidani Granodiorite formed at a temperature range of between 280°C and 390°C, close to the transition from subcritical to supercritical hydrothermal conditions.

1. INTRODUCTION

Neogene granite is a most important candidate for hosting a deep-seated geothermal reservoir. In Kakkonda, one of the active geothermal areas in Japan, exploration of the deep-seated reservoir was carried out by geothermal drilling (Doi *et al*., 1998). Yet from drill holes alone, it is difficult to fully understand the structure and history of a geothermal reservoir. Thus, it is useful to study well-exposed neogene granites since they provide invaluable information about potential reservoir characteristics, including fracture networks, size evaluation and various hydrothermal processes.

The Takidani pluton is reported as the youngest exposed granitoid pluton on Earth (Harayama, 1992), after rapid uplift and erosion due to orogenic movement, and represents a useful analogy to granite-hosted hydrothermal reservoirs. A geological survey of the Takidani Granodiorite was undertaken to provide basic information for evaluating possible reservoir performances in the deep subsurface.

Vollbrecht *et al*. (1991) described drill cores of the KTB (Continental Deep Drilling Program of the Federal Republic of Germany) site in Germany. He proposed a model for development of microcracks in quartz in granite based on results of details fluid inclusions study. Fluid inclusions trapped along microcracks provide important information on the characteristics of the fluid, which has passed through the fracture, and potentially on the timing of microcrack formation. Thus, development of cracks, and the character of hydrothermal processes in the geothermal reservoir may be constrained from evaluation of microcracks distribution and microthermometry of the fluid inclusions. This application of fluid inclusion research helps us to understand development of microcracks and fractures.

2. GEOLOGICAL SETTING

The Takidani Granodiorite is located in the active volcanic belt, which comprises the Japan Alps (Fig.1). Vertical and lateral variations of lithofacies within the granitoid have been exposed, due to rapid uplift eastward tilting after emplacement and erosion. The Takidani Granodiorite intruded into Mesozoic basement rocks, a Tertiary granitoid and a Pliocene Andesite complex (Hotaka Andesites), and in the southern part is unconformably covered by the Yake-dake volcanics. The Takidani pluton shows a compositionally zoned structure ranging from granite to granodiorite (Harayama, 1992; Bando and Tsuchiya, 2000). The solidification age is reported to be 1.9 to 2.4 Ma (Harayama.1992, 1994). More detailed geochronological investigations are required to obtain a precise age for this extremely young granitoid pluton.

3. FLUID INCLUSION STUDY: METHODOLOGY

Thirty rock samples, collected from all lithofacies exposed in the pluton were selected, covering a wide geophysical area (Fig.2). The fluid inclusion study was carried out using a Linkam heating-freezing stage with an Olympus 40x long focus lens. Analyses were made on 100 μm-thick doubly polished thin sections.

3.1 Microthermometry of Fluid Inclusions

After observing the fluid inclusion at room temperature, final ice melting and homogenization temperatures were measured for liquid-rich inclusions, and halite melting temperatures were obtained to calculate salinity of NaCl eq wt.% for polyphase inclusions. A phase change was observed for only one vapor-rich inclusion.

3.2 Measurements of Microcrack Distribution

Measurement of strike and dip of microcracks was carried out on 100 μm-thick sections using the universal stage and standard optical microscopy. Three thin sections, perpendicular with respect to one another, were prepared from an oriented sample to count the number of cracks. We used the same correction method as Vollbrecht *et al*. to exclude overlap of cracks in different sections. Crack poles were plotted on a Schmidt net of the lower hemisphere.

4. RESULTS

4.1 Types of Fluid Inclusions and Petrography

Most of the fluid inclusions were classified as secondary, and occur along healed crack planes in quartz. Fluid inclusions were divided into three types; liquid-rich inclusions, vapor-rich inclusions and polyphase inclusions (Fig.3). Liquid-rich inclusions and polyphase inclusions are ovoid, subangular to angular, and/or otherwise irregular. Most of vapor-rich inclusions have a negative crystal form. Daughter minerals in polyphase inclusions were mainly halite, but some unknown daughter minerals were also observed. The predominant type of inclusions varies from sample locality to locality. Most of the fluid inclusions in the samples from the "core" of the zoned pluton were identified as polyphase and vapor-rich inclusions. Some specimens contain only vapor-rich inclusions, indicating that they trapped fluid which had boiled.

4.2 Microthermometric Data

Fig.4.(a)-(h) show microthermometric data of fluid inclusions from the Takidani Granodiorite. Homogenization temperatures of inclusions ranged from 70°C to over 600°C and salinity of the fluid inclusions was between 1.2 and 73 NaCl eq wt.%. Clearly, both T_h and salinity show a wide range. Salinity of liquid-rich and vapor-rich inclusions was calculated by the method described by Bodnar (1993). The equation (number 2) of Bodnar and Vityk (1994) is applied to polyphase inclusions. High salinity fluid inclusions occur near the "core" of the zoned pluton.

A variety of lithofacies outcrops along the Shiradashi-zawa. Outcrops S3-S5 (Fig.4.(a)) are located towards the core of the pluton, based on the lithostratigraphic classification of Bando and Tsuchiya (2000). Characteristics of fluid inclusions from samples collected at S4 include a very high T_h (>570 °C) and salinity(up to 70 NaCl eq wt.%). In addition, the temperature distribution of fluid inclusion in sample from near the core is wider than that at the margin. Outcrop S8 is located nearest the roof of Takidani Granodiorite, that is, near the margin. The fluid trapped in inclusion from S8 is low salinity (about 0–3 NaCl eq wt.%). In the southeastern part of the Takidani Granodiorite, the "Kamikouchi side", fluid inclusions don't have such variations in type. Th or salinity of fluid inclusions in the "Kamikouchi side" were between 200°C and 350°C, and trapped fluids had a relatively low salinity (2 to 30 NaCl eq wt.%) as shown in Fig.5. The Relationship between homogenization temperature and salinity in the Kamikouchi side shows a linear trend, from 250°C /1.0 NaCl eq wt.% to 300/25 NaCl eq wt.%.

4.3 Microcrack Fabrics

The microcrack fabric for a sample from outcrop S1 was measured (Fig.2). According to Bando and Tsuchiya (2000), the modal abundance of this sample is quartz 27.7, plagioclase 43.6, K-feldspar 16.3, biotite 5.9, hornblende 5.7, magnetite 0.6, respectively, by vol.%.

Cracks in quartz grains were classified as healed cracks which contain fluid inclusions along the fracture plane, and open cracks which contain no fluid inclusions. Most of the microcracks in quartz were intragranular and terminated at grain boundaries. They occur do penetrate quartz-quartz grain boundaries, but are commonly terminated at the boundary with other minerals.

Healed cracks are dominant in the quartz grains. They are relatively shorter than open cracks, and the degree of adhesion along the fracture plane is different for each healed crack. There is no displacement along the fracture planes, indicating that the microcracks formed by tensile stress. Healed cracks show a strong preferred orientation, in three groupings, two N-S oriented microcracks which dip to west and east respectively, and E-W striking vertical cracks (Fig.6.(a)). The degree of preferred orientation for the open cracks is relatively weak compared with that of the healed cracks. Open cracks are oriented only N-S, and generally dip to the west. (Fig.6.(b)). Joints at outcrop show the same orientation as the healed cracks in quartz from collected samples (Fig.6.(c)).

5. DISCUSSION

5.1 Relationship of Compositional Zoning in The Pluton and Fluid Inclusion Data

Coincident to the reversely zoned structure of the Takidani pluton (Bando and Tsuchiya, 2000), high salinity fluid inclusions occur in samples from the core of the pluton, whilst fluid inclusions from the Kamikouchi area show an apparent mixing trends with meteoric water (Fig.5). We suggest that the Takidani Granodiorite derives from one emplacement of a siliceous magma, and that the fluid near the core of the pluton has been little mixed with low temperature, low salinity meteoric fluid. Magmatic fluid is considered to be one of the most likely sources of the high salinity fluid inclusions.

5.2 P-T Condition of Fluid Inclusions and Formation of Microcracks

The homogenization temperature of secondary fluid inclusions in quartz from S1 is 256°C to 340°C, and salinity varies from 2.6 to 57 NaCl eq wt.%. The pressure evaluated by PSHA method (Principle Strain Hysterias Analysis) ranges from 0.32-0.44kbars for the Takidani pluton (Bando and Tsuchiya, 2000). Here we consider pressure to closely relate to the initialization conditions for crack formation in the rock.
The homogenization temperatures were pressure corrected to estimate actual trapping temperature, by considering the PSHA pressures data and isochores. The trapping temperature is deduced to range from 280°C to 390°C (Fig.7). Assuming that the microcracks and secondary fluid inclusions formed simultaneously, then the microcracks which contain the secondary inclusions are estimated have been formed from 280°C to 390°C, which approximates the transition state from subcritical to supercritical hydrothermal conditions. It is, however possible that the trapping temperature is overestimated, because we didn't correct for salinity and other undetermined factors of related to PSHA pressure. Further investigations are required to clarify the relationship between PSHA pressure and microcrack formation.

6. CONCLUSIONS

The result of microthermometry studies of fluid inclusions from the Takidani Granodiorite helps to characterize hydrothermal processes potential deep-seated geothermal reservoirs. High salinity fluid inclusions occur in and around the core of the pluton. Magmatic fluid was considered as a possible candidate for the origin for the high salinity fluid. The orientation of microcracks, based on measurement of strike and dip in thin sections, corresponds to joint orientations evident at an outcrop scale. Hence, the orientation of microcracks in quartz is considered to be closely related to that of the overall fracture network. The temperature of the generation of microcracks, evaluated from the microthermometry of secondary fluid inclusions trapped along healed cracks, suggest a temperature of formation in the range of 280°C to 370°C. Thus, fractures in the Takidani Granodiorite are interpreted to have formed during the transition from subcritical to supercritical hydrothermal conditions.

ACKNOWLEDGEMENTS

We would like to thank Mr. I.Hino of Tohoku Univ. for preparing thin sections. Special thanks are also due to Dr. T.Sawada of Kyoto Univ, for his help throughout the fieldwork. This works was financially supported by JSPS (RFTF97P00901).

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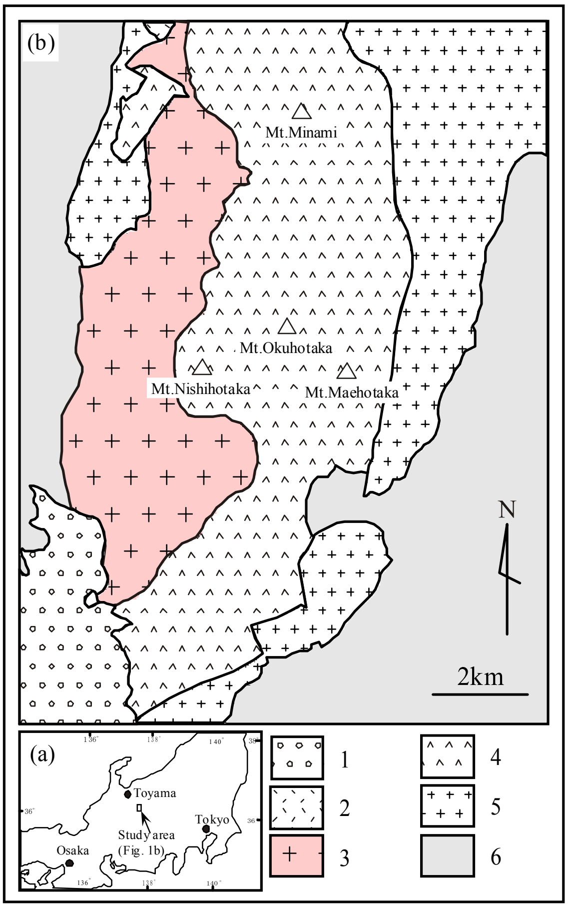


Figure. 1. Geological map of the study area (simplified after Harayama,1992)
1 : Quaternary Volcanic Group, 2 : Pyroclastic Flow Deposit, 3 : Takidani Pluton, 4 : Hotaka Andesite, 5 : Paleogene Granitic Rocks, 6 : Mesozoic Basement.

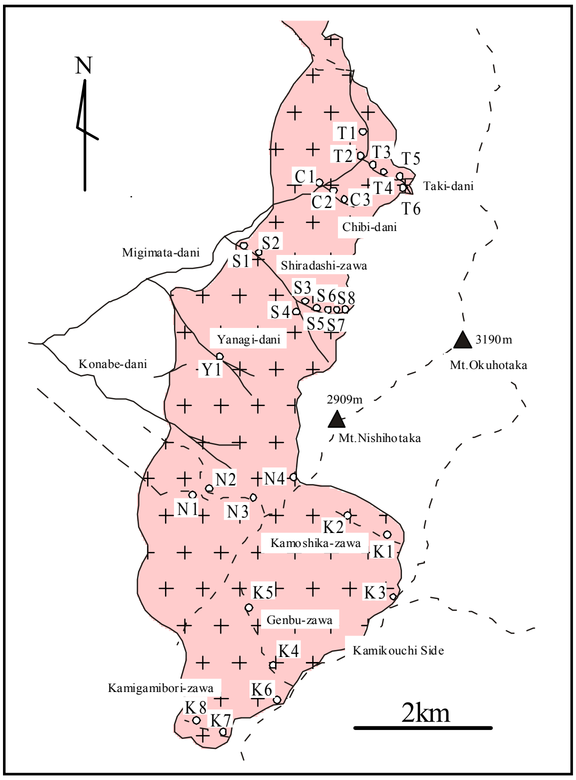


Figure. 2. Sample locality map. T1,T2, ... etc are sample numbers for which fluid inclusion microthermometry studies have been undertaken.

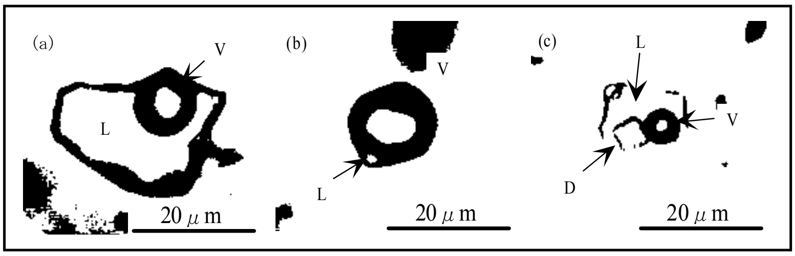


Figure 3. Optical microphotographs of fluid inclusions
(a) liquid-rich inclusion (K7) (b) vapor-rich inclusion (T3) (c) polyphase inclusion (S2)

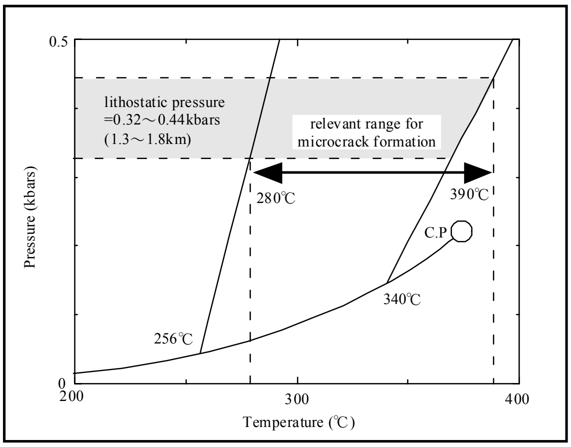


Figure 7. P-T isochore diagram for secondary inclusions collected from outcrop S1 (Shiradashi-zawa, see Fig.2).

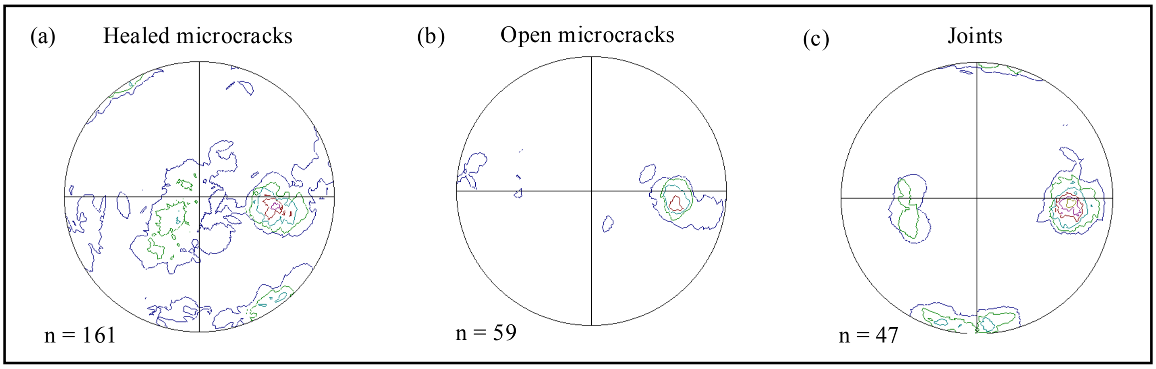


Figure 6. Orientation of microcracks and joints at outcrop S1 (Shiradashi-zawa, see Fig. 2.), projected to a lower hemisphere of the Schmidt net. (a)healed cracks (b)open cracks (c) joints

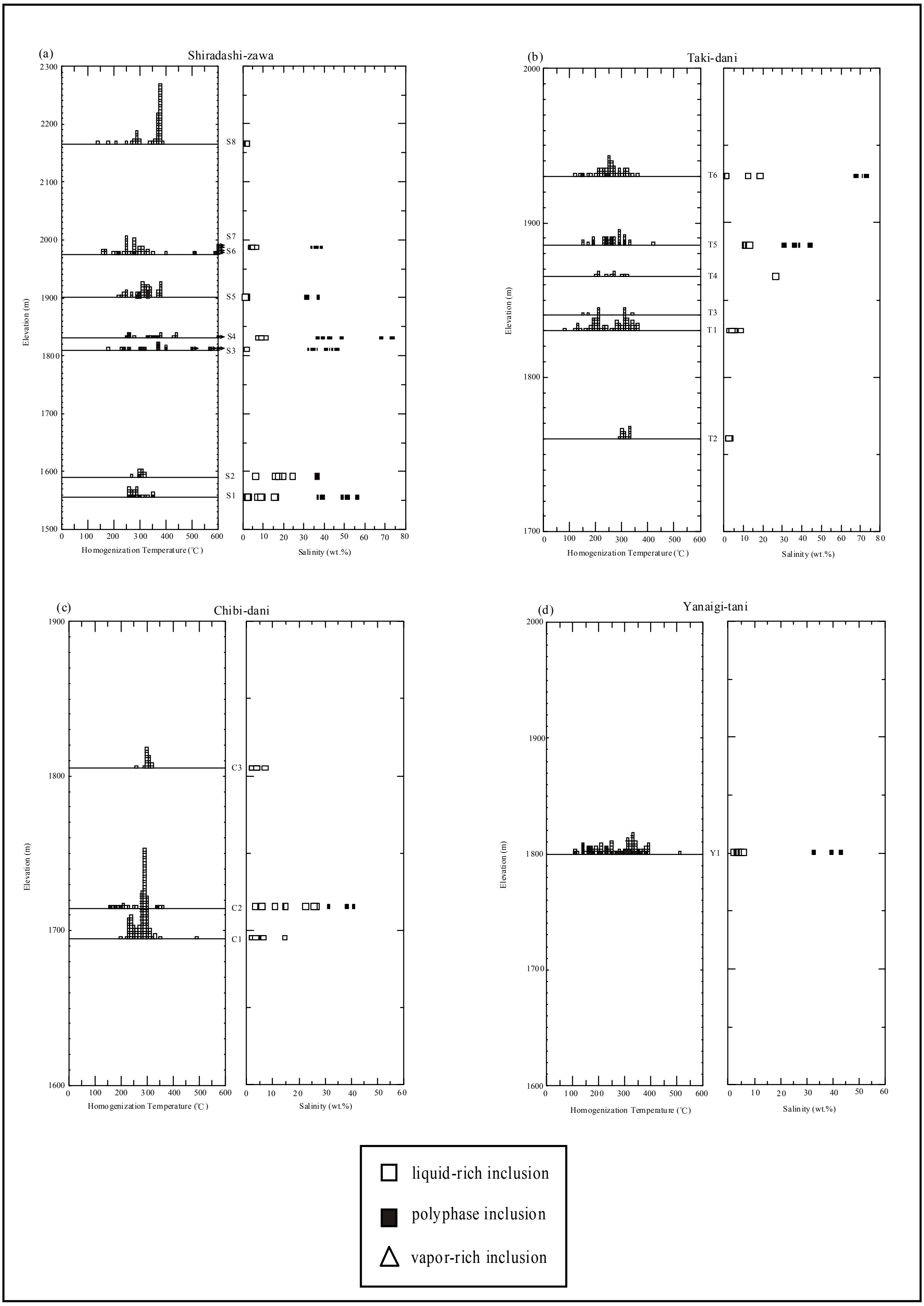
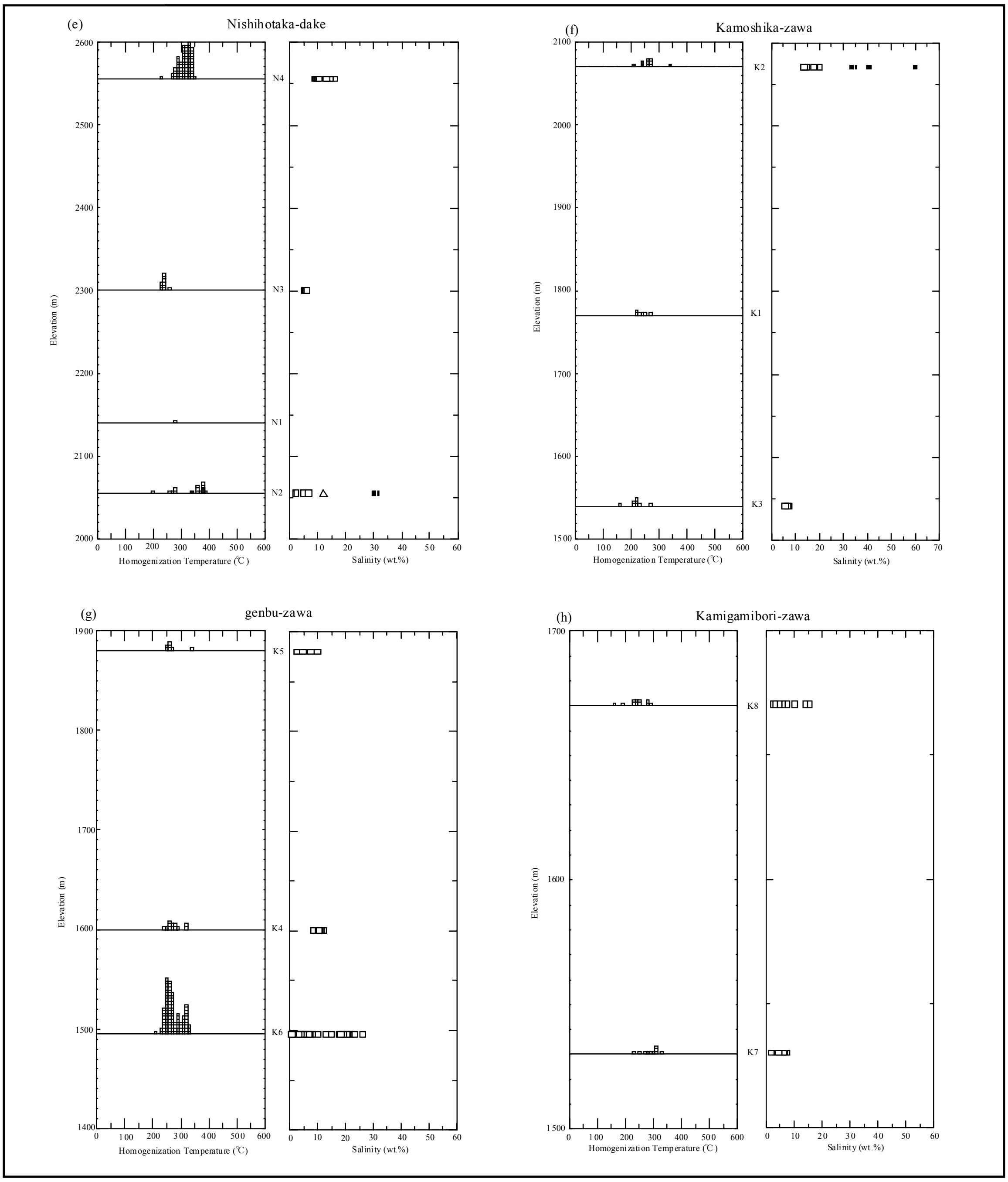


Figure 4. Microthermometirc results of fluid inclusions of the Takidani Granodiorite
(a) Shiradashi-zawa, (b) Taki-dani, (c) Chibi-dani, (d) Yanagi-zawa, (e) Mt.Nishihotaka,
(f) Kamoshika-zawa, (g) Genbu-zawa, (h) Kamigamibori-zawa



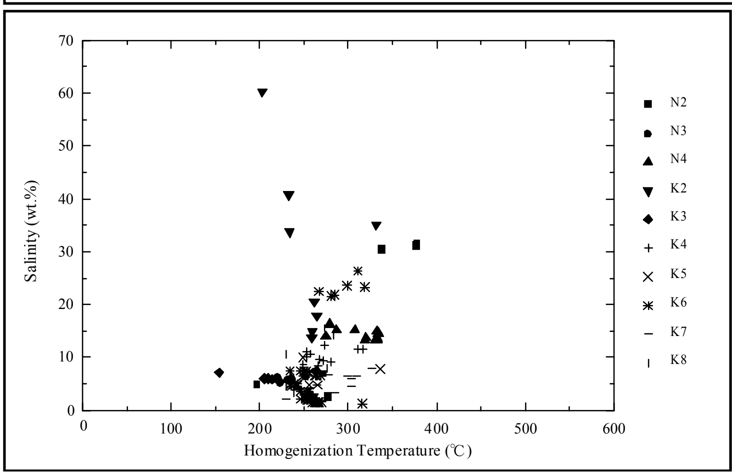


Figure 5. Characteristics of fluid inclusion of the Kamikouchi side