LETTER

Fluid inclusion study of pegmatite and aplite veins of Palaeoproterozoic basement rocks in Bangladesh: Implications for magmatic fluid compositions and crystallization depth

Ismail Hossain*** and Toshiaki Tsunogae*

*Graduate School of Life and Environmental Sciences (Earth Evolution Sciences), University of Tsukuba, Ibaraki 305-8572, Japan
**Department of Geology and Mining, University of Rajshahi, Rajshahi 6205, Bangladesh

We report the first fluid inclusion data on Palaeoproterozoic basement rocks in Bangladesh for the characterization of magmatic fluid compositions and determination of the crystallization pressure and temperature of the host rock. Fluid inclusions are present as primary and pseudosecondary types in quartz grains within pegmatite and aplite, which occur as veins in dioritic rocks. Both primary CO$_2$-rich and H$_2$O-rich inclusions are present, even in the same inclusion cluster, probably reflecting a single stage of fluid activity during the crystallization of the veins. The melting temperature ($T_m$) and homogenization temperature ($T_h$) of the dominant carbonic inclusions are in the ranges of $-56.6 \degree C$ to $-58.1 \degree C$ and $-6.8 \degree C$ to $+30 \degree C$, respectively; the $T_h$ values translate into densities of 0.59-0.97 g/cm$^3$. Rare aqueous fluid inclusions have a final $T_m$ value in the range of 0 $\degree C$ to $-10.8 \degree C$ and a $T_h$ value in the range of $+209.8 \degree C$ to $+405.5 \degree C$, which corresponds to bulk densities of 0.52-0.97 g/cm$^3$. Isochores of the inclusions and temperatures obtained from the zircon saturation thermometry of pegmatite indicate that the veins crystallized at $\sim 4.8$ kbar and 660-670 $\degree C$ (depth of $\sim 14$ km). The results of this study will be useful in understanding the magmatism and metallogeny of felsic igneous rocks of Bangladesh, which are related to the formation of the Columbia supercontinent.

Keywords: Fluid inclusion, Pegmatite, Aplite, Zircon saturation thermometry, Isochore, Bangladesh

INTRODUCTION

Recent geochronological studies on basement rocks in Bangladesh indicate that Palaeoproterozoic (1.72-1.73 Ga; Ameen et al., 2007; Hossain et al., 2007) tonalitic and dioritic rocks exist in the Maddhapara area (Fig. 1), which are regarded as a continuation of the Central Indian Tectonic Zone (CITZ) as a possible remnant of the Columbia supercontinent (Hossain et al., 2007). Although petrographical and geochemical data on basement rocks is available, no detailed geothermobarometric and fluid inclusion studies have thus far been conducted on them. Fluid inclusions in such igneous rocks are regarded as a powerful tool for the characterization of magmatic fluids and estimation of the trapping depth of the fluids, which are useful for the determination of the physicochemical conditions of the source magma.

In this study, we report the first fluid inclusion data on Palaeoproterozoic basement rocks in Bangladesh. A limited number of fluid inclusion studies have been conducted on CITZ rocks; most of these studies have been conducted on metamorphic rocks (e.g., Santosh et al., 2006). In comparison, few studies on magmatic fluid inclusions have been published in igneous rocks related to the formation of the Columbia supercontinent (e.g., Nabelek and Ternes, 1997; Reyf, 1997). Therefore, we have attempted to identify the magmatic fluid phases, densities, and $P$-$T$ conditions of the crystallization of the magma. The results of this study will be useful in understanding the magmatism and metallogeny of the felsic igneous rocks of Bangladesh, which are related to the formation of the CITZ as well as Columbia supercontinent.
SAMPLE

The basement rocks in Bangladesh are predominantly dioritic rocks. Due to the absence of fluid inclusions in this type of rock, we focused on inclusions trapped in quartz grains within pegmatite (samples PLS3 and PL12) and aplite (sample PL7). Both pegmatite and aplite occur as veins having a thickness of up to 50 cm; these veins were possibly intruded together in the cooling stage. Pegmatite is mainly composed of K-feldspar (orthoclase and microcline, up to 2 cm in length), quartz, and albite with accessory zircon, while aplite, which is a typical intrusive rock, is mainly composed of fine-grained plagioclase and quartz.

The temperature of crystallization of pegmatite was estimated using zircon saturation geothermometry. Results of previous experimental studies and the amount of zirconium required for saturation were used to estimate the temperature at which zircon was crystallized (e.g., Watson, 1979; Watson and Harrison, 1983; Ayers and Watson, 1991). Watson and Harrison (1983) revisited the thermometry and investigated the relation between zircon crystallization and melt composition, which is given by the solubility model: $T_Z = 12900/[2.95 + 0.85 \times M + \ln (496000/Zr_{min})]$, where $M =$ molar $[(Na + K + 2 \times Ca)/(Al \times Si)]$. Consequently, $T_Z$ provided a minimum estimate of the magma temperature before extensive crystallization, probably effectively on crystallization depth.

In this study, we adopted the calibration of Miller et al. (2003) to minimize the errors in the calculated value of $T_Z$. The crystallization temperature of pegmatite was estimated as 660–670 °C using the Zr content (46–47 ppm) and $M$ values (1.4–1.5, where $SiO_2 = 73.5–74.7$ wt%, $Al_2O_3 = 13.1–13.7$ wt%, $Na_2O = 2.6–3.0$ wt%, $K_2O = 5.5–6.2$ wt%, and $CaO = 1.4–1.6$ wt%) of bulk rock.

FLUID INCLUSIONS

Fluid inclusions are classified into three types on the basis of their occurrence: primary, pseudosecondary, and secondary (cf., Roedder, 1984). As the inclusions examined in this study occur as isolated aggregates or local clusters formed away from the grain margins of quartz, they are regarded as primary fluid inclusions that were probably trapped during the growth of the host mineral. However, we cannot exclude the possibility that they were trapped in healed and annealed early fractures as pseudosecondary inclusions (e.g., Touret, 2001) (Figs. 2a–2c). They are totally contained within a grain and rarely develop along identifiable cracks. These inclusions commonly occur along crystal growth surfaces and show a general scattered distribution in sections. Secondary inclusions are those inclusions that are formed after the crystallization of a mineral. They are typically located within healed...
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fractures that intersect the host crystal boundaries (Fig. 2d). Pseudosecondary inclusions are formed along microcracks that develop during the partial growth of the crystal and form arrays that pinch out within the grains.

As discussed below, both primary CO$_2$-rich and H$_2$O-rich inclusions are present, even in a single inclusion cluster (Figs. 2b and 2c). Some lengthened inclusions that form trails are also trapped during the growth of the host mineral as pseudosecondary inclusions. Further, there exist some arrays of very small secondary fluid inclusions, which are not suitable for microthermometric measurement. As shown in Figure 2d, the occurrence and size of the secondary inclusions are clearly different from those of the primary inclusions (Figs. 2a–2c). Although feldspar grains have rare primary fluid inclusions, they are very small and unsuitable for analysis. No boiling evidence is recognized in the studied samples.

Microthermometric measurements of the fluid inclusions were performed with a Linkam heating/freezing system at the University of Tsukuba. Calibration was performed using synthetic standard materials supplied by Fluid Inc., Denver. The calibrations were performed at 0 °C (triple point of H$_2$O), –56.6 °C (triple point of CO$_2$), and the critical point of pure H$_2$O with a density of 0.317 g/cm$^3$ (374.1 °C). In the heating/cooling experiment, the melting temperature ($T_m$) and homogenization temperature ($T_h$) of two-phase (gas-vapor) inclusions were measured. The heating rates of the samples were 1 °C/min for $T_m$ and 5 °C/min for $T_h$. Repeated microthermometric measurements indicated that the precision of the microthermometric results reported in this study was within ±0.1 °C for $T_m$ and ±0.2 °C for $T_h$. The results are shown in histograms (Fig. 3) and summarized in Table 1. The $T_m$ values of primary carbonic inclusions are in the ranges of −56.6 °C to −57.9 °C (pegmatite) and −56.7 °C to −58.1 °C (aplite); these values are close to the triple point of pure CO$_2$ (−56.6 °C). The slight depression in the $T_m$ values of some inclusions suggests the probable presence of traces of additional fluid components such as N$_2$ and CH$_4$ in the dominant CO$_2$-rich fluid (Fig. 3a). Continuous heating leads to the homogenization of the inclusions into the liquid phase at a $T_h$ value in the range of −5.8 °C to +30 °C for pegmatite and −6.8 °C to +29.8 °C for aplite (Fig. 3b). When the $T_h$ data is compiled into histograms, most of them show a $T_h$ range of +14 °C to +30 °C. These $T_h$ values translate into CO$_2$ densities of 0.59–0.97 g/cm$^3$.

![Figure 3. Histograms showing the distribution of (a) melting and (b) homogenization temperatures of carbonic fluid inclusions and (c) temperatures of aqueous fluid inclusions in pegmatite and aplite.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock/ fluid types</th>
<th>Melting temperature (°C)</th>
<th>Homogenization temperature (°C)</th>
<th>Density (g/cm$^3$)</th>
<th>Wt %</th>
<th>Type of inclusion</th>
<th>Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLS3</td>
<td>Pék/ CO$_2$</td>
<td>−57.6, −56.6, −56.9±0.4</td>
<td>7.4, 30.0, 23.1±12.1</td>
<td>0.59–0.88</td>
<td>-</td>
<td>Primary</td>
<td>2-7</td>
</tr>
<tr>
<td>PL12</td>
<td>Pék/ CO$_2$</td>
<td>−57.9, −56.6, −57.2±0.3</td>
<td>−6.4, 29.1, 16.1±6.3</td>
<td>0.63–0.96</td>
<td>-</td>
<td>Primary</td>
<td>2-12</td>
</tr>
<tr>
<td>PL7</td>
<td>Apl/ CO$_2$</td>
<td>−58.1, −56.7, −57.1±0.3</td>
<td>−6.8, 29.8, 16.7±9.5</td>
<td>0.60–0.97</td>
<td>-</td>
<td>Primary</td>
<td>2-16</td>
</tr>
<tr>
<td>PL12</td>
<td>Pék/ CO$_2$</td>
<td>−57.2, −56.6, −56.8±0.2</td>
<td>15.7, 30.0, 25.9±5.3</td>
<td>0.59–0.82</td>
<td>-</td>
<td>PS</td>
<td>4-10</td>
</tr>
<tr>
<td>PL7</td>
<td>Apl/ H$_2$O</td>
<td>−10.8, −6.5, −9.0±2.2</td>
<td>209.8, 405.2, 275.5±112.3</td>
<td>0.63–0.97</td>
<td>9.8–14.8</td>
<td>Primary</td>
<td>4-10</td>
</tr>
<tr>
<td>PL12</td>
<td>Pék/ H$_2$O</td>
<td>−3.4, 0, −1.0±1.5</td>
<td>249.6, 405.5, 319.0±60.9</td>
<td>0.52–0.83</td>
<td>0-5.5</td>
<td>Primary</td>
<td>4-12</td>
</tr>
</tbody>
</table>

Pg, pegmatite; Ap, aplite; PS, pseudosecondary.

* Error indicates standard deviation.

Table 1. Summary of the results of microthermometric measurements of carbonic and aqueous fluid inclusions in pegmatite and aplite
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Aqueous fluid inclusions in pegmatite and aplite. The isochore ranges correspond to errors in the calculated densities in Table 1 for (1) primary CO₂ inclusions of pegmatite, (2) primary CO₂ inclusions of aplite, (3) pseudosecondary CO₂ inclusions, and (4) aqueous inclusions. Separate isochores were computed for the highest-density carbonic inclusions of pegmatite and aplite (dashed lines). The shaded area indicates the temperature range of pegmatite obtained by zircon saturation thermometry (660–670 °C). The solidus of the Qtz-Or-Ab-H₂O system was obtained from the study of Johannes (1984).

The composition and density of the fluid phase trapped within the inclusions can be represented through a specific isochore (line of constant volume) in P-T space. The carbonic and aqueous inclusions analyzed in this study have been used for constructing the isochores shown in Figure 4. The fluid densities and isochores were calculated with the computer program “MacFlinCor,” which was developed by Brown and Hagemann (1994), using the equation and thermodynamic data of Brown and Lamb (1989). For the construction of the isochores shown in Figure 4, the minimum and maximum values of Tₘ were adopted for each category of inclusion. Separate isochores were also computed for the highest-density primary CO₂ fluid inclusion in the quartz present in pegmatite and aplite (Tₘ = −5.8 °C to −6.8 °C).

**DISCUSSION**

The petrographic and microthermometric measurements of the fluid inclusions in the pegmatite and aplite veins of the basement rocks in Bangladesh indicate that dominant CO₂-rich and rare H₂O-rich fluids are trapped in quartz at the same stage. Primary to pseudosecondary occurrences of the inclusions suggest that they were trapped during the crystallization of host minerals and that the trapped fluids are magmatic in origin. Some H₂O-rich inclusions are saline with equivalent NaCl concentrations of 0.17–14.8 wt%. Previous studies on fluid inclusions in magmatic rocks suggest that occurrences of such CO₂ + saline H₂O fluids and the dominant CO₂-rich fluid in late-stage pegmatite and aplite are common (Roedder, 1979; Konnerup-Madsen et al., 1985; Reyf, 1997; Nabelek and Ternes, 1997). This is probably due to the separation of the magmatic fluid into two immiscible phases at low temperatures—CO₂-rich gas and salt-rich liquid (brine) (Reyf, 1997)—and/or the change in fluid compositions from H₂O-CO₂ to CO₂ during the crystallization stage (Nabelek and Ternes, 1997). The primary fluid inclusions, which are probably trapped during the growth of quartz, have a wide density range (0.59–0.97 g/cm³). Although most of them have a low density (0.59–0.81 g/cm³), rare high-density inclusions (0.96–0.97 g/cm³) are also present. It is interesting to note that they are trapped together with high-Tₘ (low-density) inclusions. Such a wide density variation and the preservation of the rare high-density inclusions suggest that all the primary fluid inclusions were probably trapped together, and their density decreased significantly during exhumation (Ohyama et al., 2007). Therefore, we infer that the CO₂-rich inclusions with the highest-density values preserve the fluid at magmatic crystallization.

In this study, the crystallization temperature of pegmatite has been estimated to be 660–670 °C by the zircon saturation thermometry of pegmatite. Since both carbonic and aqueous inclusions were apparently trapped in a single stage of fluid activity during the formation of veins, the overlapping ranges of H₂O and the highest-density CO₂ isochores shown in Figure 4 (4.8 kbar at 660–670 °C) probably correspond to the pressure of crystallization of the veins. The pressure of crystallization corresponds to the depth of crystallization at ~ 14 km when the rock density is assumed to be ~ 3 g/cm³. The P-T condition is consistent with the solidus of the Qtz-Or-Ab-H₂O system (Johannes, 1984, Fig. 4), suggesting that the mineral assemblages of pegmatite discussed in this study (quartz + K-feldspar + albite) may have been stable at the P-T condition. Isochors for some low-density carbonic and aqueous inclusions possibly suggest later modification of the fluid density because the cooling path in Figure 4...
intersects the isochores, which is a common feature of retrogressed high-grade metamorphic rocks (Tsunogae and van Reenen, 2007; Ohyama et al., 2007). The crystalization depth of the host diorite is, therefore, regarded to be more than 14 km.

This study provides the first magmatic fluid inclusion data of the basement rocks in Bangladesh formed during the amalgamation of the Columbia supercontinent. The results will be useful in understanding the magmatic activity and metallogeny of basement rocks.

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