Petrography and whole-rock major and trace element analyses of igneous rocks from Iheya North Knoll, middle Okinawa Trough, SIP Expedition CK14-04 (Exp. 907)

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Abstract: The results of petrography and whole-rock major and trace element analyses of igneous rocks from Iheya North Knoll, middle Okinawa Trough, SIP Expedition CK14-04 (Exp. 907) are reported. During Expedition CK14-04, three holes were drilled for taking core samples: one at Site C9016 (Hole C9016B) and two at Site C9015 (Holes C9015B and C). Five pumice pebbles from Hole C9016B and three altered volcanic rocks from each of Holes C9015B and C9016B were analyzed. The pumices were essentially unaltered, and major and trace element compositions were similar to the literature values for middle Okinawa Trough rhyolites, except for Cu and Pb. The altered volcanic rocks appeared to be rhyolites based on microscopic core observations, and various degrees of silicification in terms of whole-rock geochemical composition were observed. Nevertheless, some of the altered rhyolites preserve igneous geochemical features that are similar to the overlying pumices and the middle Okinawa Trough rhyolites.

Keywords: Okinawa Trough, Iheya North Knoll, hydrothermal alteration, Exp. CK14-04 (Exp. 907), DS/DV Chikyu

Introduction

The Iheya North hydrothermal field is located in the middle Okinawa Trough, a young and actively spreading back-arc basin that extends for 1,200 km behind the Ryukyu arc-trench system (Lee et al., 1980; Letouzey and Kimura, 1986). The cross-ministerial Strategic Innovation Promotion Program (SIP) DS/DV Chikyu Drilling cruise, Expedition (Exp.) CK14-04 (Exp. 907), was conducted from September 8 to September 26, 2014, where logging while drilling (LWD) tools were employed to detect a common gigantic subseafloor hydrothermal fluid reservoir beneath the hydrothermal fields suggested by a result of Integrated Ocean Drilling Program (IODP) Exp. 331 (Takai et al., 2011, 2012). Since ocean drilling generally requires tremendous amounts of money and time, it is often difficult to obtain core samples from the ocean floor by regular science protocols. Therefore, such samples have important aspects as common resources for the worldwide science community. In this paper, the results of petrography and whole-rock major and trace element analyses of igneous rocks from the Iheya North Knoll, middle Okinawa Trough, obtained by the SIP Exp. CK14-04 (Exp. 907) are reported. Fore reference, the obtained geochemical data are compared to that of literature values.
(Oiwane et al., 2008). Sedimentary fills were also widely observed in local topographic lows, even on the top of the knoll.

Three active hydrothermal fields have been recognized in the Iheya North Knoll: 1) The Iheya North (original) site (Momma et al., 1996); 2) The Iheya North Natsu site (Kasaya et al., 2015); 3) The Iheya North Aki site (Kasaya et al., 2015). The Iheya North Aki site is the largest hydrothermal field on the Iheya North Knoll.

The descriptions given here are the summary of the CK14-04 Cruise Report (Takai et al., 2015). During the Exp. CK14-04 (Exp. 907), five sites around the Iheya North original site (Sites C9011-C9015) and one site in the Iheya North Aki site (Site C9016) were drilled (Fig. 1). Two holes (C9015B and C9015C) at Site C9015 and one hole (C9016B) at Site C9016 were drilled to investigate the correlation between the measured data from LWD operations and lithology of cored samples.

Site C9015 is located on the western margin of the Iheya North original site, and Holes C9015B and C were cored at this site (Fig. 1). The total penetration of Hole C9015B and Hole C9015C were 31.0 and 40.0 m below seafloor (mbsf), respectively. Hole C9015B is divided into four major lithological units. 1) Volcaniclastic drilling breccia of dacite-rhyolite fragments and sulfide grains (0–18 mbsf). 2) Highly silicified gray quartz-rich ore (keiko-ore) (18.0–23.1 mbsf). 3) Relatively abundant disseminated/semi-massive sulfide ores with minor amounts of highly silicified quartz-rich ore (23.1–23.39 mbsf). 4) Highly silicified angular volcanic rock (keiko-ore) with fine-grained sulfide minerals (23.39–31.0 mbsf). Hole C9015C consists of three major lithological units. 1) Dark gray soupy silt with pumiceous fragments (0–10.0 mbsf). 2) Allochthonous disseminated and semi-massive sulfide ore fragments (10.0–20.0 mbsf). 3) Sulfide ore fragments, fragments of dark greenish-gray highly silicified volcanic rocks with minor amounts of fine-grained pyrite (20.0–40.0 mbsf).

Site C9016 is located at the center of the newly discovered Iheya North Aki site (Fig. 1). The middles of the two active mounds were cored. The total penetration of Hole C9016B was 150.0 mbsf. Cores recovered from Hole C9016B were divided into six major lithological units. 1) Pumiceous gravel, grit, and silty clay sediments (0–9.6 mbsf). 2) Hydrothermally altered clay with lenticular and/or layer-shaped anhydrite, discrete sugary coarse anhydrite crystals and sulfide minerals (9.6–29.5 mbsf). 3) Gray to light gray disseminated sulfide ore (29.5–35.0 mbsf). 4) Gray to light gray hydrothermal altered clay with fine-grained anhydrite aggregates/patches/veins, transparent coarse-grained euohedral sugary anhydrite and very minor fine-grained sulfides (35.0–38.2 mbsf). 5) Dark gray semi-massive sulfide ore (38.2–40.0 mbsf). 6) Gray to whitish-gray highly silicified volcanic breccia or volcanic rock (including keiko-ore) supported by gray to light gray hydrothermal altered clay (40.0–150.0 mbsf).

**Results**

A total of 11 samples were taken from Holes C9015B and C9016B for igneous petrological investigation; five samples were pumices and 6 samples were fragments of igneous rocks in altered igneous rocks or volcanic breccia. The pumice samples were taken from representative portion of pumiceous gravel layers from Hole C9016B (Unit 1), and 6 samples of altered igneous materials, clearly showing igneous origin and capable of whole-rock analyses were taken from Hole C9015B (Units 1 and 2) and Hole C9016B (Unit 6). Methods of sample preparation and analyses, and analytical results of the reference materials are given in Appendix A. Analytical results of whole-rock major and trace elements are given in Table 1. XRD analyses of the bulk powders were also conducted to all samples. In order to avoid complex descriptions, simplified sample names and detailed information on site, hole, core, section and intervals are given in Table 1.

1. **Petrological descriptions**

**15B3RI, Altered rhyolite:** This sample is a subrounded altered volcanioclastic, probably drilling-origin breccia (5 cm in size). Although some degree of alteration is observed, the original igneous porphyritic texture with K-feldspar (Kfs) phenocryst (>0.5 mm in the long axis) is preserved (Fig. 2a). The Kfs phenocrysts exhibit Carlsbad twinning and are partly altered to sericite (muscovite). The groundmass was mostly occupied by granular (<0.1 mm) quartz (Qtz) and very fine-grained clay minerals (illite; Ill). Small amounts of euhedral Kfs, granular pyrite (Py), and sphalerite (Sp) are also observed. Significantly elongated zircon is rarely observed.

**15B3RCC, Altered rhyolite:** This sample is a subrounded altered volcanioclastic drilling-origin breccia (5 cm in size). A porphyritic primary igneous texture with euhedral (0.5–0.2 mm in the long axis) Kfs phenocrysts is still preserved, although some degree of alteration is observed (Fig. 2b). The Kfs phenocrysts are typically surrounded by reaction rims consisting of small granular materials with <0.1 mm width and, show Carlsbad twinning in some cases. The groundmass is composed mainly of <0.1 mm granular Qtz and Ill with minor amounts of euhedral Kfs and
### Table 1. Major and trace element composition of volcanic rocks from the Iheya North Knoll, middle Okinawa Trough.

| Lithology | Alt.Rhyolite | Alt.Rhyolite | Pumice | Pumice | Pumice | Pumice | Pumice | Alt.Rhyolite | Alt.Rhyolite | Alt.Rhyolite |
|-----------|--------------|--------------|--------|--------|--------|--------|--------|--------------|--------------|--------------|
| Site      | C9015        | C9015        | C9015  | C9015  | C9015  | C9015  | C9015  | C9015        | C9015        | C9015        |
| Hole      | B            | B            | B      | B      | B      | B      | B      | B            | B            | B            |
| Core      | 3R           | 3R           | 4R     | 1H     | 1H     | 1H     | 1H     | 1H           | 8X           | 10X          |
| Section 1 | CC           | CC           | CC     | 2      | 2      | 2      | 3      | CC           | CC           | CC           |
| Interval  | 7.10-7.60    | 0.6-0.70     | 8.5-14.0 | 17.5-23.0 | 30.0-34.0 | 44.5-49.5 | 71.0-77.5 | 40.0-44.5 | 20.0-23.0 | 29.0-33.0 |
| Depth (m) | 13.71-13.76  | 14.005-14.065 | 18.065-18.140 | 0.175-0.230 | 1.31-1.35 | 1.455-1.505 | 1.720-1.785 | 2.420-2.465 | 67.67-67.59 | 80.29-80.33 |
| Sample#   | 15B3R1       | 15B3R2       | 15B4R4 | 16B1H1 | 16B1H1A | 16B1H2B | 16B1H2B | 16B1H1B | 16B1H6XCC | 16B1H5XOC |
| FeO*      | 88.29        | 89.35        | 86.48  | 72.29  | 73.82  | 74.52  | 74.79  | 74.17        | 78.19        | 75.35        |
| Fe2O3*    | 0.29         | 0.23         | 0.09   | 0.21   | 0.16   | 0.16   | 0.15   | 0.16         | 0.17         | 0.19         |
| SiO2      | 6.67         | 5.25         | 5.43   | 14.53  | 12.98  | 13.16  | 12.94  | 13.13        | 12.21        | 14.30        |
| Al2O3     | 0.96         | 1.80         | 4.96   | 2.32   | 2.30   | 2.04   | 1.98   | 2.11         | 1.80         | 1.99         |
| Na2O      | 0.02         | 0.02         | 0.02   | 0.06   | 0.07   | 0.07   | 0.07   | 0.07         | 0.05         | 0.04         |
| MgO       | 0.69         | 0.43         | 0.36   | 0.42   | 0.20   | 0.13   | 0.14   | 0.18         | 3.88         | 4.54         |
| CaO       | 0.06         | 0.05         | 0.04   | 0.06   | 0.55   | 0.54   | 0.55   | 0.66         | 0.21         | 0.04         |
| MgO       | 0.48         | 0.27         | 0.18   | 6.04   | 5.56   | 5.46   | 5.89   | 5.89         | 0.19         | 0.20         |
| K2O       | 1.83         | 1.58         | 1.50   | 3.36   | 3.46   | 3.47   | 3.56   | 3.45         | 2.94         | 3.19         |
| P2O5      | 0.01         | 0.01         | 0.02   | 0.05   | 0.08   | 0.08   | 0.06   | 0.09         | 0.02         | 0.02         |
| Total     | 99.32        | 98.99        | 99.18  | 99.84  | 99.19  | 99.82  | 100.13 | 99.79        | 99.07        | 99.04        |
| LOI       | 3.87         | 3.33         | 3.84   | 7.19   | 5.76   | 5.98   | 5.51   | 5.75         | 4.35         | 4.32         |

Fe2O3* and LOI denote total Fe as Fe2O3, and loss on ignition(wt.%). Major elements and trace elements were shown in wt.% and ppm, respectively.
Granular Py. Some euhedral Kfs in the groundmass exhibited a flow structure.

**C9015B-IRCC, Silicified rhyolite:** This rock is a highly silicified rhyolite containing minor amounts of Py and chalcopyrite (Cp). Under the microscope, decussate texture occupied by petal-like mosaic Qtz is typically observed (Fig. 2c). Relatively coarse Qtz (0.7–0.3 mm) with minor amounts of inclusions, and inclusion-rich fine-grained Qtz (<0.1 mm) are observed. Undulatory extinction is observed in the coarse Qtz grains in some cases. Pale brown clay minerals (III) are heterogeneously distributed within the intergranular portion of the Qtz. Discrete columnar to granular-shaped Py, Cp grains (<0.4 mm), and columnar to irregular-shaped (0.8–0.1 mm) Sp grains are also observed (Fig. 2d). Totsuka et al. (2015) reported that minor amounts of apatite and bornite are also confirmed in close intervals of the same core.

**16B1H1, 16B1H2A-C, 16B1H3, Pumices:** The petrographic features of pumices are essentially similar; therefore, five samples are collectively described here. The pumices are pale yellowish-brown and 3.0–2.0 cm in size. Under a microscope, aphyric and fiberglass foam textures are observed (Fig. 2e). A broad peak of glass is also confirmed by XRD analysis. Euhedral Kfs phenocrysts (0.5–0.1 mm in the long axis) are observed in 16B1H2B and C. The fragments of feldspar (<0.1 mm) are observed in 16B1H3.
2f). Minor amounts of granular (<0.1 mm) Py and anhydrite (0.6 mm in the long axis) are also observed. Qtz also occurs as pools (1.0 mm) and veins (<0.1 mm in width).

16B10XCC, **Highly altered rhyolite**: This sample appears to be silicified altered rhyolite with a pale greenish-gray color and contains fine-grained Sp and Py. A granular texture with 0.3 mm petal-like or spotted Qtz, and a very fine-grained matrix (possibly groundmass) are observed under the microscope (Fig. 2g). A sericitic euhedral tabular (1.0 mm in the long axis) feldspar phenocryst (pseudomorph) is also observed (Fig. 2g) with the matrix consists of granular Py and Sp (<0.1 mm), kaolinite, and vermiculite.

16B15XCC, **Highly altered rhyolite**: This sample appears to be highly altered silicified rhyolite with pale yellowish-green to pale greenish-gray color. Trace amounts of fine-grained Py are observed. Under a mi-
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A decussate texture with a large amount of petal-like Qtz is observed (Fig. 2h). Pale brown chlorite and minor amounts of granular Py (<0.1 mm) occurs between Qtz grains.

2. Whole-rock major and trace elements

Pumices from Hole C9016B show a rhyolite composition with SiO₂ contents ranging from 72.3 to 74.8 wt% (Fig. 3). Although the SiO₂ content is comparable with rhyolite of the middle Okinawa Trough (MOT; Shinjo and Kato, 2000), the K₂O content of pumices and rhyolites (16B10XCC) in this study were somewhat high (Fig. 3a). Other major elements are roughly plotted on the trends for rhyolite from the MOT, although the CaO contents of the rhyolites in this study were relatively low (Fig. 4). Two samples of altered rhyolites from Hole C9016B (16B8XCC and 16B10CC) have similar compositions with the pumices, except for significantly high contents of MgO (Fig. 4). Samples from Hole C9015B and one sample from Hole C9016B (16B15XCC) show higher SiO₂ contents than the pumices and deviate from the trend of the MOT rhyolites (Fig. 4).

Although V, Rb, Y, Zr, Ba, and La in the pumices from Hole C9016B were plotted on the trend of rhyolites from the MOT, Sr and Nb from the pumices showed a large scattering without a clear trend (Fig. 5). V, Zr, and Nb for two samples of altered rhyolites from Hole C9016B (16B8XCC and 16B10XCC) could be plotted on the trend of rhyolites from the MOT, as with the major elements, while Rb, Sr, Ba, and La contents were lower than those of the MOT rhyolites. The sample 15B3RCC had a significantly high Ba content (Fig. 5g), suggesting rare occurrence of Anh or barite. Three samples from Hole C9015B and one sample from Hole C9016B (16B15XCC) showed rather different features than the MOT rhyolites, although two samples from Hole C9015B (15B3R1 and 15B3RCC) and 16B15XCC from Hole C9016B had relatively similar trace element compositions. A comparison of Cu, Zn, As, Mo, Pb, and Bi contents between the MOT rhyolites and samples from this study were unable due to lack of reference literature data. The Cu and Pb contents of pumices from Hole C9016B show some variation with respect to the rather narrow range of SiO₂ contents (Table 1). The highly silicified rhyolite from Hole C9015B (15B4RCC) contains Sp and has significantly higher Zn, Mo, and Bi contents (Table 1). All of the altered volcanic rocks from Hole C9015B show various contents of Cu, As, Mo, and Pb without a clear trend. The trace element contents in the samples from Hole C9016B were generally very low, except for significantly higher contents of Cu for 15B8XCC and of Mo for 15B10XCC (Table 1).

Shinjo and Kato (2000) proposed three geochemical groups (Types 1, 2 and 3) for MOT rhyolites. Type 1 rhyolite shows Sr and Nd isotope ratios identical to those of associated basalts, and are characterized by highly fractionated REE patterns, whereas Type 2 rhyolites have slightly higher Sr isotope ratio but similar Nd isotope ratio compared to those of the basalts (Shinjo and Kato, 2000). Type 3 rhyolite occurs only as pumice, which makes its derivation questionable (Shinjo and
Kato, 2000). Although major element chemistry of Type 1 and Type 2 rhyolites are indistinguishable, trace element patterns are clearly different. N-MORB-normalized multi-element patterns and chondrite-normalized rare earth element (REE) patterns of samples in this study were very similar to those of the Type 2 rhyolite from Shinjo and Kato (2000), except for 15B3R1, 15B3RCC and 16B15XCC (Fig. 6).

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* English translation from the original written in Japanese.

** In Japanese with English abstract.

The following Appendixs are published as the open file on the JGS-website.

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Appendix A: Methods

Appendix Table 1: Analytical results of reference materials.