Petrogenesis of middle Okinawa Trough volcanic rocks: Constraints from lead isotopes in olivine-hosted melt inclusions

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ARTICLE INFO

Editor: Catherine Chauvel

Keywords:

Melt inclusions

Pb isotopes

Petrogenesis

Slab subduction

Okinawa Trough

ABSTRACT

Olivine-hosted melt inclusions provide crucial information about their parental magma composition and evolution and represent ideal targets for determining the nature of the poorly understood and still-debated magma sources in the Okinawa Trough, a back-arc basin in the western Pacific. We present the first analyses of the lead (Pb) isotope compositions of olivine-hosted melt inclusions to evaluate the mantle properties and petrogenesis of middle Okinawa Trough volcanic rocks. The melt inclusions have more variable major and trace elements and Pb isotope compositions than the host whole-rock samples. We report the discovery of both high-²⁰⁷Pb/²⁰⁶Pb (> 0.865) and low-²⁰⁷Pb/²⁰⁶Pb (< 0.865) isotope compositions in melt inclusions in individual volcanic rocks, even within a single host olivine, indicating a compositionally heterogeneous magma source. The trace element and Pb isotope characteristics of the melt inclusions show that the magma source is affected by enriched components. We modeled the injection of enriched components into a magma source to explain the generation of the magma heterogeneity. The results indicate that the mixing of Pacific Ocean-type mantle (MORB), an EMI-like component from recycled lower continental crust and EMII-like material from subducted sediments can explain the low-²⁰⁷Pb/²⁰⁶Pb isotope values observed in the melt inclusions. The discovery of small proportions of melt inclusions with high ²⁰⁷Pb/²⁰⁶Pb ratios, high K₂O, P₂O₅, Rb and U contents and low Pb and Cu contents in the studied andesites suggests that the andesitic magma may have been formed by the mixing of materials with different elemental and isotopic compositions. Our study results suggest that pervasive magma mixing may have occurred in the magma source prior to eruption in the Okinawa Trough.

1. Introduction

Assessing the petrogenesis of volcanic rocks in subduction zone settings is important but is also complicated by many different processes, such as fractional crystallization, magma mixing and crustal assimilation, and by geochemical variations in the source components, such as the mantle wedge, subducted oceanic crust and accompanying sediments or melts; these processes and sources exert control over the geochemistry of volcanic rocks (e.g., Hawkesworth et al., 1991;

McCulloch and Gamble, 1991; Pearce and Peate, 1995) and can result in heterogeneity in the Earth's mantle (Hofmann, 1997; Saal et al., 1998; Pilet et al., 2011). Back-arc basins are important part of subduction zones and can reflect magmatism during slab subduction. Compared with intra-oceanic back-arc basins (e.g., the Mariana trough, Manus basin, Lau basin and North Fiji basin), epicontinental back-arc basins may be affected by the continental crust, and the resulting magmatic characteristics are more complex (Shinjo, 1999). Therefore, investigating magmatic activity in epicontinental back-arc basins is

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<https://doi.org/10.1016/j.chemgeo.2020.119600>

Received 20 December 2019; Received in revised form 10 March 2020; Accepted 24 March 2020

Available online 04 April 2020

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conductive to fully understanding subduction-zone magmatism.

The Okinawa Trough, which was formed by the subduction of the Philippine Sea Plate, is a young and actively spreading epicontinental back-arc basin located in the western Pacific (Shinjo, 1999) and is an ideal location in which to study mantle-crust interactions and the genesis of volcanic rocks in a subduction zone setting (e.g., Ishizuka et al., 1990; Honma et al., 1991; Shinjo, 1999; Shinjo et al., 1999; Shinjo and Kato, 2000; Hoang and Uto, 2006; Zeng et al., 2010; Guo et al., 2016a, 2016b; Yu et al., 2016; Shu et al., 2017; Chen et al., 2018; Zhang et al., 2018; Li et al., 2018a, 2018b, 2019). Previous studies have shown that the magma source of the Okinawa Trough is affected by the subductions of the Philippine Sea Plate (Shinjo, 1999), but the subduction components and mantle sources remain controversial (Yan and Shi, 2014). Indeed, the following possible origins have been proposed: (1) the magma may be generated by interactions between enriched mid-ocean ridge basalt (E-MORB)-like mantle and a subducted component (Shinjo, 1999); (2) the magma may be transitional between a Ryukyu island arc-type magma and a normal MORB (N-MORB)-like magma (Ishizuka et al., 1990); (3) the magma may be produced by the interaction between Indian Ocean-type mantle and continental lithosphere (Zeng et al., 2010); or (4) the magma may originate from a mixture of Pacific MORB-like mantle with an enriched mantle type II (EMII) component (Hoang and Uto, 2006). In addition, the identification of magma evolution processes, such as fractional crystallization (Shinjo, 1999), magma mixing (Ishizuka et al., 1990), assimilation and fractional crystallization (AFC) (Shinjo and Kato, 2000; Zhang et al., 2018) and crustal contamination (Guo et al., 2016; Chen et al., 2018), is also controversial in the Okinawa Trough.

Generally, the significant contrast between the Pb concentrations and isotope compositions of the mantle and those of marine and sediments (e.g., Gasparon and Varne, 1998; Chauvel and Blichert-Toft, 2001) indicates that the Pb isotope ratios of mantle-derived magma are highly sensitive to the addition of subduction-related material during the petrogenesis of volcanic rocks (e.g., Miller et al., 1994; Carpentier et al., 2008). However, surprisingly few published Pb isotope data are available for Okinawa Trough volcanic rocks, and all of these rocks plot in the Indian Ocean-type mantle field (Hoang and Uto, 2006; Guo et al., 2016; Shu et al., 2017; Li et al., 2018; Zhang et al., 2018), even though the corresponding samples were collected in the Pacific Ocean. In addition, most previous studies in this region were based on whole-rock data, and the chemical and isotopic signatures of magma sources can be obscured due to complex petrogenesis involving fractional crystallization, magma mixing and crustal assimilation (e.g., Sobolev, 1996; Ren et al., 2005); thus, whole-rock compositions cannot be effectively used to represent the parental magma compositions and reveal magma evolution processes. Melt inclusions are small magma droplets trapped in phenocrysts during crystallization (Sorby, 1858; Roedder, 1979), in which the trapped melt has been minimally modified by magma processes, such as assimilation, contamination or degassing processes (Zajacz and Halter, 2007; Ren et al., 2017). Therefore, melt inclusions have proven to be a valuable tool for defining the compositions of pre-aggregated melts and assessing the petrogenesis of volcanic rocks, which may not always be identifiable through the analysis of whole-rock samples (e.g., Saal et al., 1998; Sobolev et al., 2000; Ren et al., 2005, 2017; Kamenetsky et al., 2006, 2012).

In this paper, we present the first analyses of the Pb isotope compositions of olivine-hosted melt inclusions obtained from middle Okinawa Trough volcanic rocks. The results of this work provide new insights into the geochemical compositions of the magma and demonstrate that these melt inclusions are crucial for testing the petrogenesis of volcanic rocks from the Okinawa Trough.

2. Geological background

The Okinawa Trough is located on the southeastern side of the East China Sea (Fig. 1), where the Philippine Sea Plate is subducting beneath

the Eurasian Plate, forming a back-arc basin in the Ryukyu basin-arc-trench system (Shinjo, 1999). Based on its tectonic characteristics, the Okinawa Trough can be divided into three segments, i.e., the northern Okinawa Trough, middle Okinawa Trough and southern Okinawa Trough, which are separated successively by the Tokara fault and the Kerama gap (Shinjo, 1999). At present, the northern segment is experiencing crustal extension, the middle segment is undergoing propagating rift processes, and the southern segment is showing signs of initial spreading (Yan and Shi, 2014). The Okinawa Trough has experienced intense magmatic activity, which has generated abundant volcanic rocks (Shinjo et al., 1999). The northern Okinawa Trough is dominated by rhyolites (e.g., Zeng et al., 2010), and the southern Okinawa Trough is dominated by basaltic rocks (e.g., Shinjo et al., 1999). The middle Okinawa Trough volcanic rocks exhibit bimodal characteristics, forming a basaltic-rhyolitic suite containing a relatively small quantity of andesite (e.g., Shinjo and Kato, 2000). These three segments have different crustal thicknesses of 15–23 km in the northern segment, 12–18 km in the middle segment, and 10–16 km in the southern segment (Sibuet et al., 1995; Liu et al., 2016). From north to south, the subduction rate of the Philippine Sea Plate increases from 4.9 to 7.3 cm/yr (Shinjo, 1999), and the extension rate also increases from 2 cm/yr to 5 cm/yr (Arai et al., 2017).

3. Samples and analytical methods

3.1. Sample descriptions

The volcanic samples used in this study were recovered using a TV-grab sampler during the R/V Kexue HOBAB 2 cruise in 2014 and the HOBAB 4 cruise in 2016 (Fig. 1). One basalt sample (R2, 27°32′28.214″N, 126°58′37.281″E, 1309.7 m) and two andesite samples (T5-2, 27°32′51.767″N, 126°59′21.669″E, 1283 m) were collected from the middle Okinawa Trough, and whole-rock and olivine-clinopyroxene analyses show that they are co-genetic (Li et al., 2018, 2020a, 2020b) (Fig. 1). The detailed petrography of these samples has been described in our previous studies (Li et al., 2018a, 2018b, 2019). In terms of geochemical characteristics, all of the whole-rock samples are subalkaline and enriched in large-ion lithophile elements (LILEs) relative to the high field strength elements (HFSEs) and rare earth elements (REEs), with obvious positive Pb and K anomalies and negative Nb, Ta and Ti anomalies (Li et al., 2018a, 2018b, 2019) (Fig. 2a, b). The Sr–Nd isotope compositions of the whole-rock samples show that the magma source may have been affected by a subducted sediment component (Honma et al., 1991; Shinjo et al., 1999; Guo et al., 2016; Li et al., 2018) (Fig. 2c). All of the samples collected in this study are phyrlic, and olivine, plagioclase and pyroxene are the main phenocryst minerals (Fig. 3a, b). The olivine phenocrysts in all samples are euhedral to subhedral and contain abundant melt inclusions that are round or elliptical in shape, 30–80 μm in size and distributed randomly within the olivine (Figs. 3c, d and S1).

3.2. Analytical methods

3.2.1. Major element analysis

The preparation of melt inclusions was performed at the melt inclusion laboratory in the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). Photomicrographs under both transmitted and reflected light were used to select unaltered melt inclusion-bearing olivine phenocrysts for elemental and isotopic analysis. The melt inclusions, which were affected by significant post-entrapment crystallization (Fig. 3d), were homogenized in this study following the procedure in Ren et al. (2005, 2017): A 1 atm gas mixing furnace was used, and the oxygen fugacity was kept at the quartz-fayalite-magnetite (QFM) buffer using a CO₂–H₂ gas mixture in the furnace. A platinum packet containing host olivine crystals was heated at a constant temperature (1250 °C) for

Fig. 1. Regional geological map and sampling locations in the Okinawa Trough. The locations of the whole-rock samples collected in this study are shown as red circles. Other basalt sampling localities from the literature (Guo et al., 2016; Li et al., 2018; Shinjo et al., 1999; Honma et al., 1991) are shown as yellow circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

10 min, such that the crystal-glass mixture melted. Then, the packet was quickly raised (within 1 s) to the top of the furnace tube to achieve quenching. Some melt inclusions from basalt are glassy inclusions (Figs. 3c and S1) that are homogeneous and quenched in nature and do not require heating, homogenization, and quenching, so these melt inclusions can be analyzed in their present form (e.g., Streck and Wacaster, 2006; MacLennan, 2008; Hartley et al., 2013). After homogenization, the host olivines were mounted on epoxy resin disks and polished with silicon carbide and diamond powder until the melt inclusions were exposed.

The major element compositions of the melt inclusions and host olivines were analyzed with a JEOL JXA-8230 electron probe micro-analyzer (EPMA) at the Key Laboratory of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Ocean University of China, Qingdao. The operating conditions were as follows: the olivine analyses used an accelerating voltage of 20 kV, a beam current of 20 nA, a beam diameter of 2 μm , and a peak counting time of 20 s. The melt inclusion analyses used an accelerating voltage of 15 kV, a beam current of 20 nA and a beam diameter of 5 μm . For the melt inclusions, Na and K were measured first in each analysis, with 10 s as the peak counting time and 5 s as the background counting time. The standards used in these analyses included albite for Na, Al and Si; diopside for Mg and Ca; sanidine for K; rutile for Ti; almandine for Fe; bustamite for Mn and chromium oxide for Cr. The precision was better than 1% for the major element analyses and better than 5% for the minor element analyses.

3.2.2. Trace element analysis

After the EPMA measurements, the trace elements in the melt

inclusions were measured with an ELEMENT XR (Thermo Fisher Scientific) inductively coupled plasma sector field mass spectrometry (ICP-SF-MS) instrument coupled with a 193-nm (ArF) Resonetics RESOLUTION M-50 laser ablation system at the State Key Laboratory of Isotope Geochemistry, GIGCAS. Prior to this procedure, the carbon coating on each epoxy resin disk was removed completely by polishing with 0.25 μm alumina powder, and each disk was washed with purified 0.1% nitric acid. The detailed experimental procedure and data-reduction strategy are described in Zhang et al. (2019). The laser conditions were set as follows: 24 μm beam size, $\sim 4 \text{ J cm}^{-2}$ energy density and 5 Hz repetition rate. Each spot analysis comprised a 20 s gas blank collection with the laser off and a 30 s sample signal detection with the laser on. Measurements were executed under the E scan mode. A smoothing device (The Squid, Laurin Technic) was used to smooth the sample signal. Si, which was pre-measured with the EPMA, was selected as the internal standard element. The calibration line for each element was constructed by analyzing three USGS reference glasses, namely, BHVO-2G, BCR-2G and GSD-1G, from GeoReM (<http://georem.mpch-mainz.gwdg.de/>). The USGS reference glass TB-1G was measured as the unknown sample. Twenty-seven analyses of TB-1G indicated that most elements were within 8% of the reference values and that the analytical precision (2RSD) was better than 15% for most trace elements (Table S1).

3.2.3. Pb isotope analysis

Melt inclusions with diameters > 40 μm were chosen for in situ Pb isotope analysis using a Neptune Plus multiple collector inductively coupled plasma mass spectrometer (MC-ICP-MS) with a 193 nm (ArF) Resonetics RESOLUTION M-50 laser ablation system in the State Key

Fig. 2. Major element (a), trace element (b) and Sr–Nd isotope (c) compositions of the host whole-rock samples in this study. The colored data points/lines are olivine-hosting whole-rock samples used in this study, and the corresponding data are reported in our previous works (Li et al., 2018a, 2018b, 2019). The gray data points/lines are previously studied whole-rock samples that were collected from the same locations (Fig. 1) as the samples in this study and the data are from Guo et al., 2016, Honma et al. (1991) and Shinjo et al. (1999). The fields of end-members in (c) are from Li et al., 2018.

Laboratory of Isotope Geochemistry, GIGCAS. The detailed procedure for the Pb isotope analysis was previously described by Zhang et al. (2014). The laser parameters were set as follows: a beam diameter of 45 μm , an energy of 80 mJ, an attenuation value of 25%, a repetition rate of 3 Hz, and an integration time of 0.262 s. An X skimmer cone in the interface and a low flow of N_2 (2 mL L^{-1}) were used to improve the instrumental sensitivity. All isotope signals were detected with ion counters under static mode. Helium was chosen as the carrier gas (800 mL min^{-1}). The first 28 s were used to detect the gas blank with the laser beam off, and the following 30 s were used to perform laser ablation and collect sample signals with the laser beam on. The international basaltic glass standard NKT-1G (basaltic glass, Elburg et al., 2005) was chosen as the external standard. Before and after each batch of five melt inclusion analyses, a basaltic glass standard BHVO-2G was measured to monitor the instrumental drift. NKT-1G and BHVO-2G were measured repeatedly to evaluate the accuracy of the instrument before each batch analysis. Because of the low relative abundance of ^{204}Pb and the isobaric interference of ^{204}Hg , here, we present only the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios of the melt inclusions. The analyses of BHVO-2G during the course of this study yielded weighted mean values of $^{208}\text{Pb}/^{206}\text{Pb} = 2.0545 \pm 0.007$ (2SD, $n = 25$) and $^{207}\text{Pb}/^{206}\text{Pb} = 0.8332 \pm 0.0032$ (2SD, $n = 25$), which are consistent (within error) with the values reported by Weis et al. (2006) (2.0524 and 0.8345, respectively). The external precisions were better than 0.35% for $^{208}\text{Pb}/^{206}\text{Pb}$ and 0.38% for $^{207}\text{Pb}/^{206}\text{Pb}$ (2RSD, $n = 25$), whereas the accuracies were better than 0.10% for $^{208}\text{Pb}/^{206}\text{Pb}$ and 0.15% for $^{207}\text{Pb}/^{206}\text{Pb}$ (Table S2).

4. Results

4.1. Chemical compositions of the olivine

The host olivine composition data are provided in Table S3. The host olivines in the basalt yielded values of 76.3–87.3 Fo, 0.17–0.40 wt % MnO and 0.07–0.25 wt% CaO, while in the andesites yielded values of 72.9–83.2 Fo, 0.21–0.42 wt% MnO and 0.10–0.28 wt% CaO. Almost all of the olivines from the studied volcanic rocks had CaO values between 0.1 wt% and 0.3 wt%, which are higher than the values of typical mantle xenocrysts (CaO < 0.1 wt%; Cameron, 1985; Kamenetsky et al., 2006; Gavrilenko et al., 2016).

4.2. Chemical compositions of the melt inclusions

The compositions of melt inclusions (Table S4) can be changed by crystallization and/or equilibration after entrapment (Danyushevsky et al., 2000, 2002; Kent, 2008). These changes are caused by the crystallization of the host mineral on the inclusion walls or the crystallization of other daughter phases, and such processes have been experimentally reversed by remelting and homogenizing melt inclusions. The compositions of inclusions affected by such processes can be recalculated to be in equilibrium with the host olivine by applying the model of Ford et al. (1983) using PETROLOG software (Danyushevsky and Plechov, 2011). This calculation requires an independent estimate of the initial FeOt content of the trapped melt, which can be obtained using the FeOt fractionation trend exhibited by the whole-rock samples (Danyushevsky et al., 2000, 2002). Due to the small changes in the FeOt content of whole-rock samples in the study area, we used the average iron content to determine the initial FeOt contents of the trapped melts in the melt inclusions, which was 9.66 wt% in the basalt and andesites.

The major element compositions of the melt inclusions after correction are listed in Table S5 and displayed on the total alkali-silica (TAS) and SiO_2 versus K_2O diagrams (Fig. 4). On the TAS diagram (Fig. 4a), most melt inclusions from the basalt have compositions similar to those of their host whole-rock samples, and they mainly plot near the intersection of the basalt and basaltic andesite fields. The compositions of melt inclusions from the andesites are clearly more

Fig. 3. Representative photomicrographs of basalt (a) and andesite (b) from the middle Okinawa Trough. Optical images (c, d) of representative melt inclusions in olivine crystals in volcanic rocks. MI = melt inclusion; Ol = olivine; Cpx = clinopyroxene; Pl = plagioclase; Sp = spinel. Olivine (c) is from basalt, and olivine (d) is from andesite. The yellow circle in (d) denotes the MC-ICP-MS analytical spot examined for Pb isotopes, and the red circle in (d) denotes the LA-ICP-SF-MS analytical spot examined for trace elements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

primitive than those of their host whole-rock samples, and they mostly plot in the basalt field, with some plotting in the basaltic andesite and andesite fields. The SiO_2 versus K_2O diagram (Fig. 4b) shows that most melt inclusions in the basalt and andesites belong to the low-K arc-tholeiitic series and some melt inclusions in andesites belong to the medium-K calc-alkaline series. The MgO contents of the melt inclusions from the basalt and andesites are 5.53–11.04 wt% and 4.18–7.92 wt%, respectively (Table S5; Fig. 5). Some melt inclusions in the andesites have higher SiO_2 and K_2O contents but lower TiO_2 and CaO contents than those of the melt inclusions in the basalt at a given MgO content

(Fig. 5). In addition, the variations in the major oxide versus MgO contents of the melt inclusions from the basalt show continuously changing trends that closely resemble the typical evolution of fractional crystallization (e.g., Park et al., 2010). However, considerable scatter exists in the major elemental compositions at a given MgO content in the melt inclusions from the andesites, with poor correlations observed between TiO_2 (Al_2O_3 , CaO and K_2O) and MgO (Fig. 5). The K_2O contents in melt inclusions from the andesites range from 0.15 to 1.67 wt%, and some melt inclusions are clearly richer in K_2O than other melt inclusions (Fig. 5e).

Fig. 4. Plots of the corrected melt inclusions and whole-rock samples on the total alkali-silica classification ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2) (a) and SiO_2 versus K_2O (b) diagrams.

Fig. 5. Variations in SiO_2 , TiO_2 , Al_2O_3 , CaO , K_2O and Na_2O versus MgO in the whole-rock samples and corrected melt inclusions measured in this study. The symbols used for whole-rock data are the same as those in Fig. 2. The red dashed lines are the range of basaltic whole-rock compositions from the middle Okinawa Trough. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The major and trace element compositions of the melt inclusions obtained by LA-ICP-SF-MS are listed in Table S6. The major element data are consistent with the data obtained by EPMA (Fig. S2). In the primitive mantle-normalized trace element spider diagrams (Fig. 6), all of the melt inclusions in the studied volcanic rocks are markedly enriched in LILEs relative to HFSEs and slightly depleted in REEs. Notably, there are positive K and Sr anomalies and negative Nb and Ta anomalies. The trace element distribution patterns of the melt inclusions in the basalt are similar to those of their host whole-rock samples (Fig. 6a), whereas the trace element content levels of the melt inclusions in the andesites are lower than those of their host whole-rock samples (Fig. 6b). Meanwhile, compared with their host whole-rock samples, some melt inclusions in the andesites have clear negative Pb and positive P anomalies (Fig. 6b). In addition, the trace element distribution pattern of the melt inclusions in the basalt and most of the melt inclusions in the andesites are similar to that of the lower continental crust, which may suggest that the compositions of the melt inclusions were influenced by some lower continental crust components.

4.3. Pb isotope compositions of the melt inclusions

The newly obtained Pb isotope data for the melt inclusions are presented in Table S7 and Fig. 7. The $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ values of the melt inclusions in the basalt range from 0.8404 to 0.8515 and from 2.0787 to 2.1104, with mean values of 0.8464 ± 0.0048 (2SD, $n = 26$) and 2.0937 ± 0.0140 (2SD, $n = 26$), respectively. These values are similar to previously reported basaltic whole-rock values in the middle Okinawa Trough ($^{207}\text{Pb}/^{206}\text{Pb} = 0.8434$ to 0.8479 and $^{208}\text{Pb}/^{206}\text{Pb} = 2.0870$ to 2.0988 ; Hoang and Uto, 2006; Shu et al., 2017; Li et al., 2018), and most plot in the Indian Ocean-type mantle field (Fig. 7). The $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios of the melt inclusions from the andesites range from 0.8437 to 0.8798 and from 2.0834 to 2.1438, respectively (Fig. 7). These ranges of Pb isotope values are much larger than those previously reported for whole-rock samples in this area. Obviously, the Pb isotope compositions of the melt inclusions in the andesites vary significantly and can be divided into two groups: the majority of melt inclusions with low $^{207}\text{Pb}/^{206}\text{Pb}$ (< 0.865) fall around the field defined by the melt inclusions in basalt, but those with high $^{207}\text{Pb}/^{206}\text{Pb}$ (> 0.865) deviate slightly from the

Fig. 6. Trace element patterns normalized to primitive mantle concentrations for melt inclusions in the basalts (a) and andesites (b). The normalized primitive mantle values are drawn from Sun and McDonough (1989). Data on the whole-rock samples and lower continental crust are from Li et al. (2019) and Rudnick and Gao (2003), respectively.

Fig. 7. Pb isotope ratios of melt inclusions and whole-rock samples from the middle Okinawa Trough, together with the fields of Indian Ocean-type and Pacific Ocean-type mantle. Data sources: Whole-rock data are from Hoang and Uto (2006), Shu et al. (2017), Guo et al. (2016), Zhang et al. (2018) and Li et al. (2018). The EM I, EM II and MORB end-member data are from Saal et al. (1998, 2005). Data for Indian Ocean-type mantle are from Cohen et al. (1980), Sun (1980), Cohen and O'Nions (1982), Dupre and Allegre (1983), Price et al. (1986), Ito et al. (1987), Dosso et al. (1988) and Mahoney et al. (1989). Pacific Ocean-type mantle data are from Cohen et al. (1980), Cohen and O'Nions (1982), Church and Tatsumoto (1975), Ito et al. (1987), Tatsumoto (1978), Hamelin et al. (1984), White et al. (1987), Hanan and Schilling (1989) and Mahoney et al. (1994).

Pb–Pb isotope arrays toward enriched mantle type I (EMI)-like mantle (Fig. 7). In addition, the melt inclusions with high $^{207}\text{Pb}/^{206}\text{Pb}$ values in the andesites have higher K_2O , P_2O_5 , Rb and U contents but lower Pb and Cu contents than the low- $^{207}\text{Pb}/^{206}\text{Pb}$ group melt inclusions, and none of the $^{207}\text{Pb}/^{206}\text{Pb}$ values in the melt inclusions from the basalt and andesites are correlated with their MgO contents (Fig. 8a).

5. Discussion

5.1. Genetic relationship between the melt inclusions and the basaltic volcanic rocks

The olivine-hosted melt inclusions from middle Okinawa Trough

volcanic rocks show more variable element and Pb isotope compositions than the host whole-rock samples. The nature of the melt inclusions and their host olivines should be confirmed before discussing the origin and petrogenesis of the volcanic rocks. We believe that the melt inclusions and their host olivine phenocrysts are genetically related to the basaltic volcanic rocks for the following reasons: well-preserved melt inclusions are randomly distributed in the olivines from the volcanic rocks (Fig. 3c, d), suggesting that they are primary in origin (e.g., Roedder, 1979; Schiano, 2003). The fresh host olivines are generally euhedral to subhedral, have high CaO contents (> 0.1 wt%) and contain Cr-spinel inclusions (Fig. 3c), implying that the olivines crystallized from a magmatic system rather than representing mantle-derived xenocrysts (e.g., Cameron, 1985; Kamenetsky et al., 2006; Gavrilenko et al., 2016). Moreover, the compositions of the melt inclusions in the basalt reflect the same compositional trends as those of the whole-rock samples (Fig. 5). Numerous studies have shown that the chemical compositions of olivine-hosted melt inclusions vary much more widely than the associated whole-rock compositions and that erupted whole-rock compositions represent blended mixtures of a number of different melt compositions (e.g., Sobolev, 1996; Danyushevsky et al., 2000; Kamenetsky et al., 2012; Ren et al., 2017). Melt inclusions sample this variety and protect trapped melts from subsequent contamination or mixing. Therefore, melt inclusions can provide information on the initial magma composition and can be considered the unmixed equivalents of erupted lavas (e.g., Sobolev, 1996; Kamenetsky et al., 2012; Ren et al., 2017). These characteristics indicate that the studied melt inclusions and their host olivine phenocrysts are genetically related to the basaltic rocks (Ren et al., 2017) and can be used to constrain the origin and petrogenesis of the Okinawa Trough volcanic rocks.

The typical first-order trends of the major element oxides versus MgO (Fig. 5) show that the parental magma represented by the melt inclusions in the basalt reflects fractional crystallization magma evolution trends. More importantly, all melt inclusions in the basalt record nearly constant Pb isotope compositions (Figs. 7 and 8), supporting the inference that the parental magma in the basalt was derived from the same mantle source and underwent fractional crystallization during evolution of the magma (e.g., Park et al., 2010). Because the basaltic magma mainly underwent the evolution process of fractional crystallization, in this case, we can use the melt inclusions to reasonably estimate the magma source composition and discuss the contributions of enriched components to the mantle source.

Fig. 8. MgO, K₂O, P₂O₅, U, Pb and Cu contents versus the ²⁰⁷Pb/²⁰⁶Pb values of the melt inclusions. The melt inclusions in the basalt have narrower ranges of ²⁰⁷Pb/²⁰⁶Pb values compared with those observed in the andesites.

5.2. Implications for the contributions of the enriched components to the mantle source

Indian Ocean-type mantle and Pacific Ocean-type mantle are the two major types of mantle in the western Pacific, with their dividing line comprising the Australian-Antarctic Discordance (Klein et al., 1988). Despite being located in the western Pacific, the small number of previously published basaltic whole-rock Pb isotope compositions in the middle Okinawa Trough all plot in the Indian Ocean-type mantle field and could imply the existence of Indian Ocean-type mantle rather than Pacific Ocean-type mantle (Hoang and Uto, 2006; Shu et al., 2017; Li et al., 2018). However, Hoang and Uto (2006) proposed that residual Pacific Ocean-type mantle exists below the Okinawa Trough based on the Sr-Nd-Pb isotope compositional features of basalts. Guo et al., 2016 also suggested that Indian Ocean-type mantle contributed to the formerly existing Pacific-type mantle. Therefore, understanding the origin of the Indian Ocean-type mantle is crucial for understanding the magma source under the Okinawa Trough. Indian Ocean-type mantle has been attributed to recycling of detached continental material in the shallow mantle (Escrìg et al., 2004), recycling of oceanic crust plus sediment through plate subduction (Rehkämper and Hofmann, 1997) and contamination by deep-rooted mantle plumes (Storey et al., 1989; Wen, 2006). All of these models show that the Indian Ocean-type mantle represents a depleted mantle source that was contaminated by enriched components. Therefore, it is not important to determine whether the Indian Ocean-type mantle existed before the formation of the Okinawa Trough; instead, the key issue is determining how the depleted mantle was contaminated by enriched components.

Generally, the trace element compositions of magmas in subduction zones exhibit remarkable enrichment in Pb and LILEs relative to HFSEs and REEs (e.g., McCulloch and Gamble, 1991; Miller et al., 1994). Owing to their similar partition coefficients, most of these elements are rarely significantly modified during magmatic processes, such as crystallization and partial melting (e.g., Hawkesworth et al., 1993). Thus, the enrichment of LILEs and Pb in subduction zone magmas may reflect the addition of elements through plate subduction (e.g., McCulloch and

Gamble, 1991). Subducted sediment, hydrous fluids from altered oceanic basalt, and silicate melts derived from oceanic basalt and/or sediment comprise the major components of the subducted plate, and many investigations regard slab-derived fluids and melts as the most important agents for explaining the LILE and light REE enrichment and HFSE depletion in subduction zone magmas (e.g., Grove et al., 2002; Handley et al., 2007). The melt inclusions with low ²⁰⁷Pb/²⁰⁶Pb ratios in the basalt and andesites in this study are enriched in LILEs relative to HFSEs and REEs and exhibit negative Nb and Ta anomalies and positive Pb anomalies (Fig. 6). These characteristics can be reasonably interpreted as being due to the addition of materials from an enriched mantle source with a large amount of subducted plate components (McCulloch and Gamble, 1991). We introduce incompatible trace element ratios, which are mostly stable during partial melting or crystallization processes, to further evaluate the contributions of enriched components to the magma source. The concentration of Th in marine sediments and melts from altered oceanic crust (AOC) is usually more than two orders of magnitude greater than that in the mantle, and relative to REEs and HFSEs, Th is insoluble in fluids during subduction (Singer et al., 2007). Consequently, the presence of high Th/Yb ratios in the magma after normalization with Yb indicates that partially melted sediments were added to the mantle source (e.g., Class et al., 2000) (Fig. 9a). At the same time, the Nb/Yb ratios of the melt inclusions are higher than those of N-MORB (Fig. 9a), indicating that the enriched material is incorporated into the magma source. This is further supported by the high Th/Yb and low Ba/La values in the melt inclusions, which are considered to be mainly derived from sediment or sediment melts (e.g., Sun et al., 2004) (Fig. 9b). In addition, the concentration of Pb in sediments and altered ocean crusts is typically one order of magnitude higher than that in the mantle. The Pb/Ce ratio in sediment is relatively stable, is much higher than that of the mantle, and changes little during partial melting, fractional crystallization or other magmatic evolution processes (White and Duncan, 1996). In our samples, the Pb/Ce ratios of the melt inclusions with low ²⁰⁷Pb/²⁰⁶Pb values in the basalt and andesites are much higher than those of typical MORB mantle, indicating that a certain percentage of Pb-rich sediment

Fig. 9. (a) Plot of Th/Yb versus Nb/Yb for the melt inclusions. The blue arrow represents the addition of the subduction component, and the red arrow represents mantle source enrichment. (b) Plot of Ba/La versus Th/Yb for the melt inclusions, which shows that the melt inclusions were mainly affected by sediments. (c) Pb/Ce ratios and Pb concentrations of the melt inclusions in the studied volcanic rocks. Two types of mixing curves are shown to produce the observed low- $^{207}\text{Pb}/^{206}\text{Pb}$ melt inclusion compositions in volcanic rocks: one is average sediment mixed with a MORB source composition, and the other is a mixture of average sediment (< 10%) and MORB that is then mixed with enriched mantle. GLOSS refers to the global subducted sediment composition, and the data are from Plank and Langmuir (1998). N-MORB and E-MORB data are from Sun and McDonough (1989). Data for EM I-type (Pitcairn islands) basalts are from <http://georoc.mpch-mainz.gwdg.de/georoc/>, with an average of 4.62 ppm Pb and 89.28 ppm Ce. The field for the sediment is from Othman et al. (1989), with an average of 48.05 ppm Pb and 60.77 ppm Ce. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

components (< 10%) combined to form an enriched mantle in the magma sources of the middle Okinawa Trough (Fig. 9c).

5.3. Origin of the enriched components

The melt inclusions hosted by relatively high-Fo olivines could provide important information on the mantle source (e.g., Saal et al., 2005; Kent, 2008). As shown in Fig. 10, the Pb isotope compositions of the melt inclusions vary significantly compared with those observed in previously studied whole-rock samples, and the melt inclusions were divided into two groups. As the Pb isotope compositions of magmas remain constant during the processes of partial melting and

fractionation, the melt inclusions of these two groups strongly support magma compositional heterogeneity. To explain the significant Pb isotope variability in the melt inclusions, an enriched mantle end-member with high $^{207}\text{Pb}/^{206}\text{Pb}$ - $^{208}\text{Pb}/^{206}\text{Pb}$ values and relatively low $^{207}\text{Pb}/^{206}\text{Pb}$ - $^{208}\text{Pb}/^{206}\text{Pb}$ values (Fig. 10) is required, which suggests that at least two different enriched components are responsible for the origin of the mantle source of the middle Okinawa Trough volcanic rocks.

All of the melt inclusions from the basalts and the majority of melt inclusions from the andesites have lower $^{207}\text{Pb}/^{206}\text{Pb}$ ratios and higher $^{208}\text{Pb}/^{206}\text{Pb}$ ratios than those of MORB on the Pb–Pb isotopes plots (Fig. 10). High time-integrated $^{238}\text{U}/^{204}\text{Pb}$ ($= \mu$, HIMU) mantle, focus zone (FOZO)-like components and an EMII-like mantle are three potential sources that could produce low $^{207}\text{Pb}/^{206}\text{Pb}$ isotope compositions (e.g., Saal et al., 1998, 2005; Fig. 10). Because HIMU characteristics are commonly attributed to small-volume heterogeneities in the mantle, i.e., areas that are volumetrically smaller than the depleted mantle and exhibit abnormally low $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ isotope compositions, it seems to be a geodynamically less plausible end-member. FOZO components are common in the lower mantle, which may be a high $^3\text{He}/^4\text{He}$ mantle reservoir, and are always related to a mantle plume (Hart et al., 1992). However, the helium isotope compositions of the volcanic rocks from the Okinawa Trough range from 1.5 R_A to 6.04 R_A (Yu et al., 2016), which are lower than the average worldwide MORB values ($8 \pm 1 R_A$; Graham, 2002), suggesting that FOZO components are not a suitable candidate. Recent research has proposed that a subducted sediment component was involved in the Okinawa Trough magma source (e.g., Guo et al., 2016a, 2016b; Shu et al., 2017; Li et al., 2018a, 2018b, 2019), and this component is responsible for the high Pb/Ce and Th/Yb ratios in the melt inclusions in the basalt (Fig. 9), indicating that subducted sediment, as an enriched component with a low $^{207}\text{Pb}/^{206}\text{Pb}$ ratio (EMII-like end-member; Cousens et al., 1994), has played an important role in the genesis of the middle Okinawa Trough magma.

In addition, all of the Pb isotope compositions of the melt inclusions in the basalt and andesites extend toward an EM I-type isotopic end-member (Fig. 10), indicating that EM I-type isotopic components with high $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios also contributed to the magma source composition. In general, mantle EM I components have low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ and intermediate $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Zindler and Hart, 1986), and possible causes of these characteristics may be the recycling of oceanic crust and pelagic sediments (Weaver, 1991; Hauri, 1996; Hofmann, 1997, 2003; Lassiter and Hauri, 1998; Ren et al., 2017)

Fig. 10. Pb isotope characteristics of the melt inclusions and whole-rock samples compared with the modeling results. Mixing calculations show that mixing of MORB with < 10% of a subduction sediment component (EMII-like), followed by mixing with 10–40% recycled lower continental crust (EMI-like), could produce Pb isotope compositions similar to those of the melt inclusions with low $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. The mixing lines assume that the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ values of EMI, EMII and MORB are 0.888 and 2.19, 0.826 and 2.08 and 0.859 and 2.075, respectively (Saal et al., 1998, 2005). The Pb concentrations used for EMI, EMII and MORB are 0.5 ppm (Weaver, 1991), 16.7 ppm (Straub et al., 2004) and 0.3 ppm (Sun and McDonough, 1989), respectively. The field for the lower continental crust is from Qian et al. (2017). The marine sediment data are from Hemming and McLennan (2001), Plank and Langmuir (1998) and Othman et al. (1989).

or the recycling of the lower continental crust (Hanan et al., 2004; Willbold and Stracke, 2010). Some EMI-like characteristics of oceanic and continental basalts have often been attributed to the presence of recycled ancient oceanic crust and pelagic sediment in their mantle sources (Hofmann, 1997; Eisele et al., 2002; Murphy et al., 2002; Ren et al., 2017). However, as argued by Thirlwall (1997), the formation of an EMI-like signature with high $^{207}\text{Pb}/^{206}\text{Pb}$ ratios requires the source material to be isolated for a long period of time, i.e., > 1 Ga. Subducted Pacific oceanic crust in the Okinawa Trough can be precluded because of its relatively young age and low $^{207}\text{Pb}/^{206}\text{Pb}$ ratio (Saal et al., 1998, 2005; Kuritani et al., 2011; Fig. 10). The oxygen isotopes of basalts can be used to distinguish whether an EMI component represents oceanic sediment or recycled lower continental crust (e.g., Zhang et al., 2016). Generally, oceanic sediments tend to have higher $\delta^{18}\text{O}$ values (up to 25‰; Kolodny and Epstein, 1976) than those of normal mantle due to low-temperature hydrothermal alteration occurring on the surface of the oceanic crust (e.g., Eiler et al., 1996; Zheng, 2012). The $\delta^{18}\text{O}$ values of basalts near the sampling location in this study were 6.0–6.3‰ (Honma et al., 1991), which are far from the sediment values but close to lower crustal granulite xenolith values (~ 7.0 ‰, Kempton and Harmon, 1992), meaning that recycled lower continental crust rather than oceanic sediments may be the major component of their EMI sources. This is consistent with the Pb isotope compositions, in which EMI end-members plot far from the field of marine sediments but within the field of the lower continental crust (Fig. 10). In addition, the trace element distributions of the melt inclusions in the basalt and the low $^{207}\text{Pb}/^{206}\text{Pb}$ group in andesites in this study are similar to those of the lower continental crust (Fig. 6), and the ratios of incompatible trace elements, such as $\text{Ce}/\text{Pb} = 5.9\text{--}11.5$ and $\text{Nb}/\text{Yb} = 0.8\text{--}4.2$, in melt inclusions are close to those of the lower continental crust ($\text{Ce}/\text{Pb} = 5$, $\text{Nb}/\text{Yb} = 3.3$; Rudnick and Gao, 2003). Therefore, components from the recycling of the lower continental crust with relatively high $^{207}\text{Pb}/^{206}\text{Pb}$ and high $^{208}\text{Pb}/^{206}\text{Pb}$ ratios may have been involved in the source of this EMI-type end-member.

To explain the Pb isotope variability of the majority of melt inclusions in the low- $^{207}\text{Pb}/^{206}\text{Pb}$ group, we modeled a mixture of Pacific Ocean-type mantle (MORB) and EMI-like and EMII-like materials, wherein the EMI-like component was derived from the lower continental crust and the EMII-like component was derived from the subducted sediments associated with the Philippine Sea Plate (Fig. 10). The modeled results indicate that the input of $< 10\%$ EMII-like subduction sediments to a Pacific Ocean-type mantle source, followed by mixing with different proportions of EMI-like lower continental crust (10–40%), can explain the isotopic variations observed in the low- $^{207}\text{Pb}/^{206}\text{Pb}$ group melt inclusions in the basalt and andesites (Fig. 10).

The small amount of melt inclusions with high $^{207}\text{Pb}/^{206}\text{Pb}$ ratios, high K_2O , P_2O_5 , Rb and U contents and low Pb and Cu contents in andesites represent an important finding of this study, as they are far from the range determined from the melt inclusions in basalt (Figs. 8 and 10). In subduction zones, continental crust, AOC, and subducted sediments may be potential sources for such enriched component melts with high $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. The high $^{207}\text{Pb}/^{206}\text{Pb}$ compositions of the melt inclusions in the andesites also have high K_2O contents (Fig. 8b), and high K_2O volcanic rocks have been found in the Ryukyu Arc (Shinjo et al., 1999), the Northern Taiwan Volcanic Zone (Wang et al., 2004) and the Okinawa Trough (Zhang et al., 2018), which suggests that a potassium-rich source may have been present in this area. Studies have shown that such potassium-rich melts may represent a small degree of partial melting of the phlogopite-bearing garnet-peridotites from the sub-continental lithospheric mantle (SCLM), which has been metasomatized by delaminated, old lower continental crust (Wang et al., 2004; Tolstykh et al., 2012; Chu et al., 2013). However, these high- $^{207}\text{Pb}/^{206}\text{Pb}$ group melt inclusions have low Pb and Cu contents and high P_2O_5 , Rb and U contents (Fig. 8), which are clearly different characteristics than those of the lower continental crust (Fig. 6)

(Rudnick and Gao, 2003). The elements U, Pb, Ce and Nb can undergo high degrees of fractionation during subduction processes. U and Pb are more mobile and Nb less mobile than Ce during the dehydration of slabs (e.g., McCulloch and Gamble, 1991). Therefore, the high Pb/Ce and low Nb/U ratios may indicate the addition of slab-derived fluids, which is inconsistent with the low Pb/Ce ratios of these melt inclusions. In addition, the high $^{207}\text{Pb}/^{206}\text{Pb}$ compositions of the melt inclusions are far from the range of sediment and AOC in Fig. 10, suggesting that the AOC and subduction sediments cannot be the main source of these high- $^{207}\text{Pb}/^{206}\text{Pb}$ melts. During magma evolution, the fractionation of Pb and Cu-rich sulfide phases during magmatic differentiation could shift Pb and Cu to lower contents in residual melts, such as in the case of the negative Pb anomaly clinopyroxene in andesites and rhyolites from the middle Okinawa Trough (Li et al., 2020b), and may be a potential cause of the low Pb and Cu contents in the high- $^{207}\text{Pb}/^{206}\text{Pb}$ group melt inclusions. In addition, melts from carbonated oceanic crust can also show high P_2O_5 contents and low Pb/Ce ratios (e.g., Zhang et al., 2017). However, due to insufficient data and the lack of further constraints from other isotopic compositions, further work needs to be carried out to identify the exact source of the high- $^{207}\text{Pb}/^{206}\text{Pb}$ group melt inclusions.

5.4. Petrogenesis of the volcanic rocks inferred from the melt inclusions

The basalts may have been formed by the fractional crystallization of an isotopically homogeneous mantle magma source, as evidenced by studies of melt inclusions, which is consistent with the results of studies on whole-rock samples (e.g., Shinjo, 1999; Shinjo and Kato, 2000; Li et al., 2018). However, the genesis of the andesitic volcanic rocks in the Okinawa Trough is poorly understood. The AFC process of basaltic magma (Shinjo and Kato, 2000) and magma mixing between basaltic and rhyolitic melts (Ishizuka et al., 1990) are two main models that have been proposed to explain the origins of andesites in the Okinawa Trough. However, these results were based on geochemical analyses of whole-rock samples that erupted as magmatic end-products, which represent only an 'average' composition formed by a variety of complex processes and do not provide robust evidence for magma mixing in their evolutionary process (Sobolev, 1996; Kamenetsky et al., 2012; Ren et al., 2005, 2017). The compositions of the melt inclusions in the andesites represent a more primitive magma, which had a larger range of variation in its major and trace element contents than the whole-rock samples and had no compositional correlations with the MgO content (Figs. 5 and 6), thus indicating that simple fractional crystallization cannot explain the content change during magma evolution. More importantly, the Pb isotopes of these melt inclusions span a wide range, with most falling into the basalt field (low- $^{207}\text{Pb}/^{206}\text{Pb}$ group); however, some showed high $^{207}\text{Pb}/^{206}\text{Pb}$ ratios that were not correlated with the associated MgO contents (Fig. 8a), which reflects the involvement of components with high $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. This finding indicates that crystallization-driven differentiation and partial melting may be the main (but not the only) process producing andesitic volcanic rocks, whereas the mixing of magmas with different elemental and isotopic compositions is needed to explain the melt inclusion compositions in the andesites observed in this study.

To summarize the above discussion, we present a petrogenetic process that explains the origin and evolution of melt inclusions with a wide range of Pb isotope compositions. Due to Philippine Sea Plate subduction, EMII-like melts were released from sediments by dehydration of the subducting slab and interacted with the overlying mantle. The injection of EMII-like subducted sediment melts or fluid and EMI-like recycled lower continental crust components into the mantle source produced the low- $^{207}\text{Pb}/^{206}\text{Pb}$ group components recorded in the basalts and melt inclusions (Fig. 10). Due to the high proportion occupied by the low- $^{207}\text{Pb}/^{206}\text{Pb}$ group in the melt inclusions in andesites, crystallization-driven differentiation and partial melting of basaltic magma may represent the main process that produced the andesitic

magma in the Okinawa Trough, which inherited the low $^{207}\text{Pb}/^{206}\text{Pb}$ compositions of the basaltic magma. At the same time, a small amount of hybrid melt mixed with the andesitic magma, as reflected by the high $^{207}\text{Pb}/^{206}\text{Pb}$ ratios, high P_2O_5 , Rb and U contents and low Pb and Cu contents in the melt inclusions. The mixing extensively affected the magma compositions and resulted in magma heterogeneity beneath the Okinawa Trough. Both low- and high- $^{207}\text{Pb}/^{206}\text{Pb}$ melt compositions have been found in melt inclusions from individual volcanic rocks, whereas previous studies of whole-rock samples only presented low $^{207}\text{Pb}/^{206}\text{Pb}$ values, suggesting that evidence of exotic melts is readily obscured in the whole-rock compositions formed by mixing processes and that magma source characteristics should be better understood before whole-rock data are used to constrain the history of magma evolution in the Okinawa Trough.

6. Conclusions

We present the major and trace element compositions and Pb isotope compositions of olivine-hosted melt inclusions from basalt and andesites in the middle Okinawa Trough. The geochemical characteristics of the melt inclusions indicate the presence of enriched components in the magma source. Both high- and low- $^{207}\text{Pb}/^{206}\text{Pb}$ compositions were found in melt inclusions in individual volcanic rocks, suggesting that a compositionally heterogeneous magma was produced by mixing of the magma source with different proportions of recycled lower continental crust and subducted sediments. The variable major element compositions and homogeneous low- $^{207}\text{Pb}/^{206}\text{Pb}$ compositions of the melt inclusions in basalt suggest that the basalt was derived from a mantle source that had undergone fractional crystallization during the evolutions of magma, while the production of andesitic magma occurred through mixing between low- $^{207}\text{Pb}/^{206}\text{Pb}$ components, which were similar to the basalt, and a high- $^{207}\text{Pb}/^{206}\text{Pb}$ component, which had low Pb and Cu contents but high K_2O , P_2O_5 , Rb and U contents. This study of melt inclusions provides some key information on the composition of the magma source and the genesis of volcanic rocks that may be obscured in whole-rock analyses.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chemgeo.2020.119600>.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript and due care has been taken to ensure the integrity of the work.

Acknowledgements

We extend our heartfelt thanks to the Institute of Oceanology, Chinese Academy of Sciences for supplying the samples and to Dr. Zhiqing Lai of the Key Laboratory of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Ocean University of China for assisting with our electron probe microanalysis of melt inclusions and their host olivines. Constructive reviews by two anonymous reviewers and the editorial work of Catherine Chauvel are greatly appreciated. This work was supported by the National Natural Science Foundation of China (Grant No. 91958213), the National Programme on Global Change and Air-Sea Interaction (Grant No. GASIGEOGE-02), the Open Fund of the Key Laboratory of Marine Geology and Environment, Chinese Academy of Sciences (Grant No. MGE2019KG07), the International Partnership Program of Chinese Academy of Sciences (Grant No. 133137KYSB20170003), the National Special Fund for the 13th Five Year Plan of COMRA (Grant No. DY135-G2-1-02), the Special Fund for the Taishan Scholar Program of Shandong Province (Grant No. ts201511061), the Qingdao Postdoctoral Applied Research Project, the National Key Basic Research Program of China (Grant No. 2013CB429700) and Shandong Provincial Natural

Science Foundation, China (Grant No. ZR2019BD010).

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