Late Cretaceous lithospheric extension in SE China: Constraints from volcanic rocks in Hainan Island

Yun Zhou a,*, Xinquan Liang b,⁎⁎, Alfred Kröner c, Yongfeng Cai a, Tongbin Shao d, Shunv Wen a, Ying Jiang b, Jiangang Fu b, Ce Wang b, Chaoge Dong b

⁎⁎ College of Earth Sciences, Guilin University of Technology, Guilin, Guangxi 541004, China
⁎⁎ State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
⁎⁎ Département des Génies Civil, Géologique et des Mines, École Polytechnique de Montréal, Montréal H3C 3A7, Canada

1. Introduction

Late Mesozoic igneous rocks are widely distributed in eastern South China, on the western Pacific margin, and provide a good opportunity to understand the tectonic evolution of the South China Block. These igneous rocks consist of voluminous granites and felsic rocks associated with small volumes of mafic and intermediate rocks, which show an oceanward younging trend and were emplaced during three episodes, of which two occurred in the inland area with ages of 180–180 Ma and 160–140 Ma, and one on the eastern coastal area with Cretaceous-ages (140–90 Ma) (Zhou et al., 2006) (Fig. 1b). Different models have been proposed to explain their petrogenesis. A subduction model suggests that late Mesozoic magmatism in eastern South China resulted from subduction of the Paleo-Pacific plate beneath the Eurasian plate (e.g., Jiang and Li, 2014; Jiang et al., 2005; Li and Li, 2007; Y.H.M. Li et al., 2014; Z. Li et al., 2014; Martin et al., 1994; Tang et al., 2014; Xia and Zhao, 2014). A mantle plume model argues that a granite-type (G-type) large igneous province (LIP), characterized by the development of numerous granitoid bodies, resulted from partial melting at the bottom of the crust and probably induced by a Mesozoic super mantle plume (Zhang, 2013; Zhang et al., 2009). Recently, a model for tectono-magmatism in Eastern China during the Yanshanian tectonic event (200–135 Ma) was discussed by Wan and Zhao (2012). In this model, magmatic activity was controlled by regional faults and spheres (such as Moho) causing a partial decrease in pressure and increase in temperature, during which a tectonic detachment and Late Mesozoic igneous rocks were formed. Although the Late Mesozoic mafic and felsic igneous rocks in eastern South China have been extensively studied (e.g., Qiu et al., 2014; Zheng et al., 2013a; Zhou and Li, 2000), intermediate assemblages recording crucial information on crust–mantle interaction (Griffin et al., 2002; Kemp et al., 2007; Rahman, 2014) are lacking. This paper presents data for a newly discovered suite of basalt–andesite–rhyolite volcanic rocks emplaced during the late Mesozoic in Liuluocun area, Hainan Island, SE China. Field investigations, petrography, geochemical studies, zircon U–Pb–Hf, and whole-rock Nd–Sr isotope analysis were carried out.
Fig. 1. (a) Simplified geological map of Southeast Asia showing the distribution of principal continental blocks; (b) Distribution of Jurassic–Cretaceous granites and volcanic rocks in southeastern China. (a) Modified after Metcalfe (1996). (b) Modified after Z. Li et al. (2014), Zhou et al. (2006).

Fig. 2. Geological sketch map of Hainan Island. Modified after Wang et al. (2012).
Fig. 3. Photomicrographs of the Liuluocun volcanic rocks: (a) flow structure formed by feldspar, quartz and cryptocrystalline material (sample 2012LL01-2, rhyolite; cross-polarized light (cpl)), (b) K-feldspar phenocryst embayed by quartz with reaction rims of opaque phases (sample 2012LL01-1, rhyolite; cpl), (c) pilotaxitic texture composed of banded plagioclase crystals and magnetite (sample 2012LL03-2, andesite; plane-polarized light (ppl)), (d) macro-phenocryst consisting of olivine and hornblende and surrounded by magnetite (sample 2012LL03-3, basalt; cpl). Pl: plagioclase, Kf: K-feldspar, Q: quartz, Am: amphibole, Ol: olivine.

Fig. 4. Concordia diagrams (a, b) showing LA-ICP-MS zircon analyses and representative cathodoluminescence (CL) images (c, d) for Liuluocun volcanic rocks.
out to provide geochemical and isotopic constraints on their petrogenesis. The results are helpful to better understand the geodynamic processes of the region during the Late Mesozoic.

### 2. Geological setting

Hainan Island, located off the southern coast of South China, is separated from the Chinese mainland by the Qiongzhou Strait (Figs. 1, 2). Tectonically, the island is located at the intersection of the Eurasian, Indian–Australian and Pacific plates. It is generally considered to be part of the Cathaysia Block (Guangdong BGMR, 1988; Li et al., 2002), but an affinity with the Indochina Block has also been proposed (e.g., Hsu et al., 1990). The Baoban Group, composed of ~1.43 Ga granitoids (Li et al., 2008), is the oldest known basement exposed on the island. Granitoid rocks, containing numerous mafic enclaves, account for ca. 40% of the island’s area, which were intruded in the Triassic and Jurassic (e.g., Hsu et al., 1990). The Baoban Group, composed of ~1.43 Ga granitoids (Li et al., 2008), is the oldest known basement exposed on the island.

### Table 1

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Rhyolite, andesite and basalt samples of this study were collected from the Liuluocun Formation. The rhyolites are white-gray with porphyritic texture and mainly occur along the Jiusuo–Lingshui Fault or in the Sanya, Baoting and Ledong areas, southern Hainan Island (Fig. 2). The Liuluocun Formation consists of rhyolitic tuffa, flow-banded rhyolite on the top, rhyolitic ignimbrite, eruptive breccia with stratified basalt and andesite in the lower part and purplish red clastic rock (e.g., sandy conglomerate, sandstone, graywacke and mudstone) at the bottom (Table S3). This formation is unconformably overlain by the Tangtadaling Formation, which is mainly composed of dacitic tuff.
and the basalt and andesite experienced alteration, such as chloritization, epidotization and carbonatization.

3. Analytical methods

Analyses of the collected samples were performed at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIG, CAS). First, the samples were sawn into slabs and the central parts were selected for bulk-rock analyses. The rocks were then crushed in a steel mortar and ground in a steel mill. Only fresh samples were selected for pulverizing to 200-mesh and for elemental and isotopic analyses. Whole-rock major oxides were analyzed using X-ray fluorescence analysis.

The accessory minerals observed are apatite, magnetite and zircon. The volcanic rocks are not metamorphosed, but some of the basaltic and andesitic breccia (−15%) with cryptocrystalline or pilotaxitic texture. The accessory minerals observed are apatite, magnetite and zircon. Basalt phenocrysts include olivine, plagioclase, hornblende and pyroxene (Fig. 3d), and the matrix has an interstitial texture and dominantly consists of −45% plagioclase, −10% pyroxene, −30% volcanic glass and 10% quartz, and contains accessory apatite, chlorite, magnetite, zircon and epidote. The volcanic rocks are not metamorphosed, but some of the basaltic and andesitic breccia (−15%) with cryptocrystalline or pilotaxitic texture. The accessory minerals observed are apatite, magnetite and zircon. Basalt phenocrysts include olivine, plagioclase, hornblende and pyroxene (Fig. 3d), and the matrix has an interstitial texture and dominantly consists of −45% plagioclase, −10% pyroxene, −30% volcanic glass and 10% quartz, and contains accessory apatite, chlorite, magnetite, zircon and epidote. The volcanic rocks are not metamorphosed, but some of the basalt and andesite experienced alteration, such as chloritization, epidotization and carbonatization.

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4. Results

Zircon U–Pb and Lu–Hf isotopic data are listed in Tables S1 and S2 of the Appendix, respectively. As a convention, rare earth elements are abbreviated as REE, high field strength elements as HFSE, and large ion lithophile elements as LILE.

4.1. Zircon geochronology

Zircons from samples 2012LL01-1 and 2012LL02-2 are generally transparent to translucent, light-brown to colorless grains or grain fragments with subhedral morphology. They are ~80–240 μm in length with length-to-width ratios of 1:1 to 3:1. Cathodoluminescence (CL) images exhibit strong oscillatory zoning with variable luminescence, indicative of igneous origin (Fig. 4c, d).

4.1.1. Sample 2012LL01-1 (rhyolite)

Zircon grains have U contents ranging from 183 to 1159 ppm and Th from 41 to 892 ppm. Their Th/U ratios are in the range of 0.20–1.43 (Table S1). Thirty-nine analyses form a coherent cluster and yielded a 206Pb/238U weighted mean age of 101.5 ± 1.1 Ma with MSWD = 0.20 (Fig. 4a). In combination with the oscillatory zoning of the grains, this age can be interpreted as the formation age of the sample. One grain has a significantly older 206Pb/238U apparent age of 146 Ma (Table S1) and is considered to be an inherited zircon.

4.1.2. Sample 2012LL02-2 (basaltic andesite)

The U and Th concentrations for the thirty-nine analyzed grains range from 173 to 1640 ppm and from 98 to 2367 ppm, respectively, with Th/U ratios of 0.29–1.44 (Table S1). Thirty-seven spots yielded a coherent group with a 206Pb/238U weighted mean age of 102.4 ± 1.1 Ma (MSWD = 0.94) (Fig. 4b), representing the crystallization age of the sample. Two grains have significantly older 206Pb/238U ages of 223 Ma and 224 Ma (Table S1) and are interpreted as inherited zircons.

4.2. Major and trace elements

Major and trace element data for the Late Mesozoic volcanic rocks of the Liuluocun Formation in southern Hainan Island are listed in Table 1. The volcanic rocks range in composition from basalt to rhyolite (Fig. 5a, Table 1). They are medium- to high-K calc-alkaline rocks (Fig. 5c). The basalts have relatively low SiO2 and high MgO contents with Mg# (Mg/(Mg + 0.9FeT) × 100) of 49–58 (Table 1). The andesite/basaltic andesite samples are characterized by relatively high SiO2 and low MgO contents with Mg# of 46–51 (Fig. 6). The rhyolites have high SiO2 and K2O contents with Mg# of 22–28 (Table 1) and belong to peraluminous rocks (Fig. 5b). On a REE-normalized plot (Fig. 7b), the Liuluocun
volcanic rocks have high \((La/Yb)_n\) ratios and show considerable enrichment in light REE. The basalts and andesites have slight negative europium anomalies, whereas the rhyolites are characterized by obvious negative europium anomalies. On primitive mantle normalized trace element patterns (Fig. 7a), all volcanic rocks are enriched in LILE, such as K, Rb, Ba, Th and U, and depleted in HFSE, such as Nb, Ta, Ti and P.

4.3. Whole rock Sr–Nd isotopes

Initial Sr–Nd isotopic compositions for basalts, andesites and rhyolites were calculated to their formation age of ~102 Ma (Fig. 8a and Table 2). The basalts show \(^{87}\text{Sr}/^{86}\text{Sr}(t)\) ratios from 0.707991 to 0.708401 and \(\varepsilon_{\text{Nd}}(t)\) values of \(-4.09\) to \(-3.63\) with Nd two-stage model ages (tDM2) of 1.22–1.26 Ga. The andesites have \(^{87}\text{Sr}/^{86}\text{Sr}(t)\) ratios between 0.707532 and 0.708236 and \(\varepsilon_{\text{Nd}}(t)\) values from \(-2.35\) to \(-3.88\) with tDM2 of 1.11–1.24 Ga. The rhyolites have \(^{87}\text{Sr}/^{86}\text{Sr}(t)\) ratios of 0.708222 to 0.708965 and \(\varepsilon_{\text{Nd}}(t)\) values of \(-2.49\) to \(-2.69\) with tDM2 of 1.12–1.14 Ga.

4.4. Hf-in-zircon isotopes

In-situ zircon Hf isotopic data are listed in Table S2, showing that zircon grains from the rhyolite exhibit a wide range of \(^{176}\text{Hf}/^{177}\text{Hf}\) and \(^{176}\text{Lu}/^{177}\text{Hf}\) ratios. They have \(\varepsilon_{\text{Hf}}(t)\) values from \(-7.51\) to \(+0.47\) with Hf two-stage model ages (tDM2) of 0.91–1.30 Ga (Fig. 8b). Zircon grains from the andesite also have variable \(^{176}\text{Hf}/^{177}\text{Hf}\) and \(^{176}\text{Lu}/^{177}\text{Hf}\) ratios with \(\varepsilon_{\text{Hf}}(t)\) values from \(-9.73\) to \(-1.13\) and tDM2 of 0.99–1.41 Ga (Table S2, Fig. 8b).

5. Discussion

5.1. Petrogenesis of the Liuluocun volcanic rocks

All analyzed samples have LOI (loss-on-ignition) of less than 2.5 wt.%, indicating that they underwent some low-temperature alteration. The HFSE (e.g., Th, Ti, Y, Nb, Ta, Zr, Hf and REE) are considered as relatively immobile elements and are least susceptible to
metamorphism and alteration. They have long been used as petrogenic tracers to classify igneous rocks and their tectonic settings (Barnes et al., 1985). Thus, the following discussion will focus on the HFSE.

Trace element patterns and isotope compositions of the studied volcanic rocks from the Liuluocun Formation in Hainan Island favor a subduction-modified continental subduction mantle lithospheric source rather than a depleted mantle reservoir (Harry and Leeman, 1995; Kaygusuz et al., 2003). Their geochemical characteristics, such as depletion in Nb, Ta and Ti and enrichment in Rb, Ba and Sr, cannot be explained by fractional crystallization alone (Fig. 9). They are characterized by enrichment in both fluid-mobile (e.g., Rb, Ba and Sr) and melt-mobile trace elements (e.g., Th and LREE), suggesting that both fluid and melt were keys to the petrogenesis of the Liuluocun volcanic rocks. The enrichment in Hf isotopic composition indicates that HFSE (e.g., Hf) were added into their magma sources. In this regard, the required metasomatic agent would have higher Th, LREE and Hf contents than that proposed by experimental fluid/rock partition studies (e.g., Davidson et al., 2013; Johnson, 1998; Nelson and Davidson, 1993; Salters and Longhi, 1999). Numerous studies have shown that many geochemical features of arc-related rocks, such as enrichment in Hf isotopic composition or the depletion in Nb and Ta, can be attributed to slab-derived melts (e.g., Hernando et al., 2014; Pearce and Stern, 2006; Shao et al., 2014). In combination with geochemical and petrological features of the Liuluocun volcanic rocks, especially they show different characteristics of trace elements (Fig. 7) but similar compositions of whole-rock Nd and zircon Hf isotope (Fig. 8, Tables 2 and S2), suggesting that their source region is chemically heterogeneous but relatively homogeneous in radiogenic Nd and Hf isotopic compositions. If these features are taken into account, an explanation for these characteristics may be incomplete reaction of the mantle wedge peridotite with felsic melts derived from partial melting of subducted sediment. Such incomplete reaction could have resulted in a kind of sandwich structure at the slab-mantle interface in the subduction channel, and ultramafic–felsic rocks may have occurred as layers from the bottom of the mantle wedge to the top of the subducted slab (e.g., Zhao et al., 2013; Zheng et al., 2013b). It is important to point out that the incorporation of more felsic melt derived from sea-floor sediments into the mantle wedge is probably a crucial premise to andesitic–felsic magmatism (e.g., Chen et al., 2014). Our modeling calculation indicates that ~25% average crustal component would be required in a mantle-derived magma to match the observed Nd isotopic compositions of the Liuluocun volcanic rocks (Fig. 8a), further suggesting that felsic melts derived from seafloor sediments may have played an important role in the petrogenesis of the Liuluocun volcanic rocks.

The slab melt–mantle wedge peridotite reaction model assumes that andesitic magmas were generated from reaction of the hydrous melt liberated from the subducting slab with the overlying mantle peridotite. This may solve the discrepancy between the limited mobility of trace elements (e.g., Th, Hf and LREE) in an aqueous fluid and the high contents of these elements in andesitic magmas (e.g., Carmichael, 2002; Dostal et al., 1998; Kröner et al., 2014; Smithies and Champion, 2000; Stern and Hanson, 1991; Tatsumi, 1982). This model requires partial melting of the subducting slab and immediate reaction of the hydrous melt with the peridotite to cause the andesitic magmas to form (e.g., Kelemen et al., 2003). Such processes can only occur in an active continental arc above an oceanic subduction zone, where partial melting is triggered without obvious delay for storage of the metasomatic mantle sources in the orogenic root (e.g., Chen et al., 2014). Nevertheless, such slab melting cannot have occurred in the Mesozoic in the study area because there was no contemporary subduction in Hainan Island during this time. A possible solution is that these magmas were generated by remelting of ancient arc rocks. The Liuluocun volcanic association has Mesoproterozoic whole-rock Nd model ages of 1.11–1.26 Ga (Table 2), and the Hf-in-zircon model ages are similar to those of Neo- or Neoproterozoic igneous rocks in the South China Craton (Table S2) (Cai et al., 2014, 2015).

### Table 2

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Rock type</th>
<th>Sm</th>
<th>Nd</th>
<th>Rb</th>
<th>Sr</th>
<th>$^{143}$Sm/$^{144}$Nd</th>
<th>$^{147}$Nd/$^{144}$Nd</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr$\text{eq}$</th>
<th>$\epsilon$Nd(t) T DM2 (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012L01-2</td>
<td>Rhyolite</td>
<td>3.00</td>
<td>18.48</td>
<td>152.6</td>
<td>127.2</td>
<td>0.098171</td>
<td>0.512435</td>
<td>3.473024</td>
<td>0.713324</td>
<td>0.708314</td>
<td>-2.69</td>
</tr>
<tr>
<td>2012L01-3</td>
<td>Rhyolite</td>
<td>3.59</td>
<td>22.31</td>
<td>166.0</td>
<td>123.0</td>
<td>0.097332</td>
<td>0.512437</td>
<td>3.907225</td>
<td>0.713913</td>
<td>0.708276</td>
<td>-2.64</td>
</tr>
<tr>
<td>2012L02-1</td>
<td>Basalt</td>
<td>4.22</td>
<td>25.60</td>
<td>188.1</td>
<td>133.6</td>
<td>0.099630</td>
<td>0.512446</td>
<td>4.076491</td>
<td>0.714826</td>
<td>0.708965</td>
<td>-2.65</td>
</tr>
<tr>
<td>2012L02-3</td>
<td>Basalt</td>
<td>3.21</td>
<td>28.36</td>
<td>147.6</td>
<td>127.6</td>
<td>0.110999</td>
<td>0.512437</td>
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<td>0.713913</td>
<td>0.708276</td>
<td>-2.64</td>
</tr>
<tr>
<td>2012L03-1</td>
<td>Andesite</td>
<td>4.72</td>
<td>24.86</td>
<td>60.6</td>
<td>663.2</td>
<td>0.114680</td>
<td>0.512417</td>
<td>0.264391</td>
<td>0.708109</td>
<td>0.707729</td>
<td>-3.24</td>
</tr>
<tr>
<td>2012L03-2</td>
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<td>28.04</td>
<td>74.4</td>
<td>722.6</td>
<td>0.112195</td>
<td>0.512438</td>
<td>0.298012</td>
<td>0.708665</td>
<td>0.708236</td>
<td>-3.88</td>
</tr>
<tr>
<td>2012L03-4</td>
<td>Andesite</td>
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<td>25.05</td>
<td>27.7</td>
<td>763.9</td>
<td>0.117141</td>
<td>0.512423</td>
<td>0.104921</td>
<td>0.708149</td>
<td>0.707998</td>
<td>-3.17</td>
</tr>
</tbody>
</table>

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Fig. 8. (a) $\epsilon$Nd(t) versus ($^{143}$Sm/$^{144}$Nd), (b) $\epsilon$Nd(t) versus age for Liuluocun volcanic rocks. Data of 107 Ma mafic dikes and granites and 136–81 Ma mafic dikes are from Wang et al. (2012) and Ge et al. (2003), respectively.
This similarity implies that the incorporated crustal components probably originated from such Neoproterozoic arc-related rocks or their counterparts, suggesting that intracontinental reworking of a fossil supra-subduction zone continental margin may be a key to modern continental tectonics (e.g., Zheng et al., 2013b).

### 5.2. Geodynamic implications

Several different models have been proposed for the Mesozoic evolution of South China. A mantle plume may initiate melting of the lithospheric mantle and continental crust, but evidence (such as voluminous basalt, radiating dike swarms and crustal doming) for a Mesozoic mantle plume are lacking. Tectonic detachment is likely to be accompanied by intrusion of massive asthenosphere-derived magma and intermediate-felsic magmatism because of uplift of the asthenosphere–lithosphere thermal boundary (Wang et al., 2013; Zhang et al., 2015). However, Mesozoic asthenosphere-derived mafic and crustally-derived intermediate igneous rocks are rare in the study area. Therefore, the Liuluocun volcanic rocks in this study are best interpreted as having been emplaced in a subduction-related environment, which likely formed by the subduction of the Paleo-Pacific plate beneath the continental plate of China (e.g., back arc extension, slab roll back or foundering) in the Mesozoic.

The ~102 Ma volcanic rocks of the Liuluocun Formation are enriched in LILE (e.g., K, Rb, Ba, Th and U) and LREE, and depleted in HFSE (e.g., Nb and Ta; Fig. 7), suggestive of an arc affinity (Pearce, 1983). The basalts have high \( \text{Al}_2\text{O}_3 \) contents (average 18.88%), \( \text{La}/\text{Nb} \), \( \text{Ba}/\text{Nb} \), \( \text{Zr}/\text{Nb} \), \( \text{Sr}/\text{La} \) and \( \text{Th}/\text{Ce} \) ratios and low \( \text{Ta}/\text{La}, \text{Th}/\text{Nb}, \text{Ce}/\text{Pb} \) and \( \text{Th}/\text{Yb} \) ratios, which are distinct from those of intraplate volcanic rocks but similar to typical arc magma, indicating that these rocks were derived from a mantle source that had been modified by a subduction component (Tamura et al., 2014). The basalts plot in the field of arc volcanic rocks in discrimination diagrams (Fig. 10a, b), also suggesting the involvement of subduction-related metasomatic enrichment. Such arc features may be inherited from Neoproterozoic arc-related rocks or their counterparts, as discussed above. These rocks were heated up to remelting in
response to regional lithospheric extension in the South China Craton during the Early Cretaceous, resulting in Lulioucuon volcanism. Early Cretaceous (~125–119 Ma) A-type granites and bimodal basaltic in the eastern coastal area of China (Z. Li et al., 2014). This implies that intracratonic reworking of ancient supra-subduction zone continental margins may play a significant role in modern continental evolution. Previous studies showed that magmatism in SE China was almost dormant during 205 to 180 Ma (Zhou et al., 2006), followed by a transition from the Tethys orogenic regime to the Paleo-Pacific tectonic regime (Wang et al., 2001; Xia and Zhao, 2014; Zhou and Li, 2000). This transition resulted in the direction of compressive stress changing from N–S into NE–NW, associated with a series of magmatic belts with a NE trend in SE China (Bai et al., 2015; Wang et al., 2001). In the middle Jurassic, low-angle subduction of the Paleo-Pacific plate beneath the Eurasian plate (Li and Li, 2007; Uyeda and Miyashir, 1974) resulted in widespread magmatism in SE China, such as the mafic-ultramafic rocks in the Fujian coastal area (Zou, 1995) and the middle Jurassic (~178–170 Ma) Changchengjiang and Ningyuan basaltic rocks (Jiang et al., 2009). During the late Jurassic, broad arc magmatism and associated back arc extension developed in SE China due to an increase in the subduction angle (Jiang et al., 2005; Li and Li, 2007; Ling et al., 2009; Sun et al., 2015; Wang et al., 2001; Wu et al., 2005; Zhou et al., 2015b), and then further led to southeastward migration from the middle Jurassic to Early Cretaceous (Fig. 1). Up to the Cretaceous, the dip angle of subduction further increased, resulting in underplating of mantle-derived magma to provide heat for partial melting of the lower crust (Wang et al., 2012; Wong et al., 2009; Zhou and Li, 2000) and thus generated voluminous igneous rocks along the eastern coastal area of SE China. These geodynamic processes led to the formation of widespread igneous rocks with similar geochemical and geochronological characteristics and rock associations along the Zhejiang–Fujian–Guangdong–Hainan Island in SE China (Fig. 1 and Table S3).

6. Conclusions

A suite of Early Cretaceous (ca. 102 Ma) basalt–andesite–rhyolite volcanic rocks is recognized in the Lulioucuon area, Hainan Island. They exhibit similar whole-rock Nd and zircon Hf isotopic compositions but different trace elements characteristics. These geochemical features imply that their source region is chemically heterogeneous but relatively homogeneous in terms of radiogenic Nd and Hf isotopic compositions. These features suggest, along with other lithochronal and petrological characteristics, that the Lulioucuon volcanic rocks were most likely generated by incomplete reaction of mantle wedge peridotite with felsic melts derived from partial melting of subducted sediment. Their formation was closely related to regional lithospheric extension in the South China Craton during the Early Cretaceous, most likely caused by subduction of the Paleo-Pacific plate beneath the continental plate of China.

Supplementary data to this article can be found on http://dx.doi.org/10.1016/j.lithos.2015.06.028.

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