The temporal and spatial distribution of volcanism in the South China Sea region

Pin Yan\textsuperscript{a,b,*}, Hui Deng\textsuperscript{a,c}, Hailing Liu\textsuperscript{a,b}, Zhirong Zhang\textsuperscript{d}, Yukun Jiang\textsuperscript{d}

\textsuperscript{a}Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, No. 164 West Xin'gang Road, Guangzhou, Guangdong 510301, China
\textsuperscript{b}Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences, Guangzhou, Guangdong 510640, China
\textsuperscript{c}Graduate School of Chinese Academy of Sciences, Beijing 100039, China
\textsuperscript{d}Guangzhou Marine Geological Survey, P.O. Box 1180, Nan'gang, Guangzhou, Guangdong 510760, China

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Abstract

Cenozoic magmatism in the South China Sea, the associated continental margins, coastal South China and Indochina is reviewed. Volcanism contemporaneous with rifting and sea floor spreading in the South China Sea was very weak in the margins and adjacent areas. There was only very limited magmatic activity, most probably after the cessation of sea floor spreading. The South China Sea has non-volcanic margins. Large basement relief caused by extension formed major basins and a continental-oceanic transitional zone in the northern margin reflects high crustal rigidity during rifting and drifting. The paucity of a magma supply and presence of rigid fault blocks are unfavorable to the mantle flow model previously proposed to account for the opening of the South China Sea, which was supposedly linked to the escape of Indochina induced by Indo-Eurasia collision.

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Keywords: South China Sea; Magmatism; Non-volcanic margin; Passive extension model

1. Introduction

Magmatism is an important element in the continent breakup process. Those rifted continental margins marked by bursts of extensive and voluminous volcanism, as well as thick accreted igneous crust, are classified as volcanic continental margins. Many volcanic continental margins were genetically associated with mantle plumes, such as the margins along the South Atlantic Ocean, northern North Atlantic Ocean and the Indian Ocean (White and McKenzie, 1989). In contrast, non-volcanic rifted margins, such as the West Iberia and Newfoundland margins, are characterized by weak volcanism where the lithosphere was extensively stretched and thinned, to the point where sub-continental mantle was exhumed to the seafloor and serpentinized (Whitmarsh et al., 1993; Keen and de Voo, 1988).

However, Russell and Whitmarsh (2003) noted that even in these so-called non-volcanic rifted margins, there are obvious intrusive bodies within the serpentinized zone of exhumed sub-continental mantle. Therefore, not only the volume but also the style and nature of the volcanism are major factors in analyzing the mechanism of continental rifting.

As one of the biggest marginal seas in the West Pacific, the South China Sea remains controversial in origin and nature. There are two end-member models for the opening of the South China Sea. One is passive extension suggested by Taylor and Hayes (1980) in which the South China Sea was formed by late Oligocene-mid Miocene seafloor spreading after the continental rifting of South China was initiated in the late Cretaceous. The alternative proposed by Tapponnier et al. (1982); Leloup et al. (1995) attributes the South China Sea to extrusion and rotation of Indochina along a major strike-slip fault, the Ailao Shan-Red River Fault, in response to the collision of Indo-Eurasia initiated in the Eocene. SCSIO (1988); Clift et al. (2002), and Xu et al. (2002) have also explicitly or implicitly suggested linking the opening of the South China Sea to active mantle flow or...
lower crustal flow in response to the India-Tibet collision. Rangin et al. (1995) have argued against the extrusion-initiated model by recognizing far smaller strike-slip movements (few tens km) than the extrusion model suggested (700 km) by Tapponnier et al. (1982). Morley (2002) has comprehensively analyzed the displacement sense and timing of the strike-slip faults, and rifted basins in the Shan-Thai and Indochina areas which are situated between the Bay of Bengal and the South China Sea, and noted that the active period for major strike-slip movement (25–17 Ma) along the Ailao Shan-Red River Fault was contemporaneous with or slightly postdated the seafloor spreading of the South China Sea (Gilley et al., 2003). This is much later than the early Tertiary rift initiation and, furthermore, the geometry of the southwest subbasin of the South China Sea requires a southwestward propagating spreading center (Huchon et al., 1998), incompatible with the extrusion model that predicted a sinistral strike-slip along the eastern Vietnam margin (Tapponnier et al., 1982). Debate continues on the origin and mechanism of formation of the South China Sea.

In recent years, extensive surveys have been carried out over the South China Sea by industrial drilling (Li et al., 1994a, b), ODP (Leg 184) (Wang et al., 2000) and dredging (Kudrass et al., 1986), multiple channel seismic, expanded spreading seismic (Nissen et al., 1995a) and ocean bottom seismic surveys (Yan et al., 2001; Qiu et al., 2001; Nakamura et al., 1998), which considerably increased our knowledge of the distribution of volcanic eruption and magmatic intrusion in this region, and provide new insights on the origin of the South China Sea. This paper reviews the temporal and spatial distribution of magmatism over the South China Sea region incorporating results from the recent new surveys, and discusses the relationship of the volcanism with opening of the South China Sea.

2. Geological setting and Mesozoic magmatism

The South China Sea consists of the oceanic basin, two rifted margins, one transform margin and one subduction zone (Fig. 1). The Ailao Shan-Red River Fault and East Vietnam Fault acted as a transform boundary (32–19 Ma), separating South China and the South China Sea from Indochina. The Manila Trench forms the eastern limit. There is a series of rifted basins, i.e. Pearl River Mouth Basin, Yinggehai-Qingdongnan Basin in the west, and west Taiwan Basin in the east in its northern margin. The southern margin of the South China Sea was shown to have drifted to its present position in the Mid-Miocene after sea floor spreading (Taylor and Hayes, 1980).

During the late Triassic, the South China Block and the Indochina Block were sutured together along the Red River line (Holloway, 1982) or Song Ma belt (Hutchison, 1989). In the late Mesozoic, the western Pacific Ocean floor converged northwestward along the east margin of Asia (Uyeda and Miyashiro, 1974) and formed a wide compressive regime with widespread and extensive volcanism known as the Yenshan Orogeny (Jahn et al., 1976). During the late Mesozoic, a NE-trending Andean volcanic arc belt extended from Korea, through coastal and offshore China (Zhou and Li, 2000), into Indochina (Le, 1986; Phan, 1991; Nguyen et al., 2004). Jahn et al. (1976) suggested the belt to be a magmatic arc related to the subduction of West Pacific ocean floor. The igneous rocks in this belt consist mainly of granites, granodiorites, rhyolites, very small amounts of gabbros and basalts, and even smaller amounts of diorite and andesite. Over the four provinces (Zhejiang, Fujian, Guangdong and Guangxi) of southeast China, the Mesozoic volcanic belt is 600 km wide and the outcrop area totals 240,000 km², amounting to 39% of whole area of the provinces (613,000 km²) (Zhou and Li, 2000). These igneous rocks were dated from 180 to 90 Ma (Zhou and Li, 2000; Li, 2000). On the slope of the northern margin of the South China Sea, a basement composed of granites, which were dated as 150–70 Ma, has been penetrated by industry wells (Li and Liang, 1994). Onshore South Vietnam, there are widespread dikes of diorite, granodiorite and granite, dated as 150–131 Ma (Hutchison, 1989) or 112–88 Ma (Nguyen et al., 2004). Granitic dikes (120–70 Ma) were also drilled in the Mekong Basin offshore southeast Vietnam and Sunda Shelf (Le, 1986; Kati Li, 1973).

Over the southeastern part of the South China Sea, there are no reports of the late Mesozoic granites and marine sediments dominate (Schlüter et al., 1996). On the south Palawan islands, there are numerous areas with Cretaceous basalts and andesites (Almasco et al., 2000). Dredges offshore NW Palawan have collected rhyolitic tuff, altered diorite and altered olivine gabbro together with late Triassic-early Jurassic clastic sediments (Kudrass et al., 1986).

3. Review of Cenozoic volcanism

Fig. 2 shows the distribution of the Cenozoic igneous rocks revealed by outcrops, boreholes and geophysical surveys. Table 1 lists the sampling locations and dates of Cenozoic igneous rocks within the South China Sea.

3.1. The northern margin of the South China Sea

More than one hundred industry exploration wells have been drilled over the Pearl River Mouth Basin, among which about 20 wells have penetrated Cenozoic igneous rocks (Li and Liang, 1994). According to the drilling data and seismic data (Li and Rao, 1994; Li and Liang, 1994; Zou et al., 1995) the magmatism over the Pearl River Mouth Basin can be divided into three stages, Paleocene–Eocene, Oligocene–mid Miocene and late Miocene–Quaternary. The first stage produced intermediate-acidic extrusives, such as andesite, dacite, rhyolite and tuff, with K–Ar ages of 57–49 Ma, which form domes in the basin. The second stage
magmatism occurred along fissures or fault intersections within extensionally faulted depressions. Cored rocks were basalt and intermediate eruptives. Generally, both the first and the second stages of magmatism occurred sporadically and on a small scale. An exception is borehole BY-7-1-1, located on a gentle local topographic high, which penetrated a thick composite tuff layer (Pang, 1988). This composite layer totals 400 m in thickness and includes large amounts of fine layers composed of tuff and breccia, reflecting frequent eruptions. The eruption period was early Miocene (17 Ma K–Ar age, Table 1). At the borehole bottom, basalt beneath thick algae-rich reefal limestone was dated as 35.5 Ma (Lower Oligocene).

Neogene magmatism was imaged mainly by seismic surveys (Fig. 3). This phase of magmatism is strong along the lower slope of the northern margin of the South China Sea (Lüdmann and Wong, 1999; Lüdmann et al., 2001; Yan et al., 2001). Over the lower continental slope, there are

Fig. 1. Geographic and bathymetric map of the South China Sea. ASRRF, Ailao Shan-Red River Fault; LP, Leizhou Peninsular; L, Lianpin Basin; H, Heyuan Basin; S, Sanshui Basin.
several volcanoes covered by thin deposits or exposed on the seabed as high seamounts (Fig. 3b). Site 1148 of ODP Leg 184 is on the lowest slope where water depth is 3300 m. The hole drilled to 700 m beneath the sea floor. Lower Oligocene was drilled with laminated claystone. Except for volcanic ash, no igneous layer was drilled from ODP Leg 184. The volume of volcanic ash found in Site 1148 sediments is not large. All recovered ashes are thin, generally less than 5 cm. The ashes, dominantly dacitic-rhyolitic composition, are dated mainly as younger than 1 Ma (Pleistocene) from the upper hole section. Though not directly sampled, the volcanoes on the lower slope revealed by seismic profile (Fig. 3) are also interpreted as dacite-rhyolite or alkaline-tholeiitic basalt by correlation with ODP Leg 184 (Wang et al., 2000) and dredged rocks from the adjacent oceanic basin (to be reviewed in following section). Also shown by other survey, (Nissen et al., 1995b; Yan et al., 2001) these volcanoes form a patchy band with rugged geological features, roughly parallel to the 3000 m isobath, and extend westward to the Xisha Trough (Fig. 1), and possibly further southwestward to offshore central Vietnam where new multiple channel seismic data also revealed numerous volcanoes (Marquis et al., 1997). As most of the volcanoes occurred as highs exposed to the seabed or with thin deposits, they are deduced to have been erupted very late, at least later than the cessation of sea floor spreading. To the north of the volcanic band, the basement featured extensional blocks, whereas to the south, the basement is significantly deeper (1000–1500 m), and interpreted to be oceanic crust as indicated by its high
amplitude, high wave number magnetic anomaly (Fig. 3a). These volcanoes seem to occur along faults between the thinned continental crust and oceanic crust, and therefore form part of the continent-ocean transitional zone.

3.2. The oceanic basin of the South China Sea

The 3000 m isobath is approximately taken as the limit of the oceanic basin (Taylor and Hayes, 1980; Nissen et al., 1995b). The oceanic basin of the South China Sea comprises three parts, i.e. the roughly E–W trending central subbasin and the NE–SW trending southwest subbasin and northwest subbasin. It is commonly agreed that the central subbasin of the South China Sea was formed during the late-Oligocene-mid Miocene (Taylor and Hayes, 1980; Briais et al., 1993). However, in the oceanic basin, the igneous activity seems not to have been completely ended since the Mid-Miocene. The originally horizontal seafloor and sediments have been disturbed by intrusion to shallow levels (Fig. 4) or submarine eruption. There is a long chain of high seamounts festooning the spreading ridge in the central subbasin and the southwest subbasin (Taylor and Hayes, 1980; 1983; Jin, 1989; Pautot et al., 1990; Li et al., 2002). Also, there are some seamounts scattered within the basin, mostly adjacent

<table>
<thead>
<tr>
<th>Area</th>
<th>Station</th>
<th>Lon.</th>
<th>Lat.</th>
<th>Depth (m)</th>
<th>Rock type</th>
<th>Age (Ma)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl River Mouth Basin</td>
<td>YJ21-1-1</td>
<td>112.3</td>
<td>20.45</td>
<td>1650</td>
<td>Rhyolite</td>
<td>51.6±8.3</td>
<td>Li and Liang (1994)</td>
</tr>
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<td></td>
<td>BY7-1-1</td>
<td>114</td>
<td>19.65</td>
<td>2429</td>
<td>Basalt</td>
<td>17.1±2.5</td>
<td>Li and Liang (1994)</td>
</tr>
<tr>
<td></td>
<td>BY7-1-1</td>
<td>114</td>
<td>19.65</td>
<td>2752</td>
<td>Tuff</td>
<td>17.6±1.8</td>
<td>Li and Liang (1994)</td>
</tr>
<tr>
<td></td>
<td>BY7-1-1</td>
<td>114</td>
<td>19.65</td>
<td>3501</td>
<td>Andesite</td>
<td>35.5±2.8</td>
<td>Li and Liang (1994)</td>
</tr>
<tr>
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<td>PY16-1-1</td>
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<td>20.48</td>
<td>2384</td>
<td>Basalt</td>
<td>41.2±2.0</td>
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</tr>
<tr>
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<td>XJ33-2-1A</td>
<td>114.3</td>
<td>21.1</td>
<td>4880</td>
<td>Basalt</td>
<td>24.3±1.3</td>
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<td></td>
<td>LH11-1-2</td>
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<td>20.77</td>
<td>1800</td>
<td>Dacite</td>
<td>27.2±0.6</td>
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<td>LH4-1-1</td>
<td>115.5</td>
<td>20.85</td>
<td>1977</td>
<td>Dacite tuff</td>
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<td>HZ21-1-1</td>
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<td>4480–4696</td>
<td>Dacite</td>
<td>41.1</td>
<td>Zou et al. (1995)</td>
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<td></td>
<td>HZ27-1-1</td>
<td>115.4</td>
<td>21.26</td>
<td>3052</td>
<td>Intermediate-acid extrusive</td>
<td>57.1±2.5</td>
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</tr>
<tr>
<td>South China Sea Basin</td>
<td>LF1-1-1</td>
<td>116.05</td>
<td>21.9</td>
<td>3324–3455</td>
<td>Rhyolitic tuff</td>
<td>32±1.4</td>
<td>Li and Liang (1994)</td>
</tr>
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<td>LF1-1-1</td>
<td>116.05</td>
<td>21.9</td>
<td>3324–3455</td>
<td>Rhyolitic tuff</td>
<td>33.6±0.7</td>
<td>Li and Liang (1994)</td>
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<td>LF15-1-1</td>
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<td>21.46</td>
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<td>45.1±1.6</td>
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<tr>
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<td>1148</td>
<td>116.57</td>
<td>18.84</td>
<td>3294</td>
<td>Dacite tuff</td>
<td>&lt;1 Ma</td>
<td>Wang et al. (1999)</td>
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</table>

* The depth is bathymetry for dredge and coring depth for drill, respectively.

Table 1
Drilling and dredge samples over the South China Sea

<table>
<thead>
<tr>
<th>Area</th>
<th>Station</th>
<th>Lon.</th>
<th>Lat.</th>
<th>Depth (m)</th>
<th>Rock type</th>
<th>Age (Ma)</th>
<th>Source</th>
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<tbody>
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<td>South China Sea Basin</td>
<td>V36D10</td>
<td>115.6</td>
<td>14</td>
<td>1580–1800</td>
<td>Alkali basalt</td>
<td>3.49</td>
<td>Taylor and Hayes (1983)</td>
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<td></td>
<td>DR01</td>
<td>116.18</td>
<td>15.75</td>
<td></td>
<td>Alkali basalt</td>
<td>11–6</td>
<td>Pautot et al. (1990)</td>
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<td></td>
<td>DR02</td>
<td>115.96</td>
<td>15.3</td>
<td></td>
<td>Alkali basalt</td>
<td>11–6</td>
<td>Pautot et al. (1990)</td>
</tr>
<tr>
<td></td>
<td>DR03</td>
<td>116.21</td>
<td>14.95</td>
<td></td>
<td>Trachybasalt</td>
<td>8–6</td>
<td>Pautot et al. (1990)</td>
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<tr>
<td></td>
<td>No.8</td>
<td>116.98</td>
<td>17.75</td>
<td>3000</td>
<td>Tholeiitic basalt</td>
<td>13.35</td>
<td>Jin (1989)</td>
</tr>
<tr>
<td></td>
<td>No.9</td>
<td>116.52</td>
<td>15</td>
<td></td>
<td>Tholeiitic basalt</td>
<td>9.7</td>
<td>Jin (1989)</td>
</tr>
<tr>
<td>Southern Margin of the South China Sea</td>
<td>1143</td>
<td>113.28</td>
<td>9.36</td>
<td>2772</td>
<td>Dacitic-rhyolitic tuff, volcanic ash and glass</td>
<td>&lt;2 Ma</td>
<td>Prell et al. (1999)</td>
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<table>
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<th>Area</th>
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<th>Lat.</th>
<th>Depth (m)</th>
<th>Rock type</th>
<th>Age (Ma)</th>
<th>Source</th>
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<td></td>
<td>D1</td>
<td>111.97</td>
<td>13.37</td>
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<td>Alkali-basalt</td>
<td>4.3</td>
<td>Bellon et al. (1991)</td>
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<tr>
<td></td>
<td>D3</td>
<td>111.17</td>
<td>9.95</td>
<td></td>
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<td></td>
<td>SO23-23</td>
<td>115.87</td>
<td>9.9</td>
<td>1900–1700</td>
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<td>T1-J1(?)</td>
<td>Kudrass et al. (1986)</td>
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<td></td>
<td>SO27-24</td>
<td>115.83</td>
<td>9.88</td>
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<td>12.1</td>
<td>2373</td>
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<td>12.08</td>
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<td>0.4</td>
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<td>11.73</td>
<td>1610–1356</td>
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<td>0.5</td>
<td>Kudrass et al. (1986)</td>
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<td>SO23-40</td>
<td>118.82</td>
<td>12.35</td>
<td>1050–765</td>
<td>Vesicular porphyritic basalt</td>
<td>2.7</td>
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<td>SO27-24</td>
<td>115.83</td>
<td>9.88</td>
<td>2100</td>
<td>Rhyolitic tuff</td>
<td>Undated</td>
<td>Kudrass et al. (1986)</td>
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<td></td>
<td>SO23-15</td>
<td>119.37</td>
<td>8.17</td>
<td>3312</td>
<td>Porphyritic andesite</td>
<td>14.7</td>
<td>Kudrass et al. (1986)</td>
</tr>
</tbody>
</table>
to the northern continental-oceanic transitional zone. The seamounts rise up to 4000 m above the abyssal plain. Dredged samples from all the seamounts were basalts, dated as 14–3.5 Ma (Table 1), showing that magmatism continued after the cessation of sea floor spreading.

3.3. The southern margin of the South China Sea

The southern margin of the South China Sea also named Nansha Waters, includes Liyue (Reed) Bank and the Dangerous Grounds. It is bounded by Palawan and Borneo in the southeast, the Natuna Arch in the southwest and Southern Vietnam to the west. No sampling of Paleogene igneous rocks in the area has been reported. Younger siliceous rocks are found to the southeast, e.g. in the northwest Palawan shelf, rhyolite was dated as 22 Ma (Holloway, 1982). High-K, calc-alkaline granite, with an average $^{207}\text{Pb}/^{235}\text{U}$ age of 13.4 Ma, was found in Capoas, North Palawan. Encarnación and Mukasa (1997) suggested that the granite was formed in a non-subduction, non-collision intra-plate setting with the seafloor spreading basalt providing the heat source for the melting process. Pleistocene basalt flows are found on north Palawan Island.

Within Nansha Waters, there are scattered young volcanoes covered with thin Quaternary deposits. Some of
them occur as high seamounts above the seabed (Xia et al., 1993; Yan and Liu, 2004). They erupted after the cessation of seafloor spreading in the South China Sea and are thought to be basalts (Yan and Liu, 2004).

3.4. South China

In the coastal area of South China, there are also several small basins formed by Cenozoic rifting, e.g. Sanshui Basin, Heyuan Basin and Lianpin Basin (Fig. 1). The Sanshui Basin was filled with extrusive layers consisting of tholeiitic basalt, trachyte and rhyolite. K–Ar ages of these igneous rocks range from 64 to 43 Ma (Chung et al., 1997). In the Heyuan Basin and Lianpin Basin, tholeiitic basalt and andesitic lavas were found intercalated with latest Cretaceous-Paleogene sediments.

3.5. Hainan Island and Leizhou Peninsula

Hainan Island and Leizhou Peninsula are situated at the northwest corner of the South China Sea and in close proximity to the Red River Fault (Fig. 1). In northern Hainan Island and Leizhou Peninsula, the area of Cenozoic igneous rocks covers more than 7000 km². Lava flows from ENE–WSW trending extensional fissure eruptions form thick sequences alternating with sediments. The igneous rocks are chiefly basalt, including early tholeiitic basalt and late alkaline olivine basalt. The magmatism was vigorous in the Pliocene-Recent in the Leizhou Peninsula and the Quaternary in northern Hainan Island (Flower et al., 1992; Ho et al., 2000) but quiet or very weak before the Pliocene (6 Ma).

3.6. Ailao Shan-Red River Fault Zone and Indochina

The Ailao Shan-Red River Fault Zone is a NW–SE trending belt between southwest China and Indochina. Within the Red River Fault Zone, there are two Cenozoic magmatic episodes; an earlier one at 42–24 Ma and a more active late one from 16 Ma to recent (Wang et al., 2001). The early magmatism occurred within the Ailao Shan-Red River Fault Zone and the area to its north. The igneous rocks consist mainly of eruptive syenite, trachyte, shoshonitic lamprophyre and basaltic trachy-andesite. Using geochemical analysis of minerals in the igneous rocks, Wang et al. (2001) estimated that the depth of melt segregation ranged from 23 to 43 km. Granitoid bodies dated at 35–27 Ma intruded into the southeast portion of Ailao Shan-Red River Fault Zone (Leloup et al., 2001) and are associated with coeval metamorphic rocks. The late magmatism occurred in the southern section of the Ailao Shan-Red River Fault Zone and in central and southern Indochina. Wang et al. (2001) recognized alkali basalt, basanite, trachy-basalt and basaltic trachy-andesite. From study of xenoliths, they concluded that the younger phase high potassic melts segregated at depths of 55–76 km. In central and southern Indochina, Neogene basalts are relatively widespread. They erupted from fissures or discrete centers. Eruption became strong within the past 5 Ma and continued to the Recent (Hoang et al., 1996; 1998).

3.7. Taiwan–Luzon

The Taiwan-Luzon Arc was formed by collision of the Eurasian Plate and the Philippine Arc since the mid-Miocene. Magmatism seems to young eastward across this arc. Southwest of Taiwan, in the Penghu Islands, and west of Luzon, there was early Miocene magmatism, while to the east, volcanism was late Miocene to Quaternary (10–4 Ma) in age (Yang et al., 1996). Andesites and basalts were sampled from the island chain.

4. Crustal structures and intrusions

The northern and southern margins of the South China Sea are characterized by thinned continental crust. Major and minor Cenozoic rift basins developed on rugged basement in those regions. The margins trend NE, parallel to the structural trends of South China. The topography of the continent-ocean transitional zones has two styles, one is characterized by sharp contacts of high-standing rigid continental blocks, e.g. the Dongsha Rise, Zhongsha-Xisha Block and Liyue Bank (Reed Bank), with the adjacent deep oceanic basin; the other displays gradual deepening from the continental slope to the abyssal plain, as in the Xisha trough and SW oceanic subbasin. The different style might reflect lateral inhomogeneity of plate rigidity along the margins.

The Pearl River Mouth Basin consists of Cenozoic rifts produced by extensive stretching. The maximum sediment thickness exceeds 10,000 m, and probably reaches 15,000 m according to new seismic data collected with a 7000 m streamer. There are large faults (with 3000 m throw) between the Dongsha Rise and its northern sedimentary sag (Wang et al., 1992; Tyrrell and Christian, 1992). Several ESP and OBS-based deep surveys have recently revealed the crustal structures of the northern margin of the South China Sea (Nissen et al., 1995a; Yan et al., 2001). Across the margin, the crust displays a general thinning without voluminous syn- or post-rift magma intrusion into the upper crust except for the continental-oceanic transitional zone (COT).

Dongsha Rise is disturbed locally by strong volcanism. Deep seismic surveys found high seismic velocity crustal layers (HVL) at the base of thinned continental crust (Nissen et al., 1995a; Yan et al., 2001). Based on ESP survey, Nissen defined a magmatic intrusion-related 10 km thick HVL (with Vp ranging in 7.2 km/s) under the crust over the slope. However, in a later OBS survey near the ESP line, Yan et al. (2001) estimated the HVL to be thinner, only ca. 5 km thick. One interpretation of
the HVL as due to magmatic underplating during rifting was almost ruled out by heat flow versus subsidence modeling, which predicted considerable subsidence assuming the HVL to have been produced by underplating, which is inconsistent with the observed modest subsidence (Nissen et al., 1995b). The present heat flow is high over the margin (40–110 mw/m²), and exceptionally high landward of and over the continental-oceanic transitional zone (70–90 mw/m², Shi et al., 2003). The potential contributions to the high heat flow might come from, as proposed by Nissen et al. (1995b), highly thinned crust, high basement radiogenic heat production, or young magmatism. Nissen et al. (1995b) suggested the thick HVL to be primarily the result of a relict Mesozoic subduction-associated magmatic arc, which produced high radiogenic heat. The argument for high radiogenic heat production from the Mesozoic granite is doubtful and unconfirmed by heatflow anomalies in areas with similar Mesozoic granite basement. Considering the proximity of the HVL to the Neogene volcanoes in the continental-oceanic transitional zone (Fig. 3) and the high heat flow zone there (Shi et al., 2003), we suggest that the high heat flow is related to the Neogene volcanism, and the HVL to be linked with post-spreading magmatic intrusion.

The Yinggehai Basin, located northwest (Fig. 1) of the South China Sea, is a Cenozoic basin produced by strike-slip movements along seaward extensions of the Ailao Shan-Red River Fault. The basin underwent early sinistral strike-slip pull-apart from 36 to 5 Ma and late dextral strike slip since 5 Ma (Sun et al., 2003). The basement consists of Paleozoic metamorphic rocks (Nielsen et al., 1999). The Cenozoic sediment in the basin center is up to 17 km thick (Hao et al., 1998), and the Moho depth is ~22 km according to gravity inversion model (Yan et al., 2002). There is no evidence of large igneous eruptive and magma intrusion within this active very-deep basin despite the thin crust.

The southern margin of the South China Sea displays conspicuous lateral variation along the NEE-trending continental-oceanic transitional zone. Water depths increase sharply from tens of meters over Liyue Bank (Fig. 5) to more than 3000 m only 20 km to the north in the central subbasin. Young seabed deformation due to gravity collapse is evident in the area where SO 23–36 and SO 23–37 were dredged (Fig. 1). Dredged rocks contained Late Jurassic amphibolites and Quaternary basalts (Table 1). The basement of Liyue Bank must include Late Jurassic rocks since the Liyue Bank continental block is in sharp contact with the oceanic crust along steep and large normal faults. The major faults form the continental-oceanic boundary. The crustal thickness decreases from more than 20 to 10 km across the COT. No volcanoes are present. The variation of crustal structure across Liyue Bank is typical of continental breakup.

In contrast to Liyue Bank area, the seabed of the COT becomes deeper (ca. 2000 m) and the crust becomes thinner toward and into the west portion of the southern margin with a broader and gentler transition northward into the SW subbasin. Young volcanoes scattered across the continental-oceanic transitional zone (Yan and Liu, 2004).

Sonobuoy seismic, gravity and multiple channel seismic surveys have been carried out over the past 20 years in the oceanic basin of the South China Sea. Results from sonobuoy data show that the oceanic basin has an average crustal thickness of 4–6 km (Taylor and Hayes, 1983). Gravity inversion confirms this picture and shows that, except around high seamounts, the Moho of the oceanic basin is very smooth with the depth of 8–11 km, equivalent to a crustal depth.
thickness of 4–6 km (Liu et al., 1985; Huchon et al., 1998), slightly thinner than most oceanic crust (7 ± 1 km). In the past two decades, the South China Sea Institute of Oceanology, Chinese Academy of Sciences has carried out multi-channel seismic surveys along thousand kilometer lines across the oceanic basin. Generally, reflections from the Moho and intra-crust horizons were rarely seen in the seismic data. A short MCS portion crossing into the SW subbasin displays fragmented reflections from the Moho at 8.5–8.7 s (Fig. 6). As the two way time to the basement of sediments is 6.2–6.3 s, the thickness of oceanic layers 2 and 3 is 7 km with an assumed velocity of 6 km/s. Along with the ca. 0.5 km sediment sequence, the whole crust is 7.5 km thick, just within the averaged thickness range of the global oceanic crust (Tanimoto, 1995). Schlüter et al. (1996) also illustrated a short MCS section located in the southeastern corner of the central subbasin where the Moho is imaged at 7.8–9.2 s by strong reflection, and the thickness of the oceanic crust was 9–12 km, slightly thicker than the average oceanic crust. Schlüter et al. (1996) interpreted this thickened crust near the ocean-continent boundary to be due to probable addition of dykes and sills into the crust as evidenced by internal reflections. Nevertheless, thickening of the crust by magma intrusion must have occurred on a very limited scale as the gravity-derived Moho is generally gentle over the oceanic basin (Liu et al., 1985).

5. Summary of the magmatism within and around the South China Sea

Late Mesozoic granitic and granodioritic magmatism was widespread in South China and Indochina, but Cenozoic basalt magmatism was concentrated in the ocean basin. Volcanic activity was dispersed in the continental margins. Except during periods of sea floor spreading, Cenozoic magmatism was very limited in time and space. The Paleogene seems to have been a quiet period during which magmatism was minimal and the character of igneous activity started to shift from Mesozoic granite and rhyolite to basalt and andesite. Weak Paleogene magmatism is preserved within rifted basins on the shelf and coastal area of South China. At the time of late Oligocene–mid Miocene sea floor spreading, magmatism increased, but was still small in scale on the continental slopes. Ca. 10 Ma after cessation of sea floor spreading, volcanism was most active during the Pliocene-Recent on the margins and within the oceanic basin along previous faults.

Fig. 6. A portion of MCS line 2NS5 shows a weak Moho reflection in the oceanic basin. The seismic data show oceanic crust with normal thicknesses.
Intermediate to small high seismic velocity layers revealed by deep sounding are inferred to be linked with pre-rift crustal features or post-rift magma emplacement. Magma underplating at the bottom of the crust during rifting seems to be very modest if present. Thick igneous crust seems to be uncommon over the margins and the oceanic basin.

6. Discussion

Cenozoic syn-rift and syn-spreading igneous eruptions have occurred on a very small scale over the margins of the South China Sea. Some localities with Cenozoic flood basalts, such as northern Hainan-Leizhou Peninsula and South Vietnam, are of normal continental crustal thickness. The flood basalts significantly postdate continental rift and breakup. The oceanic basins appear to be underlain by normal thickness of oceanic crust except for a few areas with thicker oceanic crust are intruded by young dikes and sills (Schlüter et al., 1996). Therefore, it may be concluded that the margins of the South China Sea are non-volcanic, or magma-poor passive continental margins. There is little pre- and syn-rift magmatism in its northern margin (Yan et al., 2001) as well as associated areas.

Recently, Deng et al. (1998) have proposed a link between Cenozoic magmatism, opening of the South China Sea, and a mantle plume. Li et al. (1998) speculated that there was a mantle plume underneath south Indochina where a low velocity mantle anomaly is shown by seismic tomography (Maryuma, 1994). However, as Flower et al. (1998) have pointed out for East Asia and the West Pacific, the dispersed Cenozoic volcanism over the South China Sea margins is largely different from the igneous provinces in volcanic continental margins where mantle plumes have played significant role in facilitating or driving continental rifting and breakup (Menzies et al., 2002). For the South China Sea, no systematic signatures of surface magmatism are evident to indicate the presence of such a mantle plume since the initiation of rifting.

Interpretations of the origin of magmatism for the South China Sea are very different. Jahn (1976); Zhou and Li (2000) believed a compressive tectonic regime due to subduction of the Western Pacific Plate was responsible for Late Mesozoic granite magmatism beneath the margin of East Asia. In contrast, Li (2000), on the basis of geochemical analysis of A-type granites, linked them with an extensional environment induced by the subduction of the Western Pacific Plate. In despite of differences of opinion for all these authors, the late Mesozoic magmatism was ascribed to a common plate-scale tectonic event.

Whether the scattered Cenozoic magmatism over the South China Sea and its adjacent areas share a common major mechanism is unclear. Chung et al. (1997) suggested that the Paleogene volcanic activity within the Sanshui, Heyuan and Lianpin basins was related to lithospheric extension. They further deduced that the lithospheric extension had migrated southward and became focused when the breakup was initiated. Li and Rao (1994) also interpreted the Paleogene igneous rocks drilled in the Pearl River Mouth Basin as eruptives from intraplate rifting.

Lüdmann et al. (2001) concluded that a transtensional tectonic regime generated by South China Sea subduction at the Manila trench and collision with Taiwan Island since 5 Ma, together with tensile forces generated by oceanic crust cooling, caused previous faults to dilate and permitting the late Miocene-Quaternary magma upwelling over the Dongsha Rise area.

Igneous rocks in Indochina have received more geochemical study than those in the South China Sea. The 42–24 Ma volcanic rocks in the NW–SE Ailao Shan-Red River Fault and its northwest extension were interpreted as melt products affected by eastward continental subduction, which produced a N–S trending compressive belt, whereas the post-16 Ma volcanoes distributed in minor rifts in South Vietnam were interpreted to be caused by E–W directed lithospheric extension (Wang et al., 2001). Both the continental subduction and lithospheric extension were ascribed to asthenosphere flow in response to the extrusion of Indochina (Wang et al., 2001) as proposed by Flower et al. (1992).

The relationship between magmatism in the South China Sea and that in Indochina, if present, is important for understanding the opening mechanism of the South China Sea. Based on a number of seismic profiles across the Pearl River Mouth Basin and the southern margin of the South China Sea, Clift et al. (2002) have modeled the flexural rigidity, and have shown that the elastic thickness of the lithospheric plate was as small as 5 km. With the modeling, they concluded that the South China margins had a weak (low viscosity) lower crust and accommodated crustal flow before and during the onset of separation. If this were the case, there should have been a pre-rift increase in temperature to facilitate the crustal ductility. The South China Sea was interpreted to be a part of a greater weak zone spanning eastern Asia as far as the Eastern flank of the Tibetan Plateau. Several features of regional scale, such as ultra-deep subsidence (more than 10,000 m) in the Pearl River Mouth Basin, and sharp escarpments in the continental-oceanic transitional zones near to the Dongsha Rise and Liyue Bank, that indicate significant rigidity of the crust, were not considered in the flexural model. The observed large relief of the basement does not favor the weak crust model. From the South China Sea to Indochina, there seems to be no geological feature that could impede such a proposed mantle flow. No resolvable magmatism has been found in the extremely thinned Yinggehai Basin, which is situated in the offshore extension of the Ailao Shan-Red River Fault. It is not plausible to relate the magmatism of the South China Sea region to that of Indochina by mantle flow. The paucity of volcanic rocks during pre- and syn-rift stages implies a decrease of
potential temperature (Reston and Morgan, 2004), which is unfavorable for large-scale lithosphere flow.

Along with the inactivity of volcanism in the margins, the low-median spreading rate (4–5 cm/yr) of the South China Sea also indicates a paucity of magma supply during spreading (Yan et al., 2001). Analysis of ODP Leg 184 shows no apparent deepening or shallowing of the water depth of sedimentation at the site of Hole 1148 in close proximity to the oceanic basin (Fig. 1), which remains hemipelagic and probably bathyal throughout as evidenced by lack of coarse clastic material in the syn-sedimentary sequences (Wang et al., 2000). These features reflect stretch-dominant rifting and spreading. Oceanic crust magma may have been generated by decompression during regional extension while the post-drifting volcanism may be a response to local tectonic events, such as collision in Taiwan-Manila Trench, or to an unrecognized cause, such as in Hainan-Leizhou Peninsula.

7. Conclusion

Cenozoic magmatism occurred very diffusively and weakly during periods of continental rifting and drifting. Intrusions in the lower continental crust are very limited and most probably occurred after the cessation of the sea floor spreading. There was no thickening of oceanic crust by magma addition. The margins of the South China Sea were characterized by a limited magma supply. They are non-volcanic margins.

The presences of deep depressions over the northern margin and major faults over the continental-oceanic transitional zone reflect high crustal rigidity during rifting and drifting. This observation is unfavorable to the idea of mantle flow for opening of the South China Sea, linked to the escape of Indochina induced by Indo-Eurasia collision.

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