The Red River Fault zone in the Yinggehai Basin, South China Sea

Mangzheng Zhu a,⁎, Stephan Graham b,1, Tim McHargue c,2

Abstract

The Red River Fault, a major strike-slip fault of onshore Southeast Asia, is suggested to be closely related to the formation of the South China Sea and uplift of the Tibetan plateau, yet published documentation of the offshore segment of the Red River Fault is sparse. High-resolution reflection and borehole data obtained by the petroleum industry along the northwestern margin of the South China Sea permit mapping of the offshore segment of the Red River Fault in the Yinggehai Basin, as well as demonstration of the timing of its shear movement and slip reversal. Two boundary faults and two basin-center faults are mapped. Three successive deformation phases for the offshore Red River Fault zone include sinistral movement from ~30 to16Ma, slip reversal between 16 and 5.5 Ma, and dextral movement with low rates after 5.5 Ma. Although no robust piercing points were observed for the sinistral movement period, the horizontal displacement of dextral movement is estimated to be tens of kilometers. This study supports a two-stage model for the evolution of the India–Asia collision orogen. Before the middle Miocene, sinistral movement of the Red River Fault likely was linked to spreading of the South China Sea, consistent with the concept of continental extrusion. After the middle Miocene, distributed shortening better explains low rate of dextral accommodation of the Red River Fault in response to the continuing India–Asia collision.

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Keywords: Red River Fault, Yinggehai Basin, South China Sea, Slip reversal, India–Asia collision

1. Introduction

The Tibetan plateau is the highest and largest plateau on Earth, and it is an ideal place to study continent–continent collision dynamics. Understanding the evolution of the Tibetan plateau and its relationship to regional patterns of structure are of great importance. Two major hypotheses about the mechanisms for uplift of the Tibetan plateau are the continental extrusion model (Tapponnier et al., 1982, 2001) (Fig. 1) and the distributed shortening model (England and Houseman, 1986; Molnar et al., 1993). A central prediction of the continental extrusion model is that sinistral movement of the Red River Fault in response to the continuing India–Asia collision dynamics. Before the middle Miocene, sinistral movement of the Red River Fault likely was linked to spreading of the South China Sea, consistent with the concept of continental extrusion. After the middle Miocene, distributed shortening better explains low rate of dextral accommodation of the Red River Fault in response to the continuing India–Asia collision.

Compared with the sizeable amount of published work about the onshore segment of the Red River Fault (e.g., Allen et al., 1984; Tapponnier et al., 1990; Schärer et al., 1994; Leloup et al., 1995; Harrison et al., 1996; Chung et al., 1997; Wang et al., 1998a; Searle, 2006), relatively few subsurface images and supporting data have been published for assessing the character of the offshore segment of the Red River Fault (Rangin et al., 1995; Gong et al., 1997; Clift and Sun, 2006; Huyen et al., 2007).

High-resolution reflection seismic and borehole data collected by the petroleum industry along the northern margin of the South China Sea provide an excellent opportunity to study the offshore segment of the Red River Fault and its implications for the India–Asia collision. Our specific motivations in studying the offshore segment of the Red River Fault are fourfold. Our first goal is to investigate the strike-slip distribution and structure of the Red River Fault in the Yinggehai Basin, providing a more complete view of the fault by combining both onshore and offshore data. Secondly, we document the timing and strike-slip movement of the offshore Red River Fault, in order to assess its slip reversal history during the middle and late Miocene. The third objective is to investigate the relationship between the fault and seafloor spreading of the South China Sea, as a test of plausibility of the continental extrusion model. The final goal is to
assess possible driving mechanisms for strike-slip movement of the Red River Fault.

2. Background

2.1. The Tibetan plateau

The Tibetan plateau has elevation in excess of 5000 m and great crustal thickness. The timing of its uplift is still in debate (Molnar and England, 1990; Harrison et al., 1995; Coleman and Hodges, 1995; Blisniuk et al., 2001; Kirby et al., 2002; Spicer et al., 2003; Clark et al., 2004; Currie et al., 2005; Clark et al., 2005; Clift et al., 2006; Rowley and Currie, 2006; Ritts et al., 2008), as shown in Fig. 2. Besides timing, mechanisms of plateau uplift and the amount of shortening in the plateau are also controversial issues about the Tibetan plateau. To address these issues, two major contrasting hypotheses have been developed. The continental extrusion model (Tapponnier et al., 1982, 2001) emphasizes that uplift of the Tibetan plateau was caused by thickening of the Asian crust above India’s obliquely subducting mantle. Convergence was principally absorbed by crustal thickening and extrusion of the left lateral strike-slip faults between coherent lithospheric blocks (Tapponnier et al., 1982, 2001). On the other hand, the distributed shortening hypothesis suggests that the lithosphere continuously thickened as a widespread viscous sheet, and convective removal of the lower lithosphere of the Tibetan plateau buoyantly bounded its crust and triggered extension and volcanism (England and Houseman, 1986). This model-based hypothesis suggests that broadly distributed shortening of both crust and mantle accommodated plate convergence (Molnar et al., 1993).

2.2. South China Sea

The South China Sea developed through the interaction of the Eurasian, Pacific, and Indo-Australian plates. As the South China Sea opened, several Cenozoic basins formed along its northern margin, including the Yinggehai Basin, Qiongdongnan Basin, Beibu Gulf Basin, and Pearl River Mouth Basin (e.g., Holloway, 1982; Zhou, 1997; Lin and Zhang, 1997).

Timing for the spreading of the South China Sea has been interpreted to have occurred during 32–15.5 Ma based on magnetic anomalies (Taylor and Hayes, 1980, 1983; Briais et al., 1993). Subsequently, Barckhausen and Roeser (2004) interpreted that seafloor spreading of 5.6 cm/year full rate began at ~31 Ma in the central part of the South China Sea. At 25 Ma spreading accelerated to 7.3 cm/year full rate, contemporaneously with activation of a second spreading center in the southwestern part of the South China Sea. Formation of oceanic crust ended at 20.5 Ma simultaneously at both spreading centers (Fig. 2).

2.3. Red River Fault

The Red River Fault is a first-order tectonic structure that may be followed from the east margin of the Tibetan Plateau to the South China Sea, separating the South China Block to the north and the Indochina block to the south, as shown in Fig. 1. The onshore segment of the Red River Fault is exposed in four ranges about 10–20 km wide, including Xuelong Shan (XLS), Diancang Shan (DCS), Ailao Shan (ALS), and the Day Nui Con Voi (DNCV).

Fig. 1. Tectonic and geologic map of Southeast Asia. (A) Modified after Tapponnier et al. (1990). It shows the continental extrusion model proposed by Tapponnier et al. (1990). 1: The Altyn Tagh Fault. 2: The Kunlun Fault. 3: The Karakoram Fault. (B) Modified after Gilley et al. (2003) and Leloup et al. (1995). The onshore segment of the Red River Fault is exposed in four ranges about 10–20 km wide, including Xuelong Shan (XLS), Diancang Shan (DCS), Ailao Shan (ALS), and the Day Nui Con Voi (DNCV).

The onshore segment of the Red River Fault reflects at least two successive deformation phases illustrated in Fig. 3 and Table 1, but reversal of slip on the Red River Fault from 17 to 5 Ma is not well documented. Pliocene–Quaternary right-lateral movement of the Red River Fault is documented onshore by sharp geomorphic fault traces, large river offsets, and well-preserved cumulative scarps. Dextral motion on the Red River Fault likely started around 8–5 Ma, and the total slip has been estimated to be 9 m–54 km (Allen et al., 1984; Wang et al., 1998a; Replumaz et al., 2001; Schoenbohm et al., 2006). In addition, the Red River Fault was characterized by left-lateral movement about 34–17 Ma, with widely varying estimation of total slip of 100–1400 km (Tapponnier et al., 1990; Harrison et al., 1992; Leloup and Kienast, 1993; Scharer et al., 1994; Leploue et al., 1995; Harrison et al., 1996; Chung et al., 1997; Wang et al., 1998b; Zhang and Scharer, 1999; Wang et al., 2000; Leploue et al., 2001; Gilley et al., 2003; Searle, 2006).

Following the pioneering work of Tapponnier et al. (1990), many geologists have posited that the ductile, left-lateral deformation of the Red River Fault absorbed hundreds of kilometers of slip and a substantial part of Asian shortening during the Cenozoic India–Asia collision, and lead to the opening of the South China Sea (e.g., Scharer et al., 1994; An et al., 2001; Leploue et al., 2001). However, some evidence is incompatible with the continental extrusion model: 1) Lack of recent significant shortening within sediments adjacent to the Red River Fault (Schoenbohm et al., 2006); 2) The Red River Fault may extend across the Yinggehai Basin along the east Vietnam margin, but dextral motion of the east Vietnam margin is synchronous with spreading of the South China Sea (Roques et al., 1997b). Huyen (oral communication, 2007) also argued that sinistral movement may have occurred during 32–17 Ma using unpublished seismic data offshore of eastern Vietnam, which is synchronous with sea floor spreading of the South China Sea.

3. Dataset and age control

The dataset used in this study consists of 2-D and 3-D seismic reflection data, and 26-boreholes with wireline-logs provided by Chevron Corporation, as well as published 2-D seismic lines in the Yinggehai–Qiongdongnan Basin (Rangin et al., 1995; Gong et al., 1997; Roques et al., 1997a, b; Ying, 1998; Clift and Sun, 2006), as depicted in Fig. 4. The west and central Yinggehai Basin are covered with a regional grid of 2-D seismic reflection profiles with 20–80 km spacing, whereas the eastern parts of the Yinggehai Basin and Qiongdongnan Basin are covered by 2×2 km–4×4 km spaced 2-D seismic reflection profiles. The 3-D seismic reflection dataset covering 1200 km² is located at the junction of the Yinggehai and Qiongdongnan basins. The 3-D seismic data were acquired with spacing of 25 m in both inline and crossline directions. Published seismic lines are located in the Tonkin Gulf (Rangin et al., 1995), near the Zhongjian Ridge (Marquis et al., 1997; Roques et al., 1997a, b), and the Beibu Gulf basin (Ying, 1998). We map structures with greatest confidence in areas covered by the dense 2-D seismic lines with spacing from 2×2 km to 4×4 km and the 3-D seismic survey in the Qiongdongnan and southeastern Yinggehai basins. In contrast, correlation of faults and folds between profiles is reasonable but less certain in the central and western Yinggehai Basin, where our 2-D seismic lines and published seismic lines are sparse.

Age controls on seismically mapped horizons of 21, 16, 13.8, 11, 5.5, 3.6, 2.6, and 2 Ma are mainly supported by nannofossil biostratigraphy provided by Chevron Corporation from 19 drilling sites and by ages
from recent publications (Rangin et al., 1995; Lu, 1997b; Thompson and Abbott, 2003; Clift and Sun, 2006). There are no deep boreholes to confirm the ages of sedimentary rocks older than 30 Ma in the central Yinggehai Basin. Ages of horizons 30 and 26 Ma are extrapolated from biostratigraphic data from the deep wells in Tonkin Gulf (Rangin et al., 1995; Thi and Quan, 1997).

Table 1

<table>
<thead>
<tr>
<th>Movement</th>
<th>Duration</th>
<th>Displacement</th>
<th>Displacement rate</th>
<th>Evidences</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinistral</td>
<td>Tertiary</td>
<td>700(+/−200) km</td>
<td>~3.3 cm/yr (35–17 Ma)</td>
<td>Large-scale geological markers: late Mesozoic red-bed basins; later Paleozoic–Mesozoic sutures, intrusive rocks, and volcanic belts</td>
<td>Leloup et al. (1995)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>36–17 Ma</td>
<td>1400(+/−400) km</td>
<td>4–5 cm/yr (27–17 Ma)</td>
<td>Estimated by rotation of the Indochina Block</td>
<td>Leloup et al. (2001)</td>
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<tr>
<td>Sinistral</td>
<td>~23</td>
<td>&gt;500 km</td>
<td>N/A</td>
<td>Correlation with the late Archean Kangding Complex (China) and Cavinh Complex (Vietnam)</td>
<td>Lan et al. (2001)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>N/A</td>
<td>~600 km</td>
<td>N/A</td>
<td>Correlation with the late Archean Kangding Complex (China) and Cavinh Complex (Vietnam)</td>
<td>Lan et al. (2001)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>34–17 Ma</td>
<td>600 km</td>
<td>6 cm/yr (27–22 Ma)</td>
<td>40Ar/39Ar thermochronological study of the metamorphic massif at Vietnam</td>
<td>Wang et al. (1998a,b, 2000)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>30–5.5 Ma</td>
<td>Ten of kilometers</td>
<td>N/A</td>
<td>Subsurface seismic data</td>
<td>Rangin et al. (1995)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>36–5 Ma</td>
<td>200 km</td>
<td>N/A</td>
<td>Axial depocenter migration in the Yinggehai basin</td>
<td>Sun et al. (2003)</td>
</tr>
<tr>
<td>Sinistral</td>
<td>After 21 Ma</td>
<td>Unknown</td>
<td>N/A</td>
<td>No robust markers used to prove 500–1000 km offsets</td>
<td>Sun et al. (2003)</td>
</tr>
<tr>
<td>Dextral</td>
<td>Holocene</td>
<td>9 m–6 km</td>
<td>2–5 mm/yr</td>
<td>Geomorphic fault trace, large river offsets</td>
<td>Replumaz et al. (2001)</td>
</tr>
<tr>
<td>Dextral</td>
<td>Plio-Quaternary</td>
<td>25 (+/−0.5) km</td>
<td>~5 mm/yr</td>
<td>Large river offset in Yunnan</td>
<td>Schoenbohm et al. (2006)</td>
</tr>
<tr>
<td>Dextral</td>
<td>Late Miocene to present</td>
<td>~40 km</td>
<td>&gt;5 mm/yr</td>
<td>Field mapping</td>
<td>Allen et al. (1984)</td>
</tr>
<tr>
<td>Dextral</td>
<td>Present</td>
<td>1.7(+/−0.2) m</td>
<td>1–5 mm/yr</td>
<td>GPS observation, Yunnan, China</td>
<td>Zhao (1995)</td>
</tr>
<tr>
<td>Dextral</td>
<td>Present</td>
<td>Present</td>
<td></td>
<td>GPS observation in Vietnam</td>
<td>To et al. (2000)</td>
</tr>
</tbody>
</table>
4. Framework of the Yinggehai Basin

The NW-oriented Yinggehai Basin is located on the continental shelf at water depths of 50–200 m in the northwestern South China Sea. The elongate Yinggehai Basin is more than 500 km long and 150 km wide (Fig. 5). The Yinggehai Basin perhaps developed at a releasing bend of the Red River Fault (Gong et al., 1997), and it displays several features typical of strike-slip basins, as described below.

The Yinggehai Basin is bounded by high-angle faults with normal and reverse separation, consistent with strike-slip systems (Christie-Blick and Biddle, 1985; Harding, 1990), and geological mismatches of seismic facies occur across the major faults, especially basin boundary faults in the study area. Furthermore, the basin fill reflects cycles of subsidence and uplift, contributing to its longitudinal and lateral basin asymmetry, as well as migration of depocenters with time (Christie-Blick and Biddle, 1985; Harding, 1990). Depocenter migration and the thickness of basin filling are shown in Figs. 5–8. During 30–21 Ma, NE–SW oriented depocenters were localized in the northwestern basin shown in Figs. 5 and 6. Fig. 5 shows that depocenters migrated to the southeastern basin between 21 and 16 Ma. Between 16 and 5.5 Ma, the depocenters gradually migrated ~200 km northward, and paused in the northwestern basin. After 5.5 Ma, the depocenters rapidly migrated into the Qiongdongnan Basin to the east. Depocenter migration was also previously recognized by Gong et al. (1997) and Clift and Sun (2006).

The Yinggehai Basin is also characterized by rapid basin filling (Lin and Zhang, 1997; Huang et al., 2004), episodic rapid basin subsidence (about 50–270 m/m.y.; Lin and Zhang, 1997), overpressure, and high temperature (Chen et al., 1998; Hao et al., 1998; Hao et al., 2000; Dong and Huang, 1999; Dong and Huang, 2000; Zhang and Huang, 1991; Fig. 2). In addition, diapiric structures occur in the middle of the basin (Gong et al., 1997), associated with faulting and natural gas. Natural gases with high contents of CO2 ranging between 15% to 85% occur near

Fig. 4. Location of subsurface data, Yinggehai–Qiongdongnan Basins, South China Sea. Location of this map is in Fig. 1. Spacing of the 2D seismic data ranges from 2×2–4×4 km to 80×20 km in the Qiongdongnan and Yinggehai basins. Bin spacing of the 3D seismic survey is 25×25 m in both inline and crossline directions. 2-D seismic lines cited from literature, including Tonkin Gulf (Rangin et al., 1995), Belbu Gulf (Ying, 1998), and Offshore Da Nang area (Roques et al., 1997a,b).
the diapirs, and more than 10% of CO₂ samples are of inferred inorganic crustal origin with heavy carbon isotope values from −0.56 to −8.16 and lower ³He/⁴He ratio (Huang et al., 2004).

5. Stratigraphy

Although the Yinggehai Basin is associated with strike-slip tectonism, it also resembles a typical rift basin during its early history, as imaged by 2-D seismic-reflection profiles shown in Fig. 9. The faulted syn-rift sequences are overlain by relatively uniform and flat post-rift strata that gently thin to the basin margin. The Eocene–Oligocene synrift and Neogene–Quaternary post-rift megasequences are separated by an angular unconformity at the basin margins and a traceable high-amplitude reflection in the basin. The synrift strata rest on Paleozoic and Mesozoic metamorphic basement rocks (Lu, 1997a). Deeply buried synrift strata are not imaged on seismic sections in the center of the basin, where their thickness is estimated to be about 5000–7000 m (Huang et al., 2004). The post-rift megasequence is about 9000 m thick (Huang et al., 2004). The Cenozoic stratigraphic succession is about 17 km thick in total in the Yinggehai Basin (Gong et al., 1997).

Following the nomenclature of Prosser (1993) for rifting phases, the widely distributed Paleogene synrift megasequence consists of rift initiation and rift climax phases, characterized by abrupt facies changes. Eocene strata were deposited in topographic lows during the rapid rift initiation phase. Eocene strata are characterized by subparallel and chaotic reflections with low continuity, interpreted as lacustrine, fluviatile, alluvial, and marine environments (Lu, 1997a).

During the subsequent rift climax phase in the Oligocene, accommodation rapidly increased and sedimentation was outpaced by subsidence. The Oligocene synrift sequence is dominated by divergent, subparallel/continuous seismic reflections, consistent with neritic/bathyal environments (Lu, 1997a).

The Neogene–Quaternary post-rift megasequence consists of two elements. During the Miocene early post-rift stage, local differential
subsidence across faults was greatly decreased, and regional subsidence was mainly due to lithospheric thermal cooling effects (Lin and Zhang, 1997; Lu, 1997a). This element of the basin fill, characterized by continuous parallel seismic reflections and local prograding clinoforms, suggesting siliciclastic sedimentation in neritic marine environments along with basin-margin fan-delta development (Gong et al., 1997). After 10.5 Ma, the Yinggehai and Qiongdongnan basins experienced coeval subsidence, and strata of the two basins can be correlated. During the Pliocene–Quaternary late post-rift stage, faulting reactivated but rapid sedimentation rates exceeded subsidence rates. Pliocene–Holocene strata are relatively undeformed in the Yinggehai Basin. Parallel seismic reflections and regional prograding clinoforms with high continuity reflect a neritic marine environment and deltaic progradation (e.g., Zhu et al., in press).

6. Structures of the offshore Red River Fault system

Two boundary faults and two basin-center faults in the Yinggehai Basin are likely the major offshore extensions of the Red River Fault zone (Fig. 10). Two boundary faults trend along the northeast (fault A) and southwest (fault D) margins of the Yinggehai Basin are shown as basin boundaries in Chinese literature. Fault A is named No. 1 Fault, and part of Fault D is called Yingxi Fault in Chinese literature. The other two branches, C and D, are likely the two principal faults of the basin center. Faults C and D are newly documented in this study. We alphabetically name of the major faults in this study to avoid confusion with the fault nomenclature in Chinese and Vietnamese publications.

The four faults are slightly curvilinear in map view in the Yinggehai Basin (Fig. 10). In the northern basin, the Red River Fault system is narrow and consists of four main strands that diverge southward out of the Tonkin Gulf. Near the south end of the Yinggehai Basin, these faults converge again and possibly connect with the east Vietnam margin faults to the south. In this paper, we examine in detail these four major faults and associated deformation during three phases of strike-slip movement (~30–16 Ma, 16–5.5 Ma, and <5.5 Ma). Due to limited 2-D seismic survey coverage in the middle of the basin, correlating and connecting northern segments of Faults B, C, and D with their southern segments is tentative.
6.1. Oligocene–early Miocene structure of the offshore Red River Fault (~30–16 Ma)

The late Paleogene through early Neogene was a period of major strike-slip and associated deformation on faults of the Red River System in the Yinggehai Basin, based on pronounced thickness contrasts across the faults.

6.1.1. Fault A

In map view (Figs. 10 and 11), Fault A is a boundary fault, separating the Yinggehai Basin from the Beibu Gulf and Qiongdongnan Basins. The linear trace of Fault A is mapped for about 420 km from Tonkin Gulf to the Zhongjian ridge (Fig. 11). The strike of Fault A changes from NE–SW in the north to N–S in the south.

In cross-sections (Fig. 12), southwestward-dipping Fault A is a high angle normal fault with displacement decreasing with time. It became active during 36–30 Ma (Lu, 1997a), peaked around 30–26 Ma, and then faded around 21–16 Ma, based on stratal growth patterns. In addition, Fault A created great accommodation space during the syn-rift stage of sedimentation, and greatly deformed the rift and part of the post-rift megasequences.

6.1.2. Fault B

In plan view (Figs. 10 and 11), the curvilinear trace of Fault B has been mapped for about 450 km from the Tonkin Gulf, throughout the center of the Yinggehai Basin. It possibly extends to near the Zhongjian Ridge. The northern segment of Fault B strikes N–S, but it bends to NW–SE in the southern basin.

In cross-sections (Fig. 13), the northern segment of Fault B is a southwestward-dipping, high angle fault with reverse slip often associated with an anticline (L9 and L11 in Fig. 13). The wavelength of the fold adjacent to the fault decreases from 19 km to 11 km southeastward. Displacement across Fault B diminished upward until around 26 Ma in the northern basin, thereby defining the upper age limit of its activity.

The southern segment of Fault B is localized along the axis of the basin (L19 in Fig. 13), accompanied by diapiric structures. The chaotic seismic facies that characterize diapir-like structures apparently are influenced by gas effects. High content of crustal gas (Huang et al., 2004) found in these diapir-like structures suggests that Fault B is a deep-rooted fault. Initial movement of these diapiric structures occurred in the Oligocene (He, 1990). Thermogenic gas migration along Fault B occurred after 21–10 Ma, as suggested by isotope data.
In addition, the diapirs formed earlier in the middle of the basin and later in the south basin (Lu, 1997a). This diachronous development of diapir structures possibly suggests that movement of Fault B propagated from north to south.

6.1.3. Fault C

Fault C extends about 480 km from the Tonkin Gulf, cuts across the center of the Yinggehai Basin, and approaches the Zhongjian Ridge (Figs. 10 and 11). In general, the trend of Fault C is NW–SE. The separation sense of Fault C changes significantly from reverse separation in the northern basin to normal separation in the southern basin (Fig. 14).

In the northern basin, the magnitude of reverse faulting decreases southward along Fault C, as does related stratal folding. In Tonkin Gulf, the steeply southwestward dipping Fault C is characterized by positive flower structures (L1 and L5 in Fig. 14) with intense reverse faulting and oblique N–S en echelon folds (Rangin et al., 1995). Deformation was most intense during the Oligocene and then stopped around 16 Ma. After the deformed Oligocene–Miocene strata were exhumed and partly eroded until 5.5 Ma, the fault was unconformably overlapped by flatlying Pliocene–Holocene deposits (L1 in Fig. 14). Oligocene strata adjacent to Fault C are separated by more than 1500 m of structural relief in Tonkin Gulf. Further southward, Fault C is associated with a large anticline (L5, L9, and L13 in Fig. 14). The wavelength of the anticline decreases southward from ~30 km to ~10 km.

6.1.4. Fault D

Fault D extends ~500 km along the west margin of the Yinggehai Basin (Figs. 10 and 11), where its trend varies from N–S in its northern segment to NW–SE in its southern segment. The dip direction and separation sense apparently alternate along the strike of this fault from a northeastward dipping fault segment with reverse separation in the northern basin, to a northeastward dip with normal separation in the southern basin (Fig. 15).

In cross-sections (Fig. 15), the northern segment of Fault D is a high angle thrust fault associated with positive flower structures (L3 and L7 in Fig. 15), with deformational magnitude decreasing southward. The unbackstripped fold’s amplitude is about 300–700 m in the Tonkin Gulf, and it decreases to ~200 m southward. Fault D motion climaxed around 26 Ma; thereafter, its deformation decreased and stopped around 21 Ma. The southern segment of Fault D is a high angle normal fault (L19 in Fig. 15), separating the Yinggehai Basin and Hue basin.
Fault distribution is highly complex here, likely owing to the merging of the Red River Fault and offshore Song Ma fault in the Hue basin (Fig. 11).

6.2. Middle–late Miocene structural inversion of the offshore Red River Fault (16–5.5 Ma)

Most of the basement-involved faults were quiescent during the post-rift phase between 16 and 5.5 Ma (Figs. 16, and 17). During this time frame, Fault B was inactive and structural inversion prevailed in the Yinggehai Basin, as described below.

6.2.1. Fault A

A large positive structural inversion is demonstrated across a 30 km wide zone between points X and Y (L3 in Fig. 12). This inversion structure was associated with syn-tectonic sedimentation, enhanced by uplift of the previous sag. There are at least three periods of deformation associated with this inversion structure. Thick Oligocene to lower Miocene sediments were deposited in the previous sag, thinning along the sag margins on the adjacent fault’s hanging wall. Later, the Oligocene–lower Miocene deposits in the previous sag were deformed and folded by thrust faulting. It is followed by uplift and erosion to form an unconformity dated at 16 Ma. This change is a positive inversion structure (cf. Williams et al., 1989), indicating the polarity of structural relief from a previous low to high. Positive structural inversion is consistent with a shift from a transtensional regime to a transpressional regime.

To the south, Fault A is associated with slightly positive inversion structure with reverse reactivation of normal faults (L5 in Fig. 12). Reverse-slip separation and folding of sedimentary reflections occurs locally. Reactivation of this fault occurred between 16–13.8 Ma and stopped around 3.6 Ma.

6.2.2. Fault C

Fault C displays intense structural inversion in Tonkin Gulf (L1 in Fig. 14), as recognized by Rangin et al. (1995). Oligocene–Miocene strata were uplifted by structural inversion between 16 and 5.5 Ma, and were eroded and overlain by Pliocene–Holocene deposits.

6.2.3. Fault D

Strata that accumulated after 26 Ma are thin in the vicinity of Fault D (L1 in Fig. 14). Undeformed strata at 5.5 Ma indicate that deformation ended by that time, as also recognized by Rangin et al. (1995). In addition, the hanging wall of Fault D was slightly upthrown on line L15 (Fig. 15), indicating the development of a positive inversion after 16 Ma. Sediments deposited in the hanging wall are thinner than those at the footwall during 5.5–3.6 Ma, which suggests that the reverse rejuvenation of this fault ended prior to 3.6 Ma.

Fig. 9. Transverse 2-D seismic sections L1, L7, L19 and L25, Yinggehai Basin, South China Sea. Panel a is an uninterpreted transverse 2-D seismic sections. Panel b is an interpreted transverse 2-D seismic sections. A, B, C, and D are fault names. L1, L7, L19 and L25 are numbers of 2-D seismic reflection profiles. Location of the 2-D seismic lines is in the inset Fig. 2.
6.3. Pliocene–Holocene structure of the offshore Red River Fault (after 5.5 Ma)

6.3.1. Fault A
Fault A was reactivated near Hainan Island after 5.5 Ma (Fig. 17). Its reactivation is indirectly supported by present fluid expulsion observed near Fault A. More than 100 modern gas seepages occur adjacent to Fault A, as detected by sidescan sonar (Xie, 2003). Reactivation of Fault A is also accompanied by reactivation of basement faulting and submarine channel incision (Figs. 17 and 18).

Slope parallel submarine channel A formed at the basin floor, and filled with more than 350 m of thick massive turbidite sandstones (Gong et al., 1997), as shown by high amplitudes in the 3-D seismic amplitude extraction map (Fig. 18).

6.3.2. Fault B
Fault B, with subvertical reverse slip, diverges and extends upward into Pliocene and Holocene strata (L18 and 19, Fig. 13), and intersects the sea floor in some locations. Fault B accompanies en echelon faults striking N–S, which are related to diapiric structures.

6.3.3. Faults C and D
Faults C and D were locally reactivated after 5.5 Ma with little vertical slip. Associated Pliocene–Holocene strata are relatively undeformed.

7. Strike-slip movement of the offshore Red River Fault zone

The Red River Fault system in the Yinggehai Basin displays features characteristic of strike-slip fault systems as defined by Christie-Blick and Biddle (1985), Harding (1990), and Sylvester (1988), including 1) four long and likely through-going deformation zones shown in Fig. 10; 2) subvertical to moderate dip of these four master faults; 3) abrupt changes in seismic stratigraphic facies across the fault system; 4) coexistence and simultaneous development of both transpressional and transtensional structures in individual transverse profiles.
(e.g., Fault B with reverse slip adjacent to Fault A with normal separation; L1 in Fig. 9); 5) flower structures in transverse profile (Faults C and D; L1 in Fig. 9), 6) coeval en echelon flanking structures; 7) structural inversion along master faults (Faults A, C, and D), 8) basement involvement, and 9) possibly inconsistent dip direction and separation sense along a single fault (Faults C and D). In addition, these major faults project into mapped horsetail splays of the Red River Fault onshore and in Tonkin Gulf (Rangin et al., 1995). Therefore, we conclude that these four faults are the major extension of the offshore Red River Fault zone. Slip motion and magnitude of the offshore Red River Fault zone are examined as follows.

7.1. Slip sense history of the Red River Fault zone

7.1.1. Oligocene–early Miocene sinistral slip (30–16 Ma)

Based on our work and published data (Rangin et al., 1995; Gong et al., 1997; Clift and Sun, 2006; Huyen et al., 2007), regional structural patterns and strain analysis are consistent with left-lateral slip for the Red River Fault zone in the Yinggehai Basin before 16 Ma: 1) The Yinggehai Basin is a strike-slip basin, formed by N–S stretching and an E–W transtensional stress field; 2) In plan view, N–S trending en echelon folds (Rangin et al., 1995) are oblique to the NW–SE shear direction of the traces of the Red River Fault zone in the Tonkin Gulf. They represent the shortening component of the strain locally; 3) NE–SW trending extensional faults are present at the junction of the Yinggehai and Qiongdongnan Basins, and they are linked to strike-slip movement of the faults in the Yinggehai Basin (Fig. 11; Zhong et al., 2004); 4) Depocenters migrated southeastward from 30 to 16 Ma along the central master faults in the Yinggehai Basin. In summary, structural and stratigraphic features are consistent with a sinistral strain ellipse with NW principal displacement (Wilcox et al., 1973).

Our interpretation of sinistral slip in the Yinggehai Basin before 16 Ma is consistent with other evidence. Results from sandbox analogue modeling of the Yinggehai Basin are consistent with sinistral extrusion of the Indochina block (Sun et al., 2003). Many onshore geological markers in China and the Indochina block along the Red River Fault imply left-lateral slip sense, as summarized in Table 1. Moreover, left-lateral kinematic indicators are ubiquitous within the
mylonites in the onshore segment of the Red River Fault (Leloup et al., 1995).

Relationships between the orientation of the Red River Fault and slip direction determines whether releasing bends or restraining bends developed along local fault segments (cf. Crowell, 1974). The northern segments of Faults C and D define restraining bends (L1 in Fig. 14), and are dominated by positive flower structures with their associated thrust faults and en echelon folds. The southern segment of Fault A likely also defines a restraining bend. In contrast, releasing bends dominate the northern segment of Fault A (L3 and L5 in Fig. 12) and southern segments of Faults C and D (L21 in Fig. 14; L19 in Fig. 15), which are characterized by transtensional faulting.

7.1.2. Middle–late Miocene structure inversion (16–5.5 Ma)

Strike-slip is often associated with inversion tectonics, and location of inversion often suggests the location of a master fault (Harding, 1990). It is difficult to reactivate steeply dipping normal faults by inversion, but it is possible to reactivate steep faults by oblique or strike-slip movements, especially where the minimum compressive stress is horizontal (Coward, 1994).

Like many other strike-slip inversions in the world (e.g., Hsiao et al., 2004), slip sense reversed from left lateral to right lateral along the Red River Fault zone in the Yinggehai Basin during 16–5.5 Ma (although reversion was also interpreted during 21–15 Ma by Clift and Sun, 2006). This view is supported by structural and stratigraphic evidence. For example, divergent bends were reactivated by convergent structures in the study area. For instance, in the northeast releasing bend of Fault A, regional subsidence ceased with development of a large-scale structural inversion around 16 Ma near Tonkin Gulf (L3 in Fig. 12), and this event likely marks the onset time of slip reversal. To the south, normal faulting ceased and thrust faulting developed along Fault A (L5 in Fig. 12). The onset of slip reversal appears to have occurred 16–13.8 Ma. At the southwest releasing bend of Fault D, slip reversal initiated after 16 Ma, climaxed around 5.5–3.6 Ma, and persists until the present in the middle of the basin (L15 in Fig. 15). Moreover, inversion is supported by stratigraphic reorganization in the Yinggehai Basin. Depocenters shifted northwestward by ~200 km from 16 to 5.5 Ma, shown in Fig. 5. In general, inversion was likely caused by dextral movement of the Red River Fault zone, which developed earlier in the northern basin and later in the southern basin.

7.1.3. Pliocene–Holocene dextral slip (after 5.5 Ma)

The Red River Fault reactivated in a right lateral sense along the present-day trend of the Red River Fault zone in the Yinggehai Basin. Our results show this movement likely climaxed around 5.5–3.6 Ma and has persisted until the present time.

Pliocene–Holocene structures are consistent with dextral strain (Wilcox et al., 1973) based on the following evidence. 1) Positive structural inversion along Faults A (e.g., L5 in Fig. 12) and D (e.g., L15 in
Fig. 15) suggest strain shifting from transtension to transpression locally, and changing the slip sense of faulting in the study area. 2) E–W stretching and a N–S transtensional stress field occurs in the Yinggehai Basin (Luo et al., 2003). 3) NNW–SSE trending en echelon faults with diapir-like structures occur along Fault B in the center of the basin (Li and Zhang, 1997), although an alternative interpretation of these en echelon faults is overpressure and diapirism. Because angular deviation and shear direction of en echelon structures commonly ranges from 10° to 35° (Harding and Lowell, 1979), regional slip lies along a NW–SE trend in the Yinggehai Basin. 4) Pliocene structures are consistent with right-lateral slip sense in the northwestern Yinggehai Basin (Rangin et al., 1995; Gong et al., 1997; Huyen et al., 2007).

Our interpretation is also supported by other evidence for dextral slip from the onshore Red River Fault zone. They include: earthquake focal mechanisms from onshore segments of the Red River Fault (Allen et al., 1984), GPS measurement along the onshore Red River Fault in China (Zhao, 1995) and Vietnam (To et al., 2000), and dextral offsets estimated by large river offset and fault scarps along the Red River (Replumaz et al., 2001).

7.2. Magnitude of strike slip

We have not recognized robust piercing points as defined by Crowell (1974) in our dataset and cannot constrain rates of lateral slip on any of these faults. However, the magnitude of strike slip on the Red River Fault system can be inferred from the reasoning used to explain the geological mismatches along major faults.

As revealed by the 2-D seismic profiles in Fig. 9, the magnitude of vertical displacement and stratal wedging associated with the four major faults indicates that these faults experienced rapid sinistral movement before 21 Ma. In contrast, the major faults show much less left lateral motion during 21–16 Ma, with only a moderate thickness of unfaulted strata. After 16 Ma, the major faults were relatively quiescent, as suggested by faulted strata with minor vertical displacement. These observations support the interpretation that the dextral slip episode accumulated much less slip than the sinistral episode in the Yinggehai Basin.

At least 20 km of sinistral slip occurred along the offshore segment of the Red River Fault in the Yinggehai Basin. No convincing piercing points are observed in our dataset to constrain the upper limit of horizontal displacement, which likely is much greater than 20 km, based on onshore evidence summarized in Table 1. However, the lower limit of the sinistral slip can be estimated from structural relationships along Fault D in the Hue Subbasin. Seismic line L19 (Figs. 9 and 15) shows that strata with southwest and northeast dip were separated before 21 Ma, and now they are juxtaposed against each other. The distance between this section and the nearest section with reasonably well documented faults (L21 in Fig. 14) is ~20 km, which is a minimum estimated distance of sinistral slip. Subsequently, the hanging wall of Fault D was translated at least 20 km from the current location, in order to avoid the problem of oppositely dipping
strata. However, the complexity of the fault system makes our estimate uncertain, because structures in the Hue basin are also possibly influenced by the Song Ma fault, as shown in Fig. 11.

We estimate that there have been tens of kilometers of dextral displacement along the major faults in the Yinggehai Basin. Our reasoning is based on the juxtaposition of similar sedimentary packages with minor vertical slip along major faults during the dextral episode after 16 Ma.

8. Discussions

8.1. Distribution and structure of the offshore Red River Fault zone

Through this study, two boundary faults (Faults A and D) and two basin-center faults (Faults B and C) have been documented using a grid of seismic reflection data in the Yinggehai Basin. These four faults are likely the offshore branching extension of the Red River Fault because: 1) they project toward the Red River Fault zone onshore and in the Tonkin Gulf, and 2) they show typical features of strike-slip faults. The structural features of the offshore Red River Fault zone are generalized as follows: 1) These four faults are long, steep, likely thoroughgoing faults with normal or reverse slip; 2) reverse faulting occurs at the restraining bends with positive flower structures, en echelon folds, and positive structural inversion; 3) transtensional structures are developed at the releasing bends; and 4) dip direction and separation sense apparently alternate along a single fault.

Different from previous structural mapping (Gong et al., 1997), this study suggests that two major fault branches (Faults C and D; Figs. 11, 13, and 14) axially cut the center of the Yinggehai Basin. These two faults likely were not recognized in previous research because they are often deeply buried, especially in the basin center. Besides directly documenting faults with 2-D seismic data, our interpretation of fault location is supported by the presence of medium to large anticlines and seeps of thermogenic gas along these central faults, and as well as by migration of depocenters along these central faults.

8.2. Tectonics of the offshore Red River Fault zone

From our studies we infer three successive deformation phases for the offshore Red River Fault zone. From ~30 to 16 Ma, the Red River Fault was characterized by sinistral movement in the Yinggehai Basin. Rapid sinistral movement of the Red River Fault was coeval with syn-rift deposition before 21 Ma. Slow sinistral movement of a few faults characterized the period of 21–16 Ma in the Yinggehai Basin. During the second stage between 16 and 5.5 Ma, the Red River Fault experienced slip reversal in the Yinggehai Basin, and slip sense changed from sinistral to dextral. Slip reversal likely happened earlier in the north basin than in the south basin, which was previously noted in Clift and Sun (2006). Diachrony of slip reversal is evidenced by the timing of structural inversion and diapir development, as well as northwestern migration of the depocenters in the Yinggehai Basin. Dextral movement of the Red River Fault appears to have climaxed...
around 5.5–3.6 Ma and diminished to the present. A large submarine channel developed at about 3.6 Ma along the basin axis, parallel to the Red River Fault strands (Figs. 17 and 18).

Our timing results are consistent with most thermochronological studies of metamorphic rocks along the onshore Red River Fault (Fig. 3), although there is a lack of age controls older than 30 Ma in this study. Geochronological information regarding the onshore Red River Fault zone comes from about 40 U/Pb ages constraining high-temperature changes, as well as more than 100 $^{40}$Ar/$^{39}$Ar ages constraining its cooling history (Tapponnier et al., 1990; Harrison et al., 1992; Leloup and Kienast, 1993; Scharer et al., 1994; Leloup et al., 1995; Harrison et al., 1996; Chung et al., 1997; Wang et al., 1998b; Zhang and Scharer, 1999; Wang et al., 2000; Leloup et al., 2001; Gilley et al., 2003; Searle, 2006). A few samples collected along the onshore Red River fault in the Ailao Shan are dated between 17 and 20 Ma, but still other samples gathered in the Ailao Shan and Day Nui Con Voi massif and most samples in Xuelong Shan and DianCang Shan show sinistral movement before 20 Ma.

8.3. Role of the Red River Fault in the formation of the South China Sea

The role of the Red River Fault in the opening of the South China Sea is a key prediction of the continental extrusion model (Tapponnier et al., 1982, 2001). Our interpretation of structures, shear timing and kinematics is consistent with a linkage between South China Sea spreading and sinistral shear of the Red River Fault. We infer that the offshore Red River Fault zone experienced fast sinistral movement from ~30 to 21 Ma, with cessation of most basement-involved fault slip around 21 Ma. Our inferred timing for sinistral movement of the offshore Red River Fault is consistent with the majority of geochronological ages onshore, especially those that display rapid cooling in the Day Nui Con Voi massif in Vietnam and the southern segment of the Ailao Shan. In the South China Sea, timing of seafloor spreading has been revised to 31–20.5 Ma (Barckhausen and Roeser, 2004), from 32 to 15.5 Ma (Briais et al., 1993) by incorporating new magnetic anomaly data. Thus, opening of the South China Sea is coeval with rapid sinistral movement of the major faults in the Yinggehai Basin and most geochronological results onshore.

Nevertheless, spatial relationships between the Red River Fault and the South China Sea cannot be conclusively demonstrated by our studies. Our data do not reveal (but do not exclude) convincing evidence for horizontal sinistral offset of hundreds of kilometers in the Yinggehai Basin, as suggested by other researchers summarized in Table 1. Onshore studies that have shown a positive correlation between the Red River Fault and spreading of the South China Sea, include: 1) more than 14° clockwise rotation of the mid-Cretaceous Indochina block relative to the South China Block along the Red River Fault zone by paleomagnetic studies (Yang and Besse, 1993; Yang et al., 2001); 2) high-grade mylonitic gneisses of the Red River Fault zone indicating sinistral slip (Leloup et al., 1995, 2001; Gilley et al., 2003); and 3) concordant
displacement of several Mesozoic geological markers by ~700 km, which is about the size of the South China Sea in its direction of extension (Tapponnier et al., 1990; Leloup et al., 1995, 2001).

8.4. Implications for regional tectonics

Our offshore studies are consistent with a linkage in timing and kinematics between Red River Fault sinistral motion and opening of the South China Sea, thereby permissively supporting the continental extrusion model before the middle Miocene. The continental extrusion model (Tapponnier et al., 1982, 1990) holds that the left-lateral movement of the Red River Fault, the largest strike-slip fault in Southeast Asia, was triggered by the shear stress component from oblique subduction of the Indian plate relative to the Eurasian plate and rotation of the Indochina block. Parts of the Tibetan plateau achieved current elevation by at least the middle Miocene (e.g., Blisniuk et al., 2001; Spicer et al., 2003), if not considerably earlier (e.g., Rowley and Currie, 2006; Wang et al., 2008). Thus, eastward extrusion and uplift of the Tibetan plateau were probably most important before the middle Miocene.

However, certain observed features along the Red River Fault and deformation of the eastern Tibetan plateau after the middle Miocene appear to be inconsistent with the continental extrusion model in at least three ways: 1) The horizontal displacement rate is much less than the minimum requirements for the continental extrusion model along the Red River Fault after the middle Miocene (Allen et al., 1984; Zhao, 1995; Wang et al., 1998a; To et al., 2000; Replumaz et al., 2001; Schoenbohm et al., 2006). 2) The eastern margin lacks large late Cenozoic shortening structures commonly associated with crustal thickening (e.g., Royden et al., 1997). 3) The extrusion model does not indicate clockwise rotation of crustal material around the eastern Himalayan syntaxis (Royden et al., 1997). This suggests that continental extrusion might be only a relatively minor tectonic factor after 16 Ma during the later stages of the India–Asia collision, and of considerably less importance after the middle Miocene than before it (cf. Yue and Liou, 1999; Yue et al., 2004; Darby et al., 2005; Ritts et al., 2004, 2008). Due to apparent deficiency of the continent extrusion model after 16 Ma, a different model is needed. Increasing evidence suggests that distributed shortening played a more important role in the later stage of India–Asia collision. The distributed shortening model holds that the partially molten middle crust underlying extruded southeastward as Poiseuille-type channel flow (Royden et al., 1997; Beaumont et al., 2004; Klemperer, 2006). Southeastern Tibet has rotated clockwise

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**Fig. 16.** Time map of 16 Ma structure, Yinggehai–Qiongdongnan basins, northwestern South China Sea. Isochron contours are two way traveltime (TWT) in seconds.
without major crustal shortening around the eastern Himalayan syntaxes, with initiation and prolonged history of eastward extrusion of crustal material from the plateau around the strong crust of the Sichuan basin (Royden et al., 1997; Clark et al., 2005). This model better explains the deformation record in response to the continuing India–Asia collision, specifically the regional low rate of dextral accommodation of the Red River Fault zone. In addition, this model may better explain slip reversal of the Red River Fault, as well as initiation of right-lateral displacement along the Gaoligong fault (Hsu, 2000), Sagaing fault (Bertrand et al., 1999; Vigny et al., 2003; Bertrand and Rangin, 2003; Fig. 1) and Jiali fault (Armijo et al., 1989; Lee et al., 2003) after the middle Miocene.

In general, we favor a hybrid model for the evolution of the Red River Fault zone. It appears that continental extrusion was dominant in India–Asia collision before the middle Miocene, and coincident with growth of an orogen whose height may have been comparable to the modern plateau. During the second stage after the middle Miocene, distributed shortening became more important than continental extrusion along the Red River Fault, while crustal materials of the Tibetan plateau grew eastward and dextrally rotated around the east Himalayan syntax.

9. Conclusions

This study describes the structure of the offshore Red River Fault in the Yinggehai Basin, documents timing of its strike-slip movement and slip reversal, and addresses mechanisms of the India–Asia collision.

Two boundary faults and two previously undocumented, basin-center faults have been described. These four faults display typical features of strike-slip faults, and they are likely the offshore extensions of the Red River Fault. Three deformation phases for the offshore Red River Fault zone include sinistral movement before 16 Ma, slip reversal between 16 and 5.5 Ma, and dextral movement after 5.5 Ma. Slip reversal also is indicated by diachronous basin inversion from north to south, thereby partially filling an important

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Fig. 17. Time map of 5.5 Ma structure, Yinggehai–Qiongdongnan basins, northwestern South China Sea. The location of the onshore Red River Fault is from published literature (Clift and Sun, 2006), and distribution of the turbidite channel is from Gong and Xie (1997). Isochron contours are two way traveltime (TWT) in seconds.
gap in the history of the Red River Fault during the middle to late Miocene. Although no robust piercing points are observed during the sinistral movement period, the horizontal displacement of dextral movement is estimated to be tens of kilometers.

Our analysis suggests timing and kinematic linkages between sinistral movement of the offshore Red River Fault and opening of the South China Sea before the middle Miocene, consistent with the notion that extrusion was dominant along the southeastern margin of the Tibetan plateau before the middle Miocene. After the middle Miocene, distributed shortening better explains the deformation record in response to the continuing India–Asia collision, especially the regional low rate of dextral deformation of the Red River Fault zone.

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