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EDITORIAL

Introduction to special collection on geology, tectonics and hydrocarbon systems of SE Asia

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The South China Sea is a classic example of the marginal basins that typify the margin of Southeast Asia, and one with a relatively complicated tectonic history that has been linked both to the development of the active margins of the Western Pacific and to the tectonics of continental Asia following the India–Asia collision starting around 50 Ma. The tectonics of continental break-up and seafloor spreading have been studied in this area for a significant period of time, yet our understanding of why the basin formed in the first places still remains controversial. Two competing schools have suggested two opposing visions for what caused the basin to open. One of these models relates opening of the South China Sea to the rollback of subduction zones in the Western Pacific and Indonesia that generated regional extensional stresses, so that the South China Sea can be thought of as essentially a large back arc system (Hamilton 1977; Hall 2002). In an alternative view the South China Sea is envisaged as being the product of the extrusion of a rigid Southeast Asia block linked to indentor tectonics following the India-Asia collision starting in the Eocene (Tapponnier et al. 1982; Leloup et al. 1995). This collection of papers represents a significant new body of data that helps us better understand the geophysical and geological setting of the South China Sea and associated basins. Some of these works are based on study of newly released industrial data sets, while others are purely of academic origin. Taken together they represent a significant advance in our understanding of the region and help lay the groundwork for the upcoming scientific drilling in the deep-water part of the South China Sea in February–March 2014 by the International Ocean Discovery Program (IODP).

Although there remains significant debate about how strain was accommodated during opening, it is clear that the South China Sea was generated as a result of extension of relatively warm continental crust that had been influenced by an earlier phase of subduction under southern China known as the Cathaysia arc (Metcalfe 1996). This means that the lithosphere that was affected by extension behaved in a relatively weak and ductile fashion compared to the rifting of more mature continental lithosphere such as in East Africa or Baikal on the edge of the Siberian craton (Clift et al. 2002). The weak, ductile character of the South China lithosphere and especially mid-lower crust, has had an important impact on the nature of the rifting in this region, favoring crustal flow (Davis and Kusznir 2004; Sun et al. 2006). Other potential complexities related to the opening of the South China Sea involve the possible involvement of deep-seated mantle plumes (Lei et al. 2009; Liang et al. 2004). Although early geophysical studies of the continental margin of southern China suggested that there might be magmatic underplated bodies under the rifted structure (Kido et al. 2001; Nissen et al. 1995; Wei et al. 2011; Yan et al. 2001) later studies have failed to reveal the tell-tale seaward-dipping reflectors that are normally associated with the formation of a rifted volcanic margin (Clift et al. 2001).

Nonetheless, many workers continue to believe that elevated mantle thermal anomalies have been involved in the opening of the South China Sea (Shi et al. 2003; Tu et al. 1991). It is undoubted that magmatism has occurred

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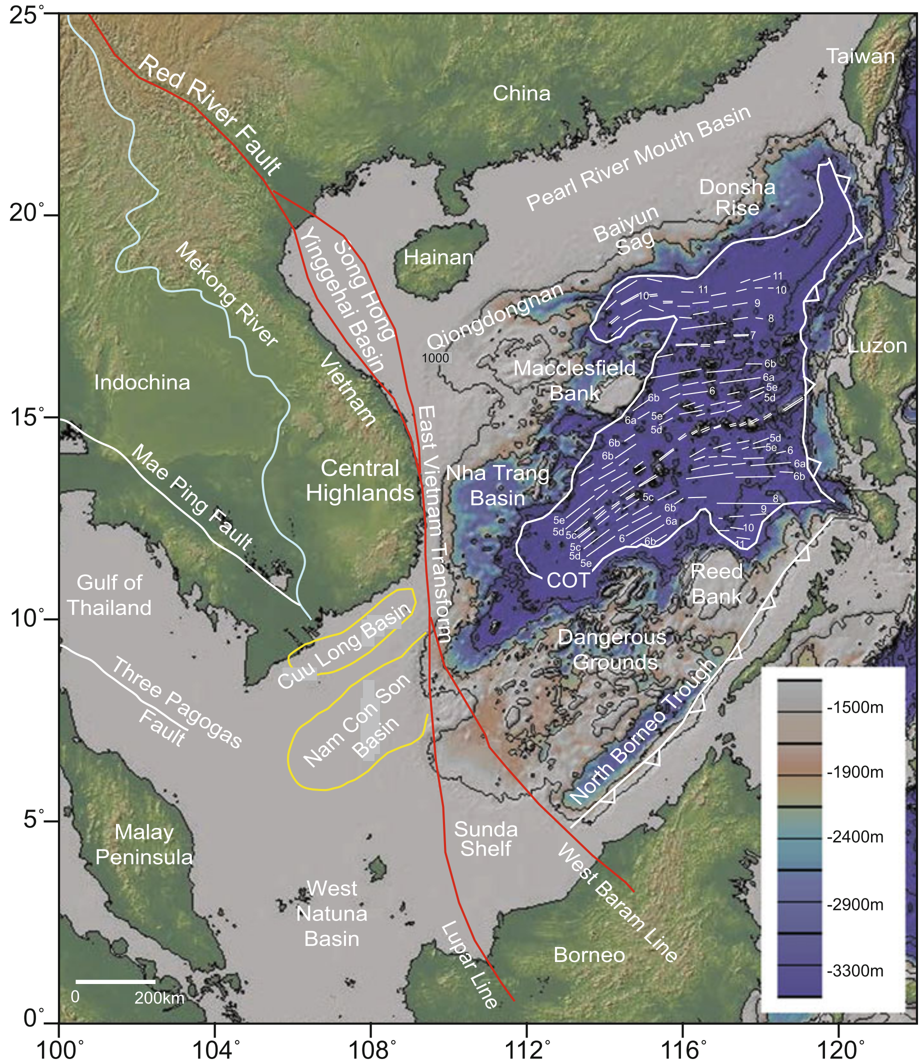

Fig. 1 Topographic and shaded bathymetric map of the South China Sea showing the various basins that are the subject of the papers in this collection, as well as the Red River Fault Zone, Central Highlands of Vietnam, the Nam Con Son Basin and the Sunda Shelf. *Solid white line* indicates approximate location of the continent–ocean transition (COT) based on seafloor spreading anomalies of Briais et al. (1993). The *numbers* represent the seafloor spreading anomalies. Map generated by GeoMapApp

away from the sea floor spreading centers during and after the opening of the South China Sea but whether these are plume-related is debated. Significant volumes of basaltic magma have been mapped in central Vietnam around 8 Ma (Carter et al. 2000), well after the end of seafloor spreading whether that was at 20 or 15 Ma (Briais et al. 1993; Barckhausen and Roeser 2004), while the passive margin of southern China is also marked by the intrusion of seamounts some of which appeared to be of Quaternary age (Xu et al. 2012). However, these differ significantly from traditional hotspot tracks linked to classic mantle plumes, like Hawaii or Iceland, because the volumes of magmatism are rather small and the distribution of the magmatism is both widespread and not time-progressive in the traditional fashion of the seamount chain, such as the Emperor-Hawaiian seamount chain. Subsidence analyses of the continental margins also tend to indicate the lack of any significant thermal anomaly (Wheeler and White 2000; Clift and Lin 2001; Ru and Pigott 1986), which would normally be expected to generate significant degrees of uplift. Analysis of the seismic stratigraphy in the Southwestern South China Sea, adjacent to the Nam Con Son Basin by Li et al. now reveals that post-rift magmatism is dated as Late Miocene to Pliocene in that area effectively synchronous with similar volcanism seen on the South China continental margin.

The development of basins in the South China Sea has been not only of academic interest but also of economic significance. Large oilfields have been known in the region of Brunei and offshore northern Borneo for some time now, as well as within the transtensional basins offshore peninsular Malaysia, in the Gulf of Thailand (Madon and Watts 1998). Although initial attempts to find hydrocarbons on the passive margin of southern China were not very successful this situation has changed in the last decade so that there is now significant gas production within the Yinggehai–Song Hong Basin, south of Hainan Island in the Qiongdongnan Basin, as well as in the Pearl River Mouth

Basin itself (Fig. 1). Through mathematical simulation, Lei et al. suggested that formation of the Yinggehai–Song Hong Basin was strongly influenced by the strike–slip faulting of the Red River Fault. However, its influence on other parts of the South China Sea is questionable. Structures closely linked with rifting are imaged on seismic data in Qiongdongnan Basin, which instead favors subduction of a proto-South China Sea oceanic crust toward NW Borneo during the Eocene–Early Miocene as being necessary to explain rifting and thinning on northern continental margin of South China Sea.

Some of these basins are particularly deep, reaching more than 15 km in the Yinggehai–Song Hong Basin (Clift and Sun 2006), as well as in the Baiyun Sag on the edge of the continental shelf offshore southern China. The vertical tectonics associated with these super deep basins has often been hard to reconstruct, but there seems to be significant evidence that not all of the rapid subsidence occurred during the traditional syn-rift that preceded the onset of seafloor spreading around 30 Ma (Sun et al. 2008; Zhao et al. 2011). Recognition that rapid subsidence might occur in the post-rift period contradicts traditional models of continental extension (McKenzie 1978) and has led to a variety of potential solutions for understanding the origin of these economically important sags. Although the mechanisms that caused the subsidence still remain obscure, in a new study Xie et al. have now reconstructed the magnitude and timing of rapid subsidence within the Baiyun Sag for the first time. This degree of detail now allows us better to correlate these processes with potential tectonic triggers across the region, whether related to tectonic stresses, magmatism or sediment loading.

In a related study of the Baiyun Sag Wang et al. determined that this basin is not characterized by many long-reaching boundary faults. The shape of the Baiyun Sag is not a typical half-graben. In contrast to the sags in the Northern Depression Zone of the Pearl River Mouth Basin, the Baiyun Sag has been controlled by two groups of NWW-trending en echelon faults with opposing inclinations. These en echelon faults, together with narrow synclines, partial flower structures and fluid diapirs indicate the effects of left-lateral transtensional stresses, which controlled the distribution of sand bodies during basin opening. Zhang and Sun proposed that this basin was a region of thin crust even before the onset of major regional extension during the Oligocene. They proposed using an analog modeling method that magma must have played an active part in the rifting process and that this intruded a crust that is more ductile than normal, so resulting in contrasting faulting patterns between the shelf and slope. The pre-existing thin crust beneath Baiyun Sag might be related to its Mesozoic tectonic history. By conducting a stratigraphic division and depositional analysis of the Mesozoic in the northern South China Sea, Xu et al. demonstrated that major geological events during basin filling (e.g., seawater withdrawal from the epicontinental region at the end of the Early Jurassic, submarine volcanism and Late Jurassic-Early Cretaceous uplift of the northern South China Sea shelf) indicate that there had been a collision between a Mesozoic oceanic plate located to the south and the continental crust of southern China in the north.

Basin modeling was pursued in the Qiongdongnan Basin south of Hainan by Zhao et al. who identified three episodes of subsidence, one being rapid during Oligocene regional extension, a subsequent Miocene post-rift phase which was slow and related to thermal subsidence, and then a final rapid phase starting in the Late Miocene. Analysis of the faults seen in the seismic profiles shows that the amount of brittle faulting after 21 Ma is very low and so they conclude that there was no active extension during the post-rift period. They inferred that the younger phase of rapid subsidence was driven by lower crustal thinning linked to a depth-dependent crustal rheology of this basin, a hypothesis supported by gravity data and probably linked to the larger scale flow of ductile lower crust away from the Tibetan Plateau and into Southwest China (Bai et al. 2010; Clark and Royden 2000). Further analysis of the Qiongdongnan Basin was undertaken by Zhang et al. who noted important differences in the structure between the East and West ends of the basin. They concluded that the western basin is strongly influenced by strike slip faults linked the Red River system and that this area experienced inversion between 30 and 21 Ma. In contrast, the eastern sector is dominated by NE-striking faults before 30 Ma and is typified by a composite symmetrical graben, unlike the asymmetric situation in the West. The eastern basin is proposed to be underlain by mantle upwelling and greater heatflow whose influence is not seen further towards the west. This analysis suggests that before 36 Ma the tectonics are dominated by Western Pacific subduction forces, followed by greater influence from subduction of the proto-South China Sea to the south and increasing degrees of extrusion of Indochina, especially after 30 Ma.

The nature of the crust underlying Qiongdongnan Basin was investigated by the study of Qiu et al. who integrated data sets of sedimentary horizons, wells, seismic reflection data and gravity in order to derive the first integrated crustal scale model of the basin. This compilation showed that the sediment fill is 6 km greater in the west compares to the east, but that the Central Depression contains 10 km more sediment compared to the northern and southern flanks. Modeling of the basement under the sediment fill suggests the presence of 2–4 km thick high-velocity bodies which probably represent underplated igneous bodies emplaced during the final rifting process, similar to those proposed from further to the east in the Pearl River mouth basin. These are associated with extreme crustal thinning in the central part of the basin (<3 km of original crystalline material).

It is one thing to generate a sedimentary basin by tectonic forces and yet another to fill this with sedimentary deposits making it a viable hydrocarbon system. Sediment is delivered to the basin by a number of major rivers and this is then reworked deep into the basin and onto the lower part of the continental slope via a series of submarine canyons. In their study Ding et al. reported on a series of ancient buried canyons that have supplied sediment from the Pearl River into the Baiyun Sag. The morphology of these canyons appears to be dictated by the nature of the basement and the degree of tectonic subsidence, with a strong structural control governing the orientation and shape of the canyons. Rapid subsidence within Baiyun Sag has promoted the development of a broad *U* shaped morphology. These authors concluded that the multi-phases of cutting and filling of each canyon reflected changing sediment supply driven by a varying sea level as well as the erosive climate onshore. Further to the west a study by Jiang et al. examined the generation of sediment waves in the Qiongdongnan Basin. Combined seismic and drilling data showed that sediment waves have been formed in deep water in this region, often in association with a major channel flowing west to east through the central part of the basin. These workers concluded that the sediment waves were caused by the overflow of turbidity currents along the canyon and not by contourite sedimentation as previously argued. They further concluded that such deposits might act as good hydrocarbon reservoirs because of the better sorting of turbidite sands compared to gravity flow deposits. Chen et al. believes that morphological changes may have led to different styles of sediment transport, from a depositional complex of contourite depositional systems, mass-wasting deposits and canyons in the east to only sliding and canyon deposits in the western Qiongdongnan Basin.

A study by Lambiase and Tulot looked at sediment transport processes in shallow water on the southern side of the basin, in particular examining the Miocene Belait and Sandakan Formations in northwestern Borneo. Sands within these units act as potential hydrocarbon reservoirs. While the Belait Formation appears to have been deposited under low energy conditions, similar to the modern Brunei coast the coarser Sandakan Formation shows high energy trough cross-bedding linked to the formation of barrier islands and low energy lagoons in the back barrier regions, which are however not associated with tidal deltas.

The eastern edge of the South China Sea has historically been relatively ignored compared to the divergent passive margins that dominate the rest of the basin. In their study Zhu et al. used seismic reflection data that crossed the Manila Trench in order to define the nature of this subduction plate boundary. Based on this data they divide the system into three segments, a North Luzon segment, a Seamount Chain segment and West Luzon segment, which are largely dominated by the nature of the accretionary prism. They argue that although subduction accretion dominates the northern part of the trench, reflecting rapid sediment supply from Taiwan, that the southern section close to Mindoro is in a state of long-term subduction erosion because of the sediment starved character of the trench. Through seismic analysis and analogue modeling, coupled with gravimetric modeling, Li et al. suggested that the seamount subduction in the northern part of the Manila Trench has resulted well-developed backthrusts in the accretionary wedge, followed by gravitational collapse and normal faulting. At the same time multiple successive seamount subduction events erode the normal faults and leave no permanent record of forearc collapse. Density distributions of South China Sea crust are laterally heterogeneous, and the subducted segments have a relatively lower density compared to the non-subducted parts.

Much of our understanding of the regional tectonics both ancient and modern is based on seismic data and thus our understanding of how seismic waves propagate through the lithosphere in this region is critical to our interpretation of these data sets. A study by Sun et al. investigated seismic noise related to the landing of large atmospheric storms on the coast of southern and eastern China. It is clear that these storms are identifiable in seismic records and that the character of this impact is different in the South and East China Seas, reflecting the thicker sediment deposits in the East China Sea. The shape of the coastline seems very important in controlling the polarity of the seismic noise depending on the location of the impact, although the seismic noise can be carried far inland. The transferred elastic energies are preferentially polarized in directions perpendicular to the general trend of the coastline. Further study of seismic waves in the South China Sea has been used to investigate the processes responsible for the opening of the South China Sea. Xue et al. used data from 23 seismic stations and conducted spectral analysis in order to define the direction of fastest seismic wave propagation. This approach showed that the mantle lithosphere and crust are closely coupled in northern Vietnam, which is in contrast to the situation in the south of that country and reflecting the influence of large strike slip faults in the region of the Red River. NE–SW fast directions under the South China Block indicates that surface deformation and mantle flow are linked in this region. Under Hainan Island there is no evidence for any deep-seated, hot mantle plume, while under northern Borneo velocities support the idea that this is a region of ancient subduction linked to the opening of the South China Sea as a response to the elimination of the paleo-South China Sea. The study concludes that no single geological process was likely responsible alone for the opening of the South China Sea.

Huo and Yang suggest that the single frequency microseism (SFM) and the double frequency microseism (DFM), show striking alternating variation patterns both seasonally and spatially. These variation patterns, along with the bathymetric feature near the seismic observation stations, indicate that SFM and DFM are generated through different physical mechanisms. Interestingly, seasonal and spatial variations of DFM appear to be consistent with the basin-scale surface circulation model of the South China Sea, in which the upper part of the water column experiences cyclonic conditions in winter and anti-cyclonic conditions in summer. These consistencies provide observational evidence for the hypothesis that it is cyclonic depressions result in favorable conditions for generating DFM.

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