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Starting a New Ocean and Stopping It

By Chun-Feng Li, Peter D. Clift, Zhen Sun, and Hans Christian Larsen

ABSTRACT. Small marginal sea basins are often short-lived and typically not older than several to tens of million years, but they play critical roles in global plate tectonic cycles. This paper highlights some recent achievements in answering a range of geodynamic questions stemming from scientific ocean drilling by International Ocean Discovery Program Expeditions 349, 367, 368, and 368X in the South China Sea. Together, results from these expeditions provide new insights into continental breakup in terms of the opening style and time of spreading cessation, magmatism, and sedimentation during the formation of this marginal basin. The outcomes of these expeditions have revealed new challenges and spawned new hypotheses in mantle dynamics and crustal accretion that need to be addressed by future drilling on carefully identified drill targets in the tectonically active western Pacific.

EXTENSION IN A LARGE-SCALE SUBDUCTION REGIME

Beginning in the Mesozoic, subduction of the Paleo-Pacific Plate and the India-Australia Plate in the western Pacific and Southeast Asia, respectively, has left us the largest subduction graveyard to be found worldwide (e.g., C. Li and van der Hilst, 2010). At subduction zones, slab retreat and roll back as well as trench suction are believed to be responsible for the development of many of the region's marginal basins (e.g., Hall et al., 2003; Schellart et al., 2003). However, the mechanism that initiated the opening of the South China Sea basin (SCS) has been much debated because the SCS does not appear to be a typical back-arc basin, but rather may have been formed either by the tectonic extrusion of Indochina triggered by the India-Eurasia collision (e.g., Tapponnier et al., 1982; Briais et al., 1993; Flower et al., 2001) or by the active southeastward slab-pull force in a nearby subduction zone of the proto-SCS. This older basin existed to the south of the present-day SCS. In the latter case, the driving forces for the opening of the SCS may have been similar to those active during the opening of the Tethys Sea, where the closure of an older basin was accompanied by the opening a new one nearby (e.g., Metcalfe, 2013). Recent International Ocean Discovery Program (IODP) Expeditions 349, 367, 368, and 368X did not directly address the mechanisms that triggered SCS development. Instead, these expeditions provided critical constraints on the crustal ages and structures within the continent-to-ocean transition zone, which can help answer fundamental questions concerning the driving forces behind marginal basin opening (C.F. Li et al., 2015; Sun et al., 2018).

SHORT-LIVED MARGINAL BASINS

Unlike in the large open ocean basins, seafloor spreading in the small western Pacific marginal basins occurs over relatively short time periods, mostly over a few tens of millions of years. These short time periods reflect frequent changes in tectonic regimes in a region that is characterized by multiple subduction zones and the complex interplay of numerous plates of various sizes. Subduction is a major factor in marginal basin development because while initiation of a subduction zone can cause back-arc extension, it also alters the regional tectonic stress field, which can terminate seafloor spreading. This scenario might apply to the SCS, where the termination of spreading likely coincided with the initiation of subduction along the Manila Trench to the east (e.g., Hayes and Lewis, 1985). Subduction at the Manila Trench is rather unique, where a very young SCS oceanic lithosphere is being subducted under the relatively old Philippine Sea Plate. Here, it is hypothesized (e.g., J. Li et al., 2004) that the westward movement of the older Philippine Sea Plate, rather than the slab pull force of the younger SCS slab, drove its active obduction over the younger SCS plate. Alternatively, cessation of seafloor spreading in the SCS may be linked to the final southeastward subduction of the proto-SCS under Borneo and the collision of the southern continental margin (Dangerous Grounds) terrane with the trench at that time (e.g., Holloway, 1982; Hutchison, 2004). These complex plate boundary configurations and processes remain poorly understood. The SCS offers an ideal laboratory for testing hypotheses for marginal basin initiation and improving understanding of marginal basin evolution worldwide through the application of scientific ocean drilling.

TESTING MODELS OF CONTINENTAL BREAKUP, OPENING STYLES, AND MARGIN CONJUGATION

Despite its small size, the SCS offers a remarkable diversity of continental margin structures, from wide extended continental margins to the west to very narrow ones to the east. This lateral variability in margin structures coincides with sharp changes in the physical and chemical characteristics of the oceanic lithosphere in the central basin (C.F. Li et al., 2008, 2015). IODP Expeditions 367, 368, and 368X were designed to test how the continent-ocean transition in the SCS differs from classical Atlantic-type volcanic rifted margin models (Larsen et al., 2018; Sun et al., 2018). The small size of the SCS also facilitates comparison of extension structures of the two conjugate margins.

MANTLE DYNAMICS, CRUSTAL ACCRETION, AND MAGMATISM

IODP Expedition 349 recovered mid-ocean ridge basalts and volcaniclastic sediments that are critical to understanding the previously poorly known SCS mantle geochemistry and dynamics (C.F. Li et al., 2015). Carbonated silicate melt, which had only been predicted by experimental studies, was first reported in the SCS (Zhang et al., 2017). Experiments conducted on volcanic rocks recovered during IODP Expedition 349 indicate that a CO_2-rich silicate melt evolved continuously to an alkali basalt that erupted during the later stages of seamount magmatism and was emplaced near the extinct spreading axis in the Late Miocene (Zhang et al., 2017). Distinct trace element and isotope ratios in the volcanic rocks also indicate differences in mantle sources between the southwest and the east sub-basins in the SCS, which are also characterized by a sharp contrast in magnetic anomalies (C.F. Li et al., 2008; Zhang et al., 2017).

Finally, fulfilling the early proposed goals of IODP Expeditions 349, 367, and 368, IODP Expedition 368X in 2018 successfully drilled through the thick sedimentary cover in the SCS and cored over 100 m of basaltic basement near the northern continent-ocean boundary. Samples collected there provide an important reference point between the initial breakup basaltic magmas collected by Expeditions 367 and 368 near the northern margin and basement sections previously cored by Expedition 349 in younger parts of the central basin, near the extinct seafloor spreading centers. Altered and fresh basalts recovered at different locations during these four expeditions provide unparalleled evidence concerning how this marginal sea basin evolved from a continental rift to a mature ocean.

Geochemical analysis and $^{40}Ar/^{39}Ar$ dating of oceanic plagiogranite hint that seafloor spreading in the SCS may have initiated prior to 32 million years ago, as early as 38 million years ago (Zhong et al., 2018). This older age could be possible because the opening of the SCS propagated westward, with the onset of seafloor spreading first occurring in the northeast, meaning that magnetic anomalies within this piece of the extended continental crust must reflect later-stage and thus younger post-spreading volcanism (e.g., Song et al., 2017). Future $^{40}Ar/^{39}Ar$ dating of the Expedition 368 and 368X basement basalts will shed further light on the early stages of SCS continental rifting and evolution during initial breakup.

The role of magmatism in the opening of the SCS remains unclear. Some have attributed the opening of the SCS and extensive post-spreading magmatism to the nearby Hainan hotspot (e.g., Fan and Menzies, 1992; Xu et al., 2012), although deepwater syn-rift sediments and lack of seaward-dipping basaltic sequences indicate that this is not a typical volcanic rifted margin (e.g., Clift et al., 2001; Larsen et al., 2018). Middle Miocene mid-ocean ridge basalts recovered by IODP Expedition 349 record progressive mantle enrichment and possibly signal the (later) contribution of the Hainan mantle plume, which also may have contributed to the latest Oligocene/earliest Miocene ridge jump and propagation in the SCS (Yu et al., 2018). The lack of significant depth anomalies across the SCS, however, implies the absence of a major mantle thermal anomaly (Wheeler and White, 2000). The ridge jump event may be coeval with the onset of the opening of the adjacent southwest sub-basin at around 23.6 million years ago (C.F. Li et al., 2015), as well as with a major far-field event that caused a change in the direction of slip along the Red River Fault ~21 million years ago (e.g., Xie et al., 2006; Zhu et al., 2009).

Post-spreading seamount magmatism, demonstrated in many other basins worldwide, could alternatively be triggered by regional extension and decompression melting related to the cooling and shrinking of the oceanic lithosphere (Song et al., 2017). Although the degree of post-spreading extension measured within the SCS ocean floor is overall too restricted to allow the generation of melt above ambient mantle asthenosphere (McKenzie and Bickle, 1988), extension is expected to be more localized along weak zones, such as the extinct spreading center and extended margins, where the local degree of extension and magmatism may be higher (Song et al., 2017). Late-stage post-spreading magmatism tended to be preferentially emplaced along the extinct spreading center, and in narrow zones subparallel to the continent-ocean boundary along the northern margin, often recognized as linear bathymetric highs (Figure 1).

HIGH SEDIMENTATION RATE IN MARGINAL SEAS

It is not surprising that marginal basins such as the SCS have high sedimentation rates compared to the pelagic open ocean, due to the erosional flux from the adjacent continent. High sedimentation rates along the SCS margin and within the deep basin potentially provide high-resolution records that reflect regional tectonic-climate interactions, as well as provenance changes that are linked to variations in the onshore drainage pattern. IODP Expedition 349 recovered abundant carbonate sediments at a scale not expected in the central basin (C.F. Li et al., 2015). This discovery suggests that marginal basins may play a critical role in global carbon recycling by accumulating rapidly deposited carbonates, which are then transported into the mantle at subduction zones that are responsible for the basins' eventual closures (e.g., along the Manila Trench). Further quantification by scientific drilling in similar basins will be needed to assess the budget for Cenozoic sedimentary carbonate subduction (e.g., Clift, 2017).

Cores recovered during IODP

Expeditions 349, 367, and 368 (C.F. Li et al., 2015; Sun et al., 2018) in the central SCS also include reddish clay-rich layers directly above the basaltic basement in early post-spreading sequences. Similar layers were also found in the nearby Sulu Sea. Are the SCS clays identical to Pacific-type red layers deposited under slow depositional rates and high oxidation conditions? Or did they result from chemical exchange between sediments and cooling basalts, or are they somehow related to unstable water conditions during or soon after the formation of the basin? Isotope work at Site U1433 drilled during IODP Expedition 349 indicates that the clays were not purely volcanic-derived but were also mixed with sediment from Indochina (C. Liu et al., 2017). From current IODP coring, we know they were deposited slowly (C.F. Li et al., 2015). Systematic physical, chemical, and biological characterization of the red layers will shed light on an early critical period of evolution of a young oceanic basin.

FUTURE DRILLING IN THE SCS AND OTHER SIMILAR SETTINGS

Diverse tectonic structures and their complex interplay make the Western Pacific the best active tectonic region for testing a wide range of geodynamic hypotheses. Future scientific ocean drilling could contribute critical information by addressing studies of the following subjects in the SCS and other areas:

1. To further constrain the continental breakup process, the southern conjugate margin of the SCS should remain a target for drilling so that we can compare its symmetry with that of the northern SCS margin (Sun et al., 2016). Seismic data suggest the presence of hyper-extended continental crust (Franke et al., 2011; W.N. Liu et al., 2014) and thick syn-rift sediment near the continent-ocean boundary on the southern margin (Song and Li, 2015).
2. Widespread post-spreading magmatism in the SCS needs to be further sampled in order to understand when and how magmatism and the mantle sources evolved over the entire history of this marginal basin. In addition, the spatial variability in SCS mantle sources observed during formation of two sub-basins offers the possibility to better understand regional-scale mantle heterogeneity in a marginal basin setting.

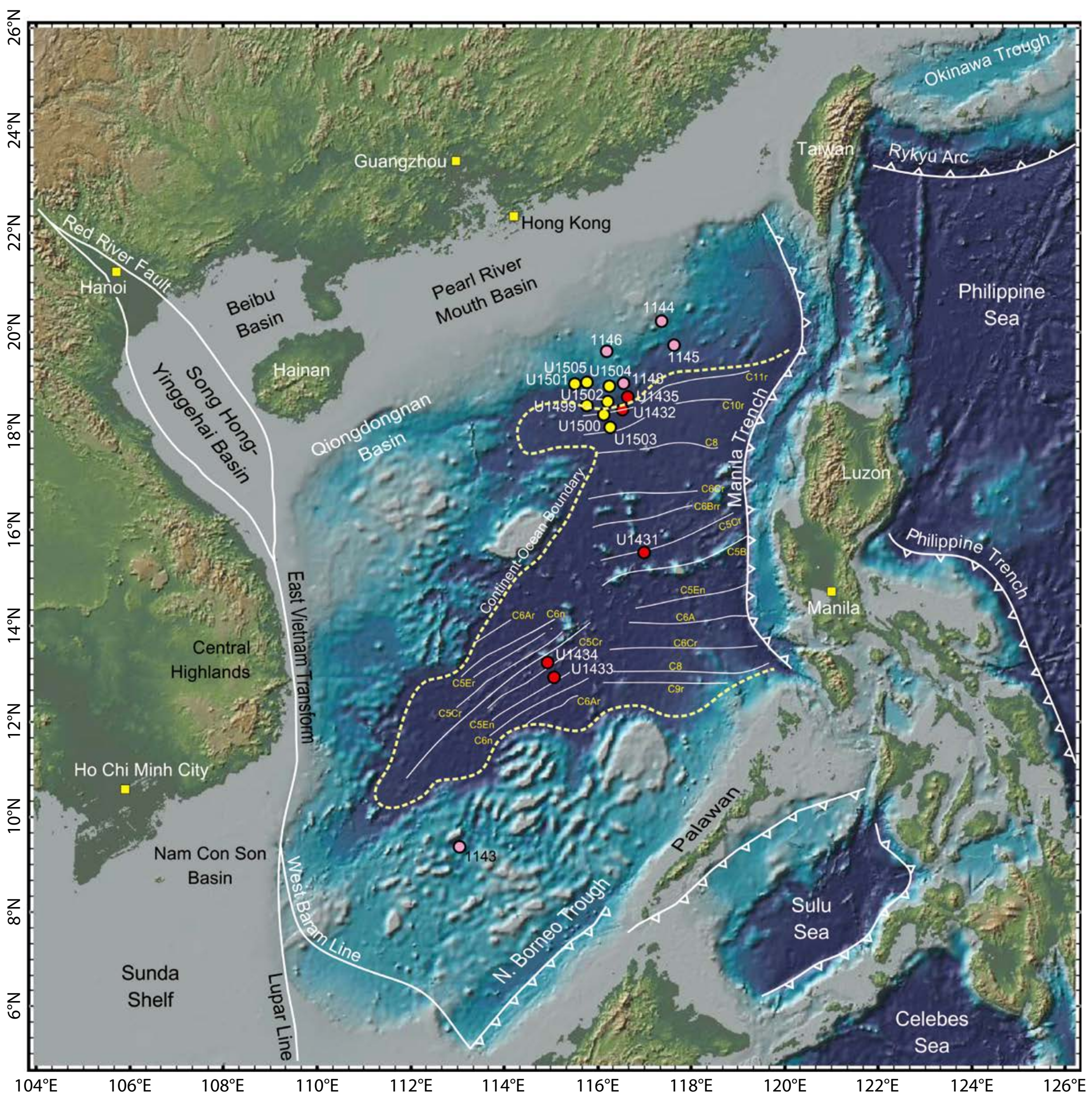

FIGURE 1. Regional geodynamic framework of the South China Sea. Circles mark the drill sites of Ocean Drilling Program Leg 184 (pink), International Ocean Discovery Program (IODP) Expedition 349 (red), and IODP Expeditions 367, 368, and 368X (yellow). The yellow dotted line around the basin marks the continent-ocean boundary. Magnetic isochrons are based on C.F. Li et al. (2014).

3. Similar studies can be carried out in other marginal basins, such as the Caroline Basin, where the nature of various tectonic and volcanic structures, such as intraplate upwellings, juvenile subduction zones, and ridges, along with their links to the nearby Ontong Java large igneous province, are poorly understood.
4. As a partly isolated small ocean basin receiving sediments from the major river systems of Southeast Asia, the SCS has great potential for source-to-sink studies addressing both tectonic and paleo-environmental processes within the last 30 million years.
5. The SCS and adjacent areas are ideal places to study subduction initiation and the development of the early stages of seafloor spreading. Documenting seismogenic behaviors in multiple subduction zones will help us to understand the very wide spectrum of interplate earthquakes.

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