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Major unconformities/termination of extension events and associated surfaces in the South China Seas: Review and implications for tectonic development

C.K. Morley

Petroleum Geophysics Program, Department of Geological Sciences, Chiang Mai University, 50200, Thailand

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ABSTRACT

The distribution of unconformities and end of Cenozoic rifting events in the South China Seas (SCS) reflects both the modes of rift development, and the effects of driving mechanisms. Continental rifting began in the eastern basins during the Paleocene, and propagated westwards to the Vietnam basin margin in the Late Eocene. Continental breakup around 32–28 Ma caused a regional reduction or cessation in extensional activity, particularly affecting basins furthest from the spreading centre. Basins in the slope and deepwater area north of the spreading centre exhibit reduced fault activity until 21–20 Ma. Propagation of oceanic crust westwards between ~25 and 23 Ma, and termination of seafloor spreading sometime between 20.5 and 16 Ma affected fault activity in the Qiongdongnan, and Nam Con Song basins. In the Phu Khanh Basin and South, in the Dangerous Grounds area, extension continued until about 16 Ma, ending at the Red Unconformity. The end of seafloor spreading around 20.5 Ma reflects loss of extensional driving force as thinned continental crust entered the NW Borneo subduction zone. Controversially, a key component of the driving force maybe attributed to slab-pull. A transitional period of about 5–7 my between the onset of subduction of continental crust, and final jamming of the subduction zone (Deep Regional Unconformity, DRU) is inferred. The last pulse of extension was focussed in the western SCS, and terminated around 10.5 Ma. Detailed understanding of proto South China Seas development remains uncertain and controversial.

1. Introduction

The continental crust of the South China Seas area has been extensively explored for hydrocarbons and consequently considerable seismic and well data exist for the region (e.g. Chen et al., 1994; Jiang et al., 1994; Ru et al., 1994; Luedmann and Wong, 1999; Nielsen et al., 1999; Petronas, 1999; Clift et al., 2008; Fyhn et al., 2009a,b; Wang et al., 2014). In addition academic 2D seismic surveys and drilling have also been conducted (e.g. Taylor and Hayes, 1983; Hinz and Schlüter, 1985; Yan and Liu, 2004; Li et al., 2007; Franke et al., 2011, 2014; Wang, 2012; Expedition 349 Scientists, 2014; Li et al., 2015). Hence a very large published and unpublished data base covers the offshore area. This paper discusses the distribution of regionally significant Cenozoic unconformities and end of rifting events in continental crust that have affected the South China Seas compiled from published and unpublished data. The locations of key published seismic lines utilized in this paper to construct maps of the extent of key unconformities are shown in Fig. 1. The timing and geographic distribution of the unconformities and their equivalent conformable surfaces provides insights into the regional tectonic processes affecting the South China Seas.

There are a number of issues concerning the unconformities and end of rifting events including: (1) reliability of dating, (2) how the unconformities are correlated regionally on different data sets, (3) understanding the tectonic and/or eustatic significance of the unconformities, and (4) terminology. This is not the first paper to address these issues and several recent papers discuss the timing, and nature of individual unconformities in detail, particularly for the Vietnam and southern margins (e.g. Cullen, 2010; Hutchison and Vijayan, 2010; Madon et al., 2013; Franke et al., 2014; Steuer et al., 2014; Savva et al., 2014; Wang et al., 2014; Bache et al., 2015; Morley and Sweicicki, 2015). Since there is considerable variability in the interpretation of the timing and distribution of rifting events and unconformities in the literature, this paper reviews the published dating, and where necessary discusses decisions on which of the alternative dates to use. The distribution of unconformities and end of rift events as implied from the published data are mapped out regionally. This exercise enables

E-mail address: chrissmorley@gmail.com

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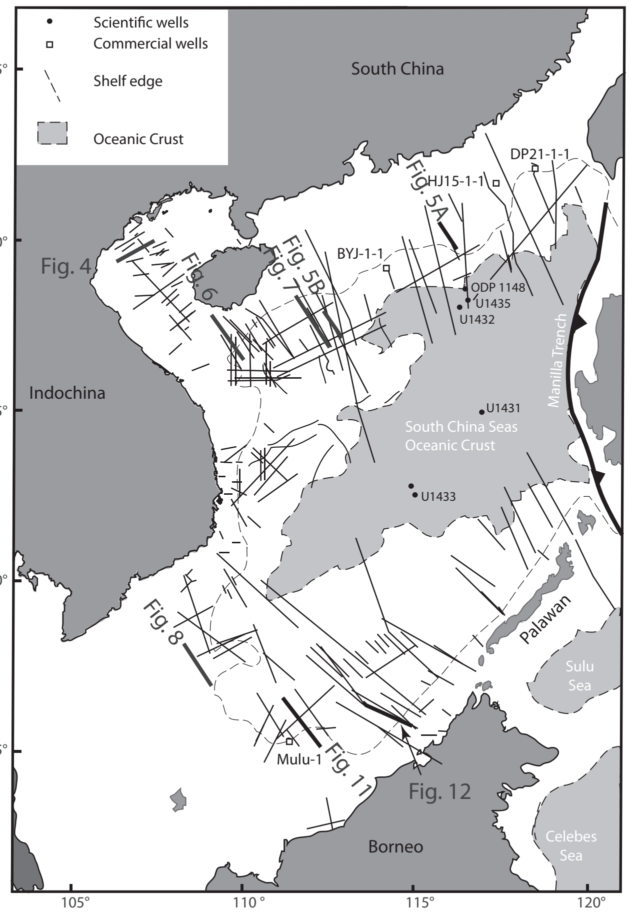

Fig. 1. Regional map showing the locations of published seismic lines used in this study. The data are from: Andersen et al. (2005), Clift and Sun (2006), Clift et al. (2008), Cullen (2010), Ding et al. (2013), Franke et al. (2011, 2014), Fyhn et al. (2009b), Hutchison and Vijayan (2010), C.-F. Li et al. (2014), L. Li et al. (2014), Madon et al. (2013), Mat-Zin and Tucker (1999), McIntosh et al. (2014), Rangin et al. (1995), Savva et al. (2013, 2014), Song et al. (2014), Steuer et al. (2013, 2014), Wang et al. (2013), Wu et al. (2014a), Yan and Liu (2004), Zhu and Lei (2013) and Zhu et al. (2009).

a better understanding of the key tectonic events that have affected the region, which are discussed at the end of this review. It is argued that understanding the changing distribution of extensional basins, unconformities and end of rifting events with time within continental crust provides key insights into the driving forces affecting the SCS.

2. Geological background

From the late Cretaceous to Present Day the South China Sea (SCS) has been the focus of numerous tectonic events, commencing with Mesozoic subduction of the paleo-Pacific plate under Eurasia, which occurred somewhere around the southern margin of the present South China Sea (e.g. Jahn et al., 1976; Hilde et al., 1977; Hamilton, 1979; Holloway, 1982; Taylor and Hayes, 1983; Zhou and Li, 2000; Xiao and Zheng, 2004; Zhou et al., 2008; Li et al., 2008; Hall, 2102; Morley, 2012). Subduction ceased in the Late Cretaceous, but the exact details behind the timing and cause of this cessation, and the subsequent transition to regional extension remain unclear (see reviews in Hall, 2012; Morley, 2012; Zahirovic et al., 2014). The main focus of this paper is on the Cenozoic extension that followed. Fig. 2 shows the distribution of Cenozoic structures and rift basins in the South China Seas area.

Early work by Taylor and Hayes (1983) and Briais et al. (1993) indicated seafloor spreading in the SCS lasted from 32 to 16 Ma, which requires considerable slowing of spreading rates associated with the younger magnetic anomalies. The magnetic data used by Briais et al. (1993) were mostly based on magnetic profiles acquired by R/V *J. Charcot* during the French NANHAI and MASIN cruises, and by vessels from Chinese institutions (Chen, 1987). Challenges to interpretation of the magnetic data include difficulties in identification of anomalies due to asymmetric spreading rates and ridge jumps (Briais et al., 1993). The authors identified anomalies using comparisons with synthetic profiles, and fitting of isochrons. Geological information, heat flow, and free air gravity anomalies were used to guide the interpretation and constrain models involving different ages of oceanic crust. More recently utilizing magnetic data from 1982 and 1987 R/V *Sonne* cruises, and improved processing techniques and the Cande and Kent (1995) revised calibration of the geomagnetic polarity timescale Barckhausen and Roeser (2004) and Barckhausen et al. (2014) proposed faster spreading later in the life of the spreading centres, with the formation of oceanic crust ending at 20.5 Ma. To test the competing models, Expedition of the International Ocean Discovery Program (IODP) 349 in 2014 drilled into oceanic basement and recovered basalt at three sites (U1431, U1433, U1434; Expedition 349 Scientists, 2014; Li et al., 2015). Results of radiometric dating of oceanic crust basalts are still pending, and it is disputed as to whether the basalts in the key U143 well represent true oceanic basement or are post-spreading basalts (Barckhausen et al., 2015). In the latter case dating only provides a minimum possible age for spreading, not a precise age. The dating of sediments overlying oceanic crust (Site U1431) contains microfossils dated ~16.7–17.5 Ma (Expedition 349 Scientists, 2014). Consistently in the Central Pacific there is a time lag of ~1–3 Ma between the age of oceanic crust and the first sediments, hence these sediment ages are not conclusive proof that the 20 Ma end of spreading is incorrect (Barckhausen et al., 2015; also see Clift et al., 2001). The results of Barckhausen et al. (2014) are not universally accepted (e.g. Chang et al., 2015). However, the oldest sediments overlying igneous crust in well U1433 have an age range of 18–21 Ma, which Barckhausen et al. (2015) state fits with the interpretation of magnetic anomaly 6AA (21.8 Ma) in that location (Barckhausen et al., 2014), and is too old for other models (i.e. Taylor and Hayes, 1983; Briais et al., 1993). New modelling of magnetic data post-IODP drilling closely follows the timing around 15–16 Ma of Taylor and Hayes (1980, 1983) and Briais et al. (1993), but this requires spreading to begin at a relatively high rate for the first 3 my, drop to an average of 25 km/my from 29 to 26 Ma, then increase to about 70 km/my, and then decrease from 50 to ~30 km/my at the end of seafloor spreading (C.-F. Li et al., 2014; L. Li et al., 2014).

The origin of South China Sea seafloor spreading has traditionally been explained by main two competing models: (1) India–Eurasia collision and tectonic extrusion was responsible for >500 km of sinistral motion on the Ailao Shan-Red River Fault Zone that is accommodated by extension in the South China Seas (Tapponnier et al., 1986; Leloup et al., 2001; Replumaz and Tapponnier, 2003), and (2) Slab-pull arising from subduction of the Proto-South China Seas crust beneath NW Borneo drove extension, until the continental crust on the southern margin of the South China Seas spreading centre entered the subduction zone and jammed it (e.g. Taylor and Hayes, 1983; Holloway, 1982; Hall, 2002; Morley, 2002). These models are discussed in Section 6.4.

Recently there has been a considerable improvement in our detailed understanding of the tectonic style, stratigraphy and timing of deformation around the South China Sea as reflected in papers contained in the special issues edited by Hall et al. (2013) and Pubellier et al. (2015), as well as the regional review book by Wang et al. (2014), and Expedition 349 of the International Ocean Discovery Program (Expedition 349 Scientists, 2014; Li et al.,