Marine and Petroleum Geology 58 (2014) 612–626

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Crustal structure and inferred rifting processes in the northeast South China Sea

Kirk McIntosh[a,*], Luc Lavier[a], Harm van Avendonk[a], Ryan Lester[a,1], Daniel Eakin[a], Char-Shine Liu[b]

[a] Institute for Geophysics, University of Texas at Austin (R2200), 10100 Burnet Rd., Austin, TX 78758-4445, USA
[b] Institute of Oceanography, National Taiwan University, P.O. Box 23-13, Taipei 106, Taiwan

ARTICLE INFO

Article history:
Received 20 July 2013
Received in revised form
6 March 2014
Accepted 14 March 2014
Available online 29 March 2014

Keywords:
Rifted margin
Extension
Normal fault
Crustal structure
South China Sea
Seismic

ABSTRACT

TAIGER project deep-penetration seismic reflection profiles acquired in the northeastern South China Sea (SCS) provide a detailed view of the crustal structure of a very wide rifted continental margin. These profiles document a failed rift zone proximal to the shelf, a zone of thicker crust 150 km from the shelf, and gradually thinning crust toward the COB, spanning a total distance of 250–300 km. Such an expanse of extended continental crust is not unique but it is uncommon for continental margins. We use the high-quality images from this data set to identify the styles of upper and lower crustal structure and how they have thinned in response to extension and, in turn, what rheological variations are predicted that allow for protracted crustal extension. Upper crustal thinning is greatest at the failed rift ($\beta_{uc} \approx 7.5$) but is limited farther seaward ($\beta_{uc} \approx 1$–2). We interpret that the lower crust has discordantly thinned from an original 15–17 km to possibly less than 2–3 km thick beneath the central thick crust zone and more distal areas. This extreme lower crustal thinning indicates that it acted as a weak layer allowing decoupling between the upper crust and the mantle lithosphere. The observed upper crustal thickness variations and implied rheology (lower crustal flow) are consistent with large-scale boudinage of continental crust during protracted extension.

1. Introduction

Extensional margins worldwide show features of narrow or wide rifts (Buck, 1991). Wide rifts are classically exemplified by intra-continental rifts such the Basin and Range province (e.g., Coney, 1980). There are, however, a few examples of wide rifts at continental margins. The best example so far is that of the Santos basin in the Sao Paulo plateau of the Brazilian margin that is over 600 km wide (Zalán et al., 2011; Stica et al., 2014). It is believed that rifts can extend very wide areas of continental crust if the margin is relatively hot (e.g., Coney, 1980; Buck, 1991) and the lower crust can flow in a ductile manner and compensate regionally for the thinning of the upper crust by normal faulting. The structures resulting from this brittle-ductile interaction may show characteristics of crustal-scale boudinage (e.g., Smith, 1977) exemplified by variable thickness upper crustal blocks above a ductile lower crust. In this paper we present data from seismic lines across the northeastern part of the South China Sea (SCS), which is considered by most researchers to fall in the realm of magma-poor rifted margins (e.g., Franke, 2012; Yan et al., 2006). A distinguishing feature of this margin is that it is recognized to have a very broad zone, 100–300 km, of extended continental crust between the continental shelf and oceanic crust of the basin (Nissen et al., 1995a; Wang et al., 2006; Hu et al., 2009; Yan et al., 2001). Such a broad region of extended continental crust has been found elsewhere, such as in the central South Atlantic margins (e.g. Moulin et al., 2005; Karner and Gambôa, 2007), but it is not a common occurrence. As explained above, very wide zones of extended continental crust are thought to occur through depth dependent stretching, which allows for long range compensation of extension and rupture of the crust by middle and lower crustal flow over a likely weak mantle lithosphere (Buck, 1991; Karner and Gambôa, 2007; Huismans and Beaumont, 2011). Here we document upper and lower crustal thickness variations in the SCS that show detailed characteristics of the interaction of brittle and ductile deformation in the crust, with some crustal blocks highly thinned and others retaining nearly their original thickness.

* Corresponding author. Tel.: +1 512 471 0480.
E-mail address: kirk@ig.utexas.edu (K. McIntosh).
[1] Presently at Chevron.

http://dx.doi.org/10.1016/j.marpetgeo.2014.03.012
0264-8172/

We explore the rifted margin structure in the northeastern part of the SCS (Fig. 1) using crustal-scale seismic reflection data. These data show that the margin consists of a wide zone of extended to hyper-extended (i.e., less than 10 km thick) continental crust—approaching 300 km in width, yet classic deformational structures of rifted margins, e.g., rotated basement blocks with pre- and syn-rift strata and an overlying unconformity, are preserved in many places. The crustal-scale seismic reflection images allow us to measure approximate upper and lower crustal thickness variation in places, which suggest preferential thinning and/or flow of the lower crust. These detailed observations indicate that the South China Sea can be considered a wide rift (Buck, 1991) that reached extreme continental extension and eventual breakup.

In the following sections we review the geologic and tectonic background of the northeastern South China Sea, and then discuss existing and new data that we use in this study. We present a selection of crustal scale seismic reflection profiles, some of which have been converted to depth, and a gravity model to convey the crustal structure of the margin. This is followed by a detailed discussion of the crustal thickness variations and a discussion about the nature of a basal lower crustal unit. Finally, we discuss the implications of the observed rift structure, i.e., what conditions and processes led to the creation of this distinctively wide continental margin.

2. Geologic and tectonic background

The South China Sea is a marginal sea offshore east and Southeast Asia and separated from the Pacific Ocean by Taiwan, the North Luzon volcanic arc, and the Philippine archipelago to the east. Oceanic crust of the South China Sea has been dated by interpretation of marine magnetic anomalies to be Paleogene to Middle Miocene in age with some unresolved variations. The most widely cited ages are suggest break-up at 30–32 Ma with seafloor spreading continuing to ~15 Ma (Taylor and Hayes, 1983; Briais et al., 1993). An alternative interpretation is provided by Barckhausen and Roeser (2004) and Barckhausen et al. (2014) which includes the oldest oceanic crust formed at 32 Ma and cessation of spreading at 20.5 Ma. Additional magnetic anomaly interpretations have been made in the northeasternmost South China Sea. Hsu et al. (2004) interpreted an earlier phase of spreading in this area, beginning at ~37 Ma and Yeh et al. (2010) reiterated and extended this model. Sibuet et al. (2002) had previously interpreted a fossil transform fault just west of the northern Manila trench with a remnant of the older, proto South China Sea oceanic crust northeast of this boundary and currently subducting. On the other hand, McIntosh et al. (2013) and Lester et al. (2013) presented seismic reflection and refraction evidence indicating the presence of highly-extended, magmatically-modified continental crust in this area rather than 37 Ma oceanic crust.

Prior to the opening of the South China Sea, East Asia experienced a long history of paleo-Pacific plate subduction followed by a period of rifting. The subduction history is well documented with the broad suite of granitoids present in south and east China with ages ranging from Paleozoic through the Mesozoic (Jahn et al., 1976, 1990; Hamilton, 1979; Gilder et al., 1996; Wu et al., 2011). Several authors have interpreted left-lateral shearing in south China associated with Mesozoic oblique subduction (e.g., Gilder et al., 1996; Li, 2000). More recently, Li and Li (2007) proposed that an episode of flat-slab subduction, followed by slab foundering and/or slab roll-back could explain the migration of Paleozoic to Mesozoic magmatism through time, compressional then extensional deformation

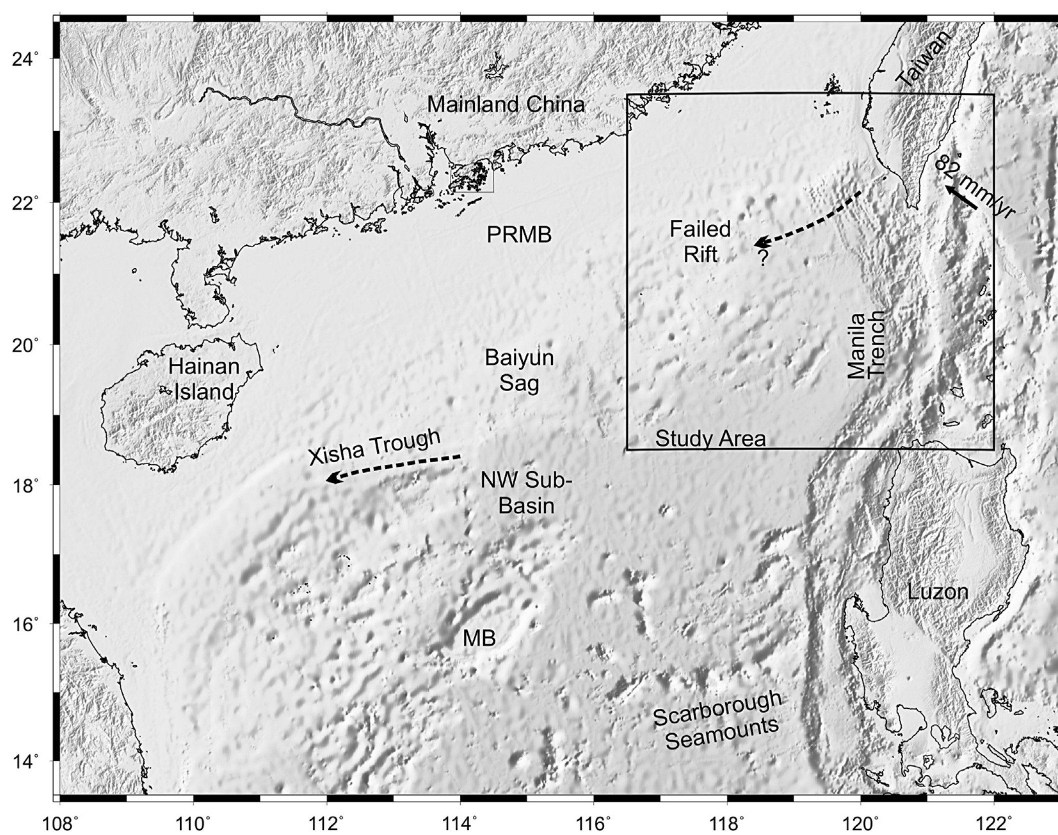

Figure 1. Regional map showing the northern South China Sea. The study area is marked by the box in the northeastern zone, from southern Taiwan to Luzon, and west to the coast of China. PRMB = Pearl River Mouth Basin; MB = Macclesfield Bank.