Marine and Petroleum Geology 58 (2014) 579–598

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Different expressions of rifting on the South China Sea margins

D. Savva [a,*], M. Pubellier [a,b], D. Franke [c], N. Chamot-Rooke [a], F. Meresse [d], S. Steuer [c], J.L. Auxietre [d]

[a] *Ecole Normale Supérieure de Paris, UMR 8538, 24 rue Lhomond, 75005, Paris, France*
[b] *UniversitiTechnologiPetronas, SDN, BHD, Bandar Seri Iskandar, 31750, Tronoh, Perak DarulRidzuan, Malaysia*
[c] *Federal Institute for Geosciences and Natural Ressources (BGR), Stilleweg 2, D-30655, Hannover, Germany*
[d] *TOTAL, Tour Coupole, 2, Place de la Coupole, F-92078, Paris La Défense CEDEX, France*

ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form
16 May 2014
Accepted 31 May 2014
Available online 14 August 2014

Keywords:
South China Sea
Polyphased rifting
Structural inheritance
Rifting zonation
Crustal thinning
Mantle exhumation
Shallow sedimentary environment

ABSTRACT

Rifting of continental margins is generally diachronous along the zones where continents break due to various factors including the boundary conditions which trigger the extensional forces, but also the internal physical boundaries which are inherent to the composition and thus the geological history of the continental margin. Being opened quite recently in the Tertiary in a scissor-shape manner, the South China Sea (SCS) offers an image of the rifting structures which varies along strike the basin margins. The SCS has a long history of extension, which dates back from the Late Cretaceous, and allows us to observe an early stretching on the northern margin onshore and offshore South China, with large low angle faults which detach the Mesozoic sediments either over Triassic to Early Cretaceous granites, or along the short limbs of broad folds affecting Palaeozoic to Early Cretaceous series. These early faults create narrow troughs filled with coarse polygenic conglomerate grading upward to coarse sandstone. Because these low-angle faults reactivate older trends, they vary in geometry according to the direction of the folds or the granite boundaries. A later set of faults, characterized by generally E–W low and high angle normal faults was dominant during the Eocene. Associated half-graben basement deepened as the basins were filling with continental or very shallow marine sediments. This subsequent direction is well expressed both in the north and the SW of the South China Sea and often reactivated earlier detachments. At places, the intersection of these two fault sets resulting in extreme stretching with crustal boudinage and mantle exhumation such as in the Phu Khanh Basin East of the Vietnam fault. A third direction of faults, which rarely reactivates the detachments is NE–SW and well developed near the oceanic crust in the southern and southwestern part of the basin. This direction which intersects the previous ones was active although sea floor spreading was largely developed in the northern part, and ended by the Late Miocene after the onset of the regional Mid Miocene unconformity known as MMU and dated around 15.5 Ma. Latest Miocene is marked by a regional basement drop and localized normal faults on the shelf closer to the coast. The SE margin of the South China Sea does not show the extensional features as well as the Northern margin. Detachments are common in the Dangerous Grounds and Reed Bank area and may occasionally lead to mantle exhumation. The sedimentary environment on the extended crust remained shallow all along the rifting and a large part of the spreading until the Late Miocene, when it suddenly deepened. This period also corresponds to the cessation of the shortening of the NW Borneo wedge in Palawan, Sabah, and Sarawak. We correlate the variation of margin structure and composition of the margin; mainly the occurrence of granitic batholiths and Mesozoic broad folds, with the location of the detachments and major normal faults which condition the style of rifting, the crustal boudinage and therefore the crustal thickness.

1. Introduction

Rifting processes have been studied extensively for decades along wide-ocean margins such as in the Atlantics (Boillot et al., 1980; Osmundsen and Ebbing, 2008; Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Péron-Pinvidic and Manatschal, 2009; Unternehr

* Corresponding author. Tel.: +33 1 44 32 22 58.
E-mail address: dimitri.savva@gmail.com (D. Savva).

http://dx.doi.org/10.1016/j.marpetgeo.2014.05.023
0264-8172/

et al., 2010; Reston and McDermott, 2011; Ranero and Perez-Gussinye, 2010). The extension was applied on varying lithologies, which are inherent to the composition and the geological record of the continents. Since these margins are relatively old, it is difficult to pinpoint the real break-up relative to the actual cessation of the extension. Various models supported by marine geophysical observations have been proposed to explain the processes of crustal extension (Boillot et al., 1980; Wernicke, 1985; Péron-Pinvidic and Manatschal, 2009; Unternehr et al., 2010), particularly in non-volcanic or moderately volcanic margins. These models have been invoked for the occurrence of mafic to ultramafic suites and detachment structures in continental margins, later involved in the development of orogens such as the Alps (Manatschal, 2004; Péron-Pinvidic et al., 2007). Recent numerical models of rifting (e.g. Lavier and Manatschal, 2006; Huismans and Beaumont, 2011) attempt to simulate the detachment structures observed in rifts (e.g., Osmundsen and Ebbing, 2008; Péron-Pinvidic and Manatschal, 2009; Unternehr et al., 2010; Reston and McDermott, 2011; Franke et al., this volume; Péron-Pinvidic et al., 2013) by accommodating extension along brittle faults rooted in ductile or semi-brittle detachments. These models favour a strong mechanical decoupling between the brittle upper crust and the ductile lower crust and mantle. Extension is accommodated first by concave upward (listric) detachment faults and after crustal/mantle mechanical coupling occurs, by concave downward detachments. Both concave upward and downward detachments underlay sets of normal faults. Illustrations of such structures have been shown for the Bay of Biscay (Charpal et al., 1978; Blaich et al., 2010, 2011) and along the Iberia magma-poor margin, where the "S-Reflector" (Krawczyk and Reston, 1995; Reston et al., 1996) has been interpreted as the boundary between highly attenuated continental crust and the underlying partially serpentinized mantle. However, good illustrations of such phenomena in nature are sparse, certainly partly due to the poor resolution of seismic data at depth. The common point between the models is the importance of the rheologies (e.g. the weak vs. strong lower crust, Huismans and Beaumont 2011) and the mechanical discontinuities. For the geologists, the discontinuities are often lithological contrasts where faults are preferentially located (Brun and Beslier, 1996; Nagel and Buck, 2004, 2007).

Because the SCS is devoid of salt and Seaward Dipping Reflector (SDR), and because of its young age it is good material for studying the transition between highly stretched continental crust and oceanic crust, and also to observe the behaviour of the rifting faults. The SCS is a basin, which has caught the attention of geoscientist for decades due to its "V" shape (characteristic of a propagation opening; Courtillot, 1982; Taylor et al., 1999) its location, and its potential for oil and gas (Fig. 1). Studies had however been focused primarily on the sea-floor dating and modelling (Taylor and Hayes, 1980, 1983; Briais et al., 1993; Barckhausen and Roeser, 2004) or on the impact of the Red River Fault (RRF) on the opening models (Tapponnier et al., 1982, 1986; Briais et al., 1993; Leloup et al., 1995, 2001; Rangin et al., 1995; Replumaz and Tapponnier, 2003).

We review hereafter the main structural characteristics of the extensional tectonics of the northern margin of the SCS from the Pearl River Mouth Basin (PRMB) in China, through the Nam Con Son Basin (NCSB) in southern Vietnam, to the Dangerous Ground in the southern margin (Fig. 2). Although we studied several basins on land, we illustrate characteristic structures only in the Sanshui basin (Guangdong Province) and we made use offshore of a large industry and academic seismic database.

2. Geological setting

The eastern margin of Sundaland has undergone long-lasting subduction since the Triassic, which resulted in a considerable amount of magmatic products widespread in a large belt which extends from Heilongjiang and Inner Mongolia in NE to Guangxi and Hainan (Wang et al., 2012a, 2012b). Important uplift and erosion since the Cretaceous exhumed many of the plutons whereas most of the volcanic products have been eroded (Chen et al., 2010). The subsequent extension from the Late Cretaceous (Ru and Pigott, 1986) took place within this waning configuration. However, rifting is generally considered to have started in the Early Eocene and ended in the Oligocene (Briais et al., 1993; Barckhausen and Roeser, 2004). The rift stages that resulted in the formation of the SCS started with an initial uplift of the rift shoulders accompanied by widespread erosion and peneplanation in the Late Cretaceous to Early Paleocene (Taylor and Hayes, 1980, 1983; Ru and Pigott, 1986; Schlüter et al., 1996; Pubellier et al., 2003). According to Sun et al. (2009), the proto-margins of the SCS experienced three main stages of deformation as the rifting propagated from North to South and then from East to West. By the end of rifting of the NE part of the SCS, spreading began and propagated gradually toward the SW (Fig. 1). In the northeastern portion of the SCS, Hsu et al. (2004) and Yeh et al. (2010) interpreted Late Eocene/Early Oligocene oceanic crust and seafloor spreading (37.8 Ma to 30.1 Ma; Chrons C17 to C11). However, the nature of the crust there is ambiguous and McIntosh et al. (2013) proposed a hyper-extended crust with a possible mantle exhumation. The timing of seafloor spreading in the central South China Sea has been revised to 31–20.5 Ma (Barckhausen and Roeser, 2004) or to 32 to 15.5 Ma (Taylor and Hayes, 1980; Briais et al., 1993). Two different directions of the oceanic magnetic lineations are recorded; East–West direction for anomalies C16 to C7a (37 Ma to 25.5 Ma) expressed in the NW sub-basin and followed by NE–SW directed lineations for anomalies C7 to C5c (25.5 Ma to 15.5 Ma) mainly expressed in the SW sub-basin (Briais et al., 1993, Fig. 1). The post Middle Miocene evolution is considered devoid of important tectonic activity except for the Northwest Borneo wedge vertical motions (Sapin et al., 2011).

The rifting is less known in terms of its evolution and had led to the separation of two margins with comparable stratigraphic evolution (Holloway, 1982). Early seismic data already showed that the northern margin underwent crustal boudinage during the Eocene (Nissen et al., 1995; Franke et al., this volume). The region has a long history of extension, which dates back from the Late Cretaceous (Ru and Pigott, 1986), although the wells never penetrated Cretaceous nor unidentified Palaeocene prerift series. Despite efforts on analysing the data in order to constraint the age of rifting, no clear result tied to well-data had so far been shown. The large basins developed in the midst of the northern margin, among which are the PRMB (Zhu1, Zhu2, and Zhu3), the Qiongdongnan basin or the Beibuwan basin have a geometry which is known by seismics, and have sediments older than the Early Eocene at the bottom (Auxiètre, 1981; Ru and Pigott, 1986; Robinson et al., 1998; Shi et al., 2013, Fig. 2). The timing of the main events may be associated with known regional unconformities at 32 Ma, 15.5 Ma, 10.5 Ma and 5.5 Ma (Fig. 3). The academic seismic lines attempting the basement (Nissen et al., 1995) and the typical ribbon morphology comparable to that of the Basin and Range province of western US (Franke et al., this volume; Fig. 2), show a severely stretched margins on the south-western part of the SCS.

Two end-member models for the opening of the South China Sea are under contention (Morley, 2002; Pubellier and Morley, this volume). It has been suggested that seafloor spreading resulted from the extrusion of Indochina relative to South China, following India's collision with Asia (Briais et al., 1993; Replumaz and Tapponnier, 2003, Fig. 4). This model excludes the necessity of a Proto-South China Sea (PSCS) to be a prerequisite for the subduction-based model. In the subduction-based model the South China Sea opened in response to the slab-pull resulting from the subduction of the PSCS beneath Borneo between Early Paleogene