Journal of Asian Earth Sciences 78 (2013) 358–370

Contents lists available at SciVerse ScienceDirect

Journal of Asian Earth Sciences

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

# Weak depth and along-strike variations in stretching from a multi-episodic finite stretching model: Evidence for uniform pure-shear extension in the opening of the South China Sea

Lin Chen [a,*], Zhongjie Zhang [a], Haibin Song [b]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

ARTICLE INFO

*Article history:*
Available online 3 January 2013

*Keywords:*
South China Sea
Stretching factor
Subsidence
Crustal thinning
Uniform pure shear

ABSTRACT

The South China Sea is widely believed to have been opened by seafloor spreading during the Cenozoic. The details of its lithospheric extension are still being debated, and it is unknown whether pure, simple, or conjunct shears are responsible for the opening of the South China Sea. The depth-dependent and along-strike extension derived from the single-stage finite stretching model or instantaneous stretching model is inconsistent with the observation that the South China Sea proto-margins have experienced multi-episodic extension since the Late Cretaceous. Based on the multi-episodic finite stretching model, we present the amount of lithosphere stretching at the northern continental margin of the South China Sea for different depth scales (upper crust, whole crust and lithosphere) and along several transects. The stretching factors are estimated by integrating seven deep-penetration seismic profiles, the Moho distribution derived from gravity modeling, and the tectonic subsidence data for 41 wells. The results demonstrate that the amount of stretching increases rapidly from 1.1 at the continent shelf to over 3.5 at the lower slope, but the stretching factors at the crust and lithosphere scales are consistent within error (from the uncertainty in paleobathymetry and sea-level change). Furthermore, the along-strike variation in stretching factor is within the range of 1.11–1.9 in west–east direction, accompanied by significant west–east differences in the thickness of high-velocity layers (HVLs) within the lowermost crust. This weak along-strike variation of the stretching factor is most likely produced by the preexisting contrasts in the composition and thermal structure of the lithosphere. The above observations suggest that the continental extension in the opening of the South China Sea mainly takes the form of a uniform pure shear rather than depth-dependent stretching.



## 1. Introduction

It is widely accepted that the South China Sea was opened by seafloor spreading in the Cenozoic. Although the duration of seafloor spreading and the extension pattern (pure shear, simple shear, or conjunct shear) are still controversial (Taylor and Hayes, 1980, 1983; Briais et al., 1993; Nissen et al., 1995a; Barckhausen and Roeser, 2004; Hsu et al., 2004; Zhang et al., 2010; Li et al., 2011), it is generally believed that prior to seafloor spreading, the proto-margins of the South China Sea had experienced multi-episodic extension since the Late Cretaceous (Ru and Pigott, 1986; Yao et al., 1994; Schlüter et al., 1996; He et al., 2001; Clift and Lin, 2001; Ding et al., 2009). According to Ru and Pigott (1986), the South China experienced three main stages of rifting, initiated during the Late Cretaceous, the late Eocene, and the late early Miocene, with two intervening stages of seafloor spreading. This idea was supported by the findings of rapid changes in the subsidence rate (Clift and Lin, 2001; He et al., 2001; Yuan, 2007), discontinuities in sediment composition (Shao et al., 2004) and unconformities observed in seismic profiles (Ding et al., 2008). As a consequence of a series of rifting events, the margin of the South China eventually evolved into a passive continental margin (Yan et al., 2001; Qiu et al., 2003) and formed the present framework of the northern and southern conjugate continental margins. According to a 3D analog modeling study by Sun et al. (2009), the rifting on the northern margin of the South China Sea propagated from north to south and east to west. However, the pattern and process of the rifting at the northern margin of the South China Sea are still unclear. Previous deep-penetration seismic studies have shown significant along-strike differences in the present-day crustal structure (Nissen et al., 1995b; Yan et al., 2001; Qiu et al., 2001). Based on such observations, Hayes and Nissen (2005) argued that much less continental crustal extension occurred along the east and central segments of the northern margin of the South China Sea than along the western segment. They

* Corresponding author. Tel.: +86 10 82998345; fax: +86 10 82998229.
*E-mail address:* chenlin@mail.iggcas.ac.cn (L. Chen).

1367-9120/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jseaes.2012.12.033

speculated that the rifting involved a greater volume of continental crust and occurred over a much broader area in the west than in the east; thus, the along-strike variations in the amount of stretching of the continental crust at the south China margin could differ by nearly a factor of two, leading to the oceanic crust being formed earlier in the east portion than in the west.

Based on the results of well-log subsidence analyses at the South China Shelf, Clift and Lin (2001) argued that extension of the crust exceeded that in the mantle lithosphere and that therefore the continental extension at the northern margin of the South China Sea is depth-dependent. Similar discrepancies between upper-crust and whole-crust stretching at the southern margin of the South China Sea were reported by Clift et al. (2002) and Ding and Li (2011). Therefore, the stretching difference at the northern margin of the South China Sea seems to not only manifest along the strike but also at depth. However, the speculation of significant along-strike variations in extension was based on analyses of three individual transects across the western, central, and eastern portion of the northern margin of the South China Sea, and the conclusion of depth-dependent stretching was mainly based on either the instantaneous stretching model, which strongly relies on the division of subsidence caused by mantle and crustal extension (Clift and Lin, 2001), or the comparison of the total subsidence and the observed amount of upper crustal faulting (Clift et al., 2002; Davis and Kusznir, 2004). The lack of dense data coverage and constraints on depth scale extension has prevented the lateral and depth variation in crustal and lithospheric extension at the northern margin of the South China Sea from being determined conclusively.

To better understand the along-strike and depth variation in the style of stretching and its implication, the amount of stretching on a lithospheric scale is measured using the subsidence analysis method, whereas crustal-scale stretching is estimated under the constraints of wide-angle seismic data using the crustal thinning method. Considering that previous subsidence analysis studies in this region were based on either the combination of separate instantaneous stretching models (Clift and Lin, 2001) or the one-stage finite stretching model (Su et al., 1989; Shi et al., 2005) and given that the northern margin of the South China Sea has experienced long-duration multi-episodic rifting, we use the multi-episodic finite stretching model to reevaluate stretching factors for a set of wells. By examining the distribution of stretching factors and comparing the stretching factors derived from subsidence analysis and those derived from crustal thinning, we investigate the implications of the variations in the crustal and lithospheric extension both along and across the northern margin of the South China Sea.

## 2. Data sources and methods

### 2.1. Data sources

The data used in this study include: (1) subsidence data for the estimation of lithosphere-scale stretching factor, (2) crustal architecture data for the estimation of crustal-scale stretching factor. These sorts of data are acquired from well-log tectonic subsidence data and wide-angle seismic profiling at the northern continental margin of the South China Sea (Fig. 1) and are summarized into the following.

#### 2.1.1. Subsidence data

The subsidence history at rifted continental margins recorded in stratigraphic data contains information that allows the amount of lithosphere stretching to be determined under the assumption of uniform extension. The subsidence analysis performed in this study is based on 41 well-log subsidence data distributed at the continental shelf of the South China Sea (Fig. 1). Nineteen observed subsidence curves have been derived from the work of Clift and Lin (2001) and the reference therein; two subsidence curves are derived from the study of Shi et al. (2005); and one curve (Zhu-C well) is derived from the study of Ru and Pigott (1986). It is noteworthy that the Zhu-C well proves sound evidence that supports the idea of a multi-episodic extension model for the South China Sea. An additional 19 stretching factors are directly taken from the work of Wheeler and White (2002) because these results were derived from strain rate inversion based on the finite extension model.

It is unrealistic to describe the subsidence histories of all wells with a uniform mode due to the complexity of the extension process and inherent lateral heterogeneity of crust composition. For most wells, three rifting episodes can be recognized at ∼50–39, ∼30–24 and ∼12–11 Ma, with the first one generally being the longest (Fig. 2). At well EP12-1-1, EP17-1-1, PY27-2-1, and YJ23-2-1, a footwall uplift and the associated erosion are often observed during ∼39–30 Ma (Fig. 2b). Although Clift and Lin (2001) indicated that rifting was mostly completed by 25 Ma at the PRMB, close to the inferred 28 Ma break-up unconformity at ODP Site 1148 (Clift et al., 2001; also see Fig. 1 for the location), a later minor rifting stage at ∼12–11 Ma can be widely observed. This stage may be caused by the later reactivation of ancient faults (Clift and Lin, 2001).

#### 2.1.2. Crustal architecture model

Crustal thickness variation along rifted continental margins is considered to be a consequence of crustal extension and thinning. Therefore, the evaluation of crustal thinning requires a crustal thickness dataset. In this study, crustal thickness is constrained by expanding spread profiles (ESPs) seismic data (Nissen et al., 1995b); wide-angle seismic data, including OBS1993 (Yan et al., 2001), OBH1996 (Qiu et al., 2001), OBS2001 (Wang et al., 2006), OBS2006-1 (Wu et al., 2012), and OBS2006-3 (Wei et al., 2011); and the distribution of the Moho depth beneath the South China Sea determined from gravity modeling (Song, 1998).

All the profiles show a general trend of seaward crustal thinning (Fig. 4). From west to east, the characteristics of crustal architecture beneath these profiles can be summarized as follows. At the northwestern margin of the South China Sea, the crustal thickness thins from ∼25 km in the northwest to less than 20 km in the southeast with a remarkably shallow Moho depth of 15 km at the center of the Xisha Trough (Fig. 4a). Along Profile EPS-W, there are two discrete locations of anomalously thin crust overlain by thick sedimentary sections and two discrete thin high-velocity layers (HVLs) at the lowermost crust (Fig. 4b); along Profile OBS2006-1, the crustal thickness decreases from 21 km at the continental slope to ∼7.7 km at the northwestern sub-basin interfered by a thickening crust of ∼18 km at Zhongsha Islands (Fig. 4c). Along Profile OBS1993, the crustal thickness constantly decreases from 22 km in the littoral area to 8 km in deep sea, with a 5–8-km-thick HVL at the lowermost crust (Fig. 4d). Along Profile OBS2006-3, the Moho depth decreases gradually along the seaward direction from 24–25 km beneath the Dongsha uplift to 17 km in the south uplift zone, with a HVL of 3–12 km within the lower crust (Fig. 4e). Along Profile OBS2001, the Moho depth decreases from 23.5 km beneath the continental shelf to 16–18 km at the continent–ocean boundary (COB) with a thin HVL of 0–5 km in thickness (Fig. 4f). Finally, along Profile ESP-E, the crust also thins continuously toward the COB, with a thick HVL in the lower crust (Fig. 4g). A detailed discussion of the HVLs will be given in the following sections.

When data for the sediment thickness and bathymetry beneath profiles were unavailable, a global distribution of sediment thickness (Divins, 2003) and bathymetry (Becker et al., 2009) are used to remove the contribution of sediment to the crustal thickness.