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Climate changes control offshore crustal structure at South China Sea continental margin

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ABSTRACT

Rifted continental lithosphere subsides as a consequence of combined crustal thinning and mantle lithosphere cooling yet basins on some continental margins experience anomalous subsidence events that postdate active extension. Deep basins on the northern margin of the South China Sea, notably the Baiyun Sag, show basement subsidence accelerating after ∼21 Ma, postdating extension by several million years. We combine geophysical observations and numerical forward modeling to show that loading of the offshore basins by increased sediment flux caused by faster onshore erosion following Early Miocene monsoon intensification is a viable trigger for ductile flow after the cessation of active extension. This illustrates that offshore basin dynamics at continental margins with weak crust can be controlled by onshore surface processes in a newly recognized form of climate–tectonic coupling.

1. Introduction

Crustal thickness in rifted continental margins largely reflects the processes of extension that are driven by plate tectonic forces. Initial crustal thicknesses are reduced by extension during continental break-up, resulting in subsidence mostly due to isostatic compensation (McKenzie, 1978). However, in certain tectonic settings significant portions of the continental crust can act in a ductile fashion (Kruse et al., 1991; Wernicke, 1990), resulting in flow away from areas of thickened crust (Clark and Royden, 2000). A flattened Moho under some extensional terrains demonstrates that flow may be important in accommodating strain and that isostatic equilibrium is not always achieved in the asthenosphere (Zuber et al., 1986). In particular, areas with higher heatflow and thicker crust tend to exhibit significant viscous mechanical behavior below the crustal brittle–ductile transition (Block and Royden, 1990; Kruse et al., 1991; Zuber et al., 1986). In this study we model the importance of ductile flow during the break-up of the South China Sea (Fig. 1), whose affected crust originally located within a Mesozoic magmatic arc that began to extend no later than the Eocene (Franke et al., 2014; Morley, 2012), and culminating in seafloor spreading around 30 Ma (Barckhausen et al., 2014; Briais et al., 1993). We show that sediment loading caused by faster erosion onshore following the onset of wetter climatic conditions can result in thinning of the crust under super-deep offshore basins after the end of tectonic extension.

2. Geological setting

The South China Sea is the largest of a series of marginal seas fringing SE and Eastern Asia and whose development has variously been ascribed to plate tectonic forces related to subduction in Indonesia and the Pacific (Morley, 2002; Taylor and Hayes, 1983) and to the relative extrusion of Indochina as a rigid block away from the India–Eurasia collision zone (Peltzer and Tapponnier, 1988). Whatever the original cause of the extension a number of sub-basins have formed on the margins of this oceanic tract and whose vertical tectonics does not follow standard models for continental extension.

Backstripping analysis has shown that the amount of subsidence observed along the northern margin of the South China Sea is much greater than that predicted from the degree of brittle upper crustal extension seen in seismic profiles (Clift et al., 2002; Davis and Kusznir, 2004). Some studies have argued that the additional subsidence is in part caused by the location of the South China Sea overlying a region of colder than normal mantle (Lithgow-Bertelloni and Gurnis, 1997), but other evidence suggests that such dynamic subsidence is <300 m in this area and cannot be responsible for short wavelength and/or rapid subsidence events (Petersen et al., 2010; Wheeler and White, 2002). If we are

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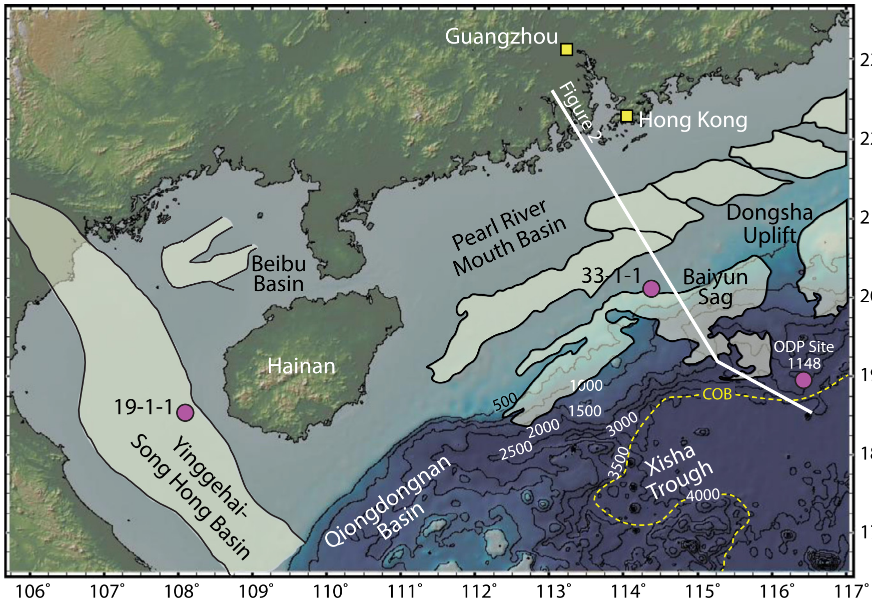

Fig. 1. Shaded bathymetric maps of the study area showing the location of features mentioned in the text. Light shaded areas show deeper areas of subsidence separated by structural highs.

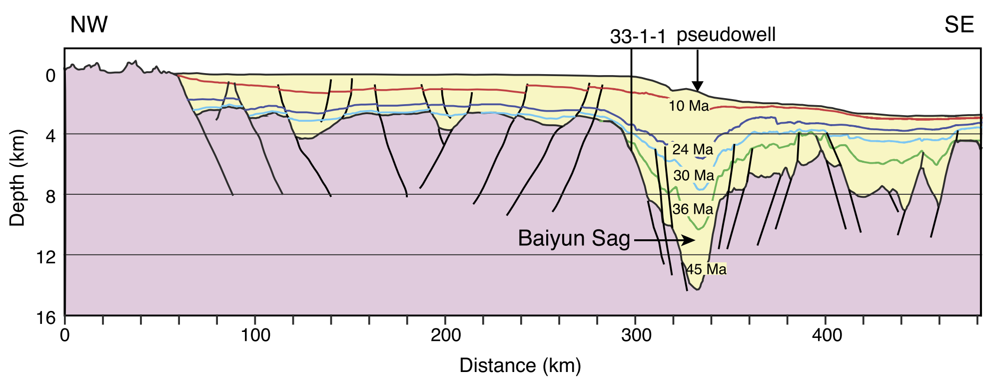

Fig. 2. Structural section across the South China margin and the Baiyun Sag compiled from Sun et al. (2008) and depth converted using drilling data from wells in the Pearl River Mouth Basin and stacking velocities from the central Baiyun Sag.

to explain the excess subsidence by crustal thinning then the extra attenuation must be assigned to the ductile part of the crust because the upper crust is well defined. Preferential lower crustal extension increases towards the continent–ocean boundary (COB) (Clift et al., 2002; Davis and Kusznir, 2004), consistent with ductile lower crustal flow from areas of thick crust towards zones of crustal thinning, as has been proposed for the Tibetan Plateau (Clark and Royden, 2000) and the rifts of the Basin and Range (Kruse et al., 1991; Zuber et al., 1986).

In order to assess the potential role of crustal flow in governing subsidence anomalies in the South China Sea we use a combination of reverse modeling of geologic data and finite element modeling to explore how post-rift subsidence can be accelerated.

3. Subsidence anomalies

A range of observations indicate anomalous subsidence at the northern continental margin of the South China Sea. In the Yinggehai–Song Hong pull-apart basin (YSHB), located to the west of Hainan Island (Fig. 1), a sharp increase in subsidence occurred at ~5 Ma (Fig. 3A) when there was very little brittle deformation (Clift and Sun, 2006). Moreover, the largest subsidence anomaly in the YSHB was spatially related to the region of fastest sedimentation, suggesting that the two might be linked. Mismatch between total subsidence and the observed degree of brittle extension is particularly noteworthy in some deep basins on the outer continental shelf, especially the Baiyun Sag (Fig. 1), where brittle faulting shows only modest degrees of horizontal extension (Sun et al., 2008; Zhao et al., 2011) (Fig. 2). In this case high degrees of crustal flow would be required to explain the total basin depths, regardless of when the extension occurred.

Analysis of tectonically driven basement motion in the Baiyun Sag accounts for sediment loading, sediment compaction and water depths of sedimentation. We applied standard backstripping methods (Sclater and Christie, 1980) to a "pseudowell" (i.e., a section which has not actually been drilled) in the center of Baiyun Sag, assuming local isostatic equilibrium in order to isolate the subsidence driven by tectonic processes. The greatest uncertainty is the assignment of palaeo-water depths of sedimentation. Modern water depths are ~1200 m in the basin center, but otherwise we follow the water depth reconstructions from a recent synthesis of drilling data (Xie et al., 2013). Well 33-1-1, which is positioned on the landward edge of the basin, is used for age control (Fig. 1; Table 1). This well is also used as a guide to lithological information, which is used to correct for the effects of sediment compaction.

Because Well 33-1-1 is located landward of the basin center we estimate that the sediment in the pseudowell would be slightly