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Development of tectonostratigraphy in distal part of foreland basin in southwestern Taiwan

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A B S T R A C T

In the young and active tectonic belt of southwestern Taiwan, reconstructed stratigraphy in the distal part of the foreland basin reveals at least two regional unconformities with the younger ones covering the areas farther from the mountain belt. In contrast with the previously proposed monotonous basin development, the temporal–spatial distribution of the unconformities indicates the back-and-forth migration of the foreland basin margin. Three distinct episodes of rapid subsidence during the foreland basin development have also been identified. The onset of the basin development can be well constrained by the initial rapid subsidence at 4.4–4.2 Ma, which happened only in the proximal part of the basin. This was followed by two younger episodes of rapid subsidence events at 2–1.8 Ma and 0.45 Ma, which were encountered initially in the areas progressively farther from the orogenic belt.

We propose a model of episodic tectonic evolution in the distal part of the foreland basin in southwestern Taiwan. During each episode of rapid subsidence, uplifting that corresponds to the forebulge began with a concurrent rapid subsidence in the areas closer to the basin center and was followed by rapid subsidence and deposition of widespread strata onlapping toward the basin margin. Part of the widespread strata and its overlying deposits would be eroded in the beginning of the next episode when the forebulge shifted toward the orogenic belt. In general, rate of forebulge migrating away from the orogenic belt during the early stage was slower than that derived from a previously proposed kinematic model of a steady migration of the orogenic belt. This might be due to a rifted and weaker lithosphere beneath the foreland basin. Once the foreland basin migrated onto the less stretched lithosphere, the basin would expand rapidly into the craton.

1. Introduction

Foreland basins have been well modeled by the flexed lithosphere under the tectonic loading of the thrust sheets and the sediments deposited in the resultant basins (Beaumont, 1981; Jordan, 1981). The tectonic loading by thrust sheet emplacement and stacking causes rapid subsidence in the foreland basin and forms an asymmetric basin geometry with an uplifted forebulge in its distal part (Shanmugam and Walker, 1980; Heller et al., 1986; Homewood et al., 1986; Jordan et al., 1988; Yang and Dorobek, 1995a). As the rising orogen advances, the asymmetric foreland basin with the forebulge progressively shifts toward the craton (Jacobi, 1981; Speed and Sleep, 1982; Mussman and Read, 1986) and leaves a regional unconformity across the basin (Cohen, 1982; Crampton and Allen, 1995; Yang and Dorobek, 1995b).

More complicated stratigraphic architecture has been documented in the research on the some foreland basins that are composed of episodically developed sequences with compound unconformities in their distal parts (Blair and Bilodeau, 1988; Sinclair et al., 1991; Catuneanu et al., 1997, 1998). Time lag effect between the mountain-side erosion and the deposition in the basin has been considered to cause cyclic asymmetric sequences that are primarily bounded by unconformity at their top (Blair and Bilodeau, 1988; Flemings and Jordan, 1990; Jordan and Flemings, 1991; Sinclair et al., 1991; Johnson and Beaumont, 1995). Other geological processes such as variations in the advancement rate of the orogenic belt front and the change of the orogenic wedge

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morphology (Flemings and Jordan, 1989; Sinclair, 1991, 1997; Yong et al., 2003; Bayona et al., 2008) might also strongly influence the temporal–spatial distribution of lithofacies and unconformities in the basin. Models based on different dominant processes could predict a distinct stratigraphic architecture across the basin. The test of the validity of various models would considerably rely on the completeness of ancient sedimentary records in a foreland basin.

In a young and active mountain belt, such as that of Taiwan, the geological records in the foreland basin, particularly in the distal part and the forebulge, not only reveal the evolutionary history of the basin itself but also provide the most crucial implications for inferring the kinematics of mountain belt development. Previous studies that have addressed the issue of the foreland basin in western Taiwan have regarded the foreland basin deposits in western Taiwan as a single megasequence unit resulting from a continuously westward-migrating orogen-foreland basin system (Covey, 1984, 1986; Shiao and Teng, 1991; Yu and Chou, 2001; Lin and Watts, 2002; Lin et al., 2003). On the other hand, other studies have identified the episodic sedimentation and cyclic stratigraphy in the foreland basin megasequence in southwestern Taiwan (Yeh and Yang, 1994; Yang et al., 1994, 2000; Yeh et al., 1999; Fuh et al., 2003, 2009; Wu et al., 2011; Chen et al., 2001). Another issue in research of the foreland basin is the age of basin initiation; numerous ages have been proposed based on various methodologies. Covey (1984) suggested that the onset of the foreland basin was at 3 Ma. Chou et al. (1994) analyzed the subsidence history of onshore and offshore western Taiwan and came to the same conclusion. However, Teng (1990) suggested that the initial subsidence in the foreland basin started from northern Taiwan in the Early Pliocene or at 3 Ma because of the tectonic loading from the growing orogenic wedge. Yu and Chou (2001), Lin and Watts (2002), and Lin et al. (2003) regarded the regional unconformity at the boundary between the Miocene and Pliocene as the base of the foreland basin and suggested that its onset age was at 6.5 Ma.

The timing of both the foreland basin onset and its following development stages in western Taiwan has been very controversial and might be the most crucial to any attempt to outline the kinematics of Taiwan orogeny. This study reconstructs the tectonic and stratigraphic development and the subsidence history in the distal part of the foreland basin of southwestern Taiwan. Based on the results of our study, we propose a tectonostratigraphic model that is more detailed than and significantly different from previous ones. Finally, we investigated the tectonic implications of the tectonostratigraphic model for the recent Taiwan orogeny.

2. Regional tectonic settings and evolution

Taiwan is located on the convergent plate boundary between the Eurasian and the Philippine Sea plates; the mountain belt is the result of the arc-continent collision between two plates, which commenced during the Pliocene (Biq, 1972; Chai, 1972; Tsai, 1978; Teng and Wang, 1981). During the orogeny, the westward-vergent fault-and-thrust belt also propagated toward the southwest because of the oblique collision (Suppe, 1984). Different initial ages of the arc-continent collision in eastern Taiwan have been proposed; they range from 7 Ma to 4 Ma (Chi et al., 1981; Teng, 1990; Huang et al., 1997, 2006). Huang et al. (2006) also suggested the timing of the arc-continent collision at 5 Ma in southern Taiwan. On the other hand, sedimentary rock studies of the thrust belt show that the oldest sediments derived from the encroaching orogen are from the Upper Pliocene (Chou, 1973).

Prior to the orogeny, western Taiwan and its adjacent area were located on the Eurasian passive continental margin and had encountered at least two discernible major phases of Cenozoic extensional tectonics (Sun, 1982; Yuan et al., 1989; Lin et al., 2003; Yang et al., 2006). The latest phase of the pre-orogenic extension began in the Middle or Late Miocene (Hsiao, 1974; Tang, 1977; Sun, 1982; Leu et al., 1985; Chow et al., 1986, 1987, 1988; Yuan et al., 1988, 1989; Lin et al., 2003; Yang et al., 1991) and formed two rifted basins, the Tainan and Taihsi basins (Fig. 1), which are separated by the Peikang Basement High standing nearly perpendicular to the front of the thrust belt (Sun, 1982; Yang et al., 1991, 2006). The extensional tectonics is characterized by normal faults striking mainly east–west in the basin (Fig. 1). The development of the extensional basin is also characterized by uplifting at the margins and subsiding in the center (Sun, 1982; Yang et al., 1991, 2006). The subsurface geology indicates that the normal faulting was not interrupted during the earlier stage of the foreland basin until the encroaching thrust sheets altered the local stress regime and caused the normal faulting to cease and step back away from the orogenic belt (Sun, 1982; Yang et al., 2006).

The study area in this paper is located exactly on the northern margin of the southern rifted basins (Figs. 1 and 2). The subsurface structures are characterized by two large-scale south-dipping normal fault zones, named B fault and Yichu or A fault, which are located on the northern and southern margins of the study area, respectively, and are accompanied by several equally-spaced north-dipping normal faults between two south-dipping fault zones (Stach, 1957; Elishewitz, 1961; Hsiao, 1970, 1971, 1974; Tang, 1977; Leu et al., 1985; Chow et al., 1986, 1987, 1988).

The foreland basin megasequence in western Taiwan is widely distributed throughout the onshore fold-and-thrust belt (the Western Foothills in Fig. 1), the coastal plain outcropping with alluvial and terrace deposits, and the offshore areas covering the Paleogene and Neogene basins (Fig. 1). The subsurface geological data indicate that the thickness of the Upper Neogene increases dramatically toward the mountain belt to the east (Sun, 1982; Lin and Watts, 2002; Yang et al., 2006). The structural cross-sections (Sun, 1985; Shiao and Teng, 1991; Chou, 1999; Chou and Yu, 2002) show that the backbulge of a foreland basin system (DeCelles and Giles, 1996) is in close proximity to the area covering the Paleogene basins in the western region of the Taiwan Strait.

3. Post-Paleogene tectonostratigraphic architecture

To analyze the tectonostratigraphic architecture below the surface, we used the subsurface well logs to construct the east–west and north–south lines of the time-stratigraphic section (Fig. 3). The latter can be used to investigate the effect of the normal faulting on the stratigraphic architecture while the former shows the typical asymmetric stratigraphic cross-section across the foreland area. To accurately illustrate the temporal–spatial distribution of the foreland basin strata, the depth of the top of the nannofossil zones has been determined using the samples obtained from the boreholes and was used as a time line to construct two time-stratigraphic cross-sections across the study area. Among the identified nannofossil zones, the boundary between NN13 and NN14 was defined based on the rapid downward decrease of *Dictyococcites minutes* (Gartner) and a small form of *Reticulofenestra pseudoumbilica* (Haq) and a rapid upward decrease of the sizable form of *Reticulofenestra pseudoumbilica* (Gartner). At some well sites, such as the Wells E and F in the area to the north of the B fault, the strata of the nannofossil zone containing a large amount of small forms of *R. pseudoumbilica* (Haq) with a limited amount of the sizable form of *R. pseudoumbilica* (Gartner) were intercalated between the NN7/6 and NN19 strata in the subsurface and, therefore, their age was determined as NN14.

We divided the sequences overlying the regional breakup unconformity, which marks the end of the Paleogene rifting, into three megasequence units that correspond to different phases of