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Crustal accretion in the Manila trench accretionary wedge at the transition from subduction to mountain-building in Taiwan

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A B S T R A C T

New marine seismic reflection and coincident wide-angle ocean-bottom seismometer data acquired offshore Taiwan provide high-resolution constraints on the crustal structure of an incipient mountain belt during the earliest stage of arc–continent collision. The new seismic reflection image and travel-time tomography velocity model show evidence for crust of the distal southern Chinese continental margin being subducted eastward beneath the Manila trench and underplated to the accretionary wedge before collision with the southern Chinese continental shelf. The distal margin crust consists of highly extended continental crust interspersed with volcanic bodies and a high-velocity lower crustal layer of likely magmatic intrusions. The distal margin crust is 10–14 km thick outboard of the trench, but thins to 6 km thick beneath the lower slope of the Manila trench accretionary wedge. Along the lower slope of the accretionary prism, we image westward-verging imbricate thrusts and folded strata up to 10 km thick. A sharp decrease in bathymetry marks the transition from lower to upper slope, where we observe a fast (> 6.0 km/s) seismic velocity anomaly at the base of the wedge that we interpret as structurally underplated crust from the distal continental margin. Our results support a model of arc–continent collision in Taiwan where the accretionary wedge is first thickened by structural underplating of distal margin crust prior to collision with the continental shelf. The crustal rocks exposed throughout the Central Range in Taiwan may be similarly derived from subducted and structurally underplated crust from the highly extended distal continental margin.

1. Introduction

Arc–continent collisions are believed to be an important mechanism for growth of the continents throughout geologic time (Sengör et al., 1993). They mark the closing of an ocean basin at the end of a Wilson cycle, and may involve subduction or accretion of a significant amount of continental material. Yet there are few examples of arc–continent collision occurring in the present day to inform models of the collision process, and as such, there are many aspects of arc–continent collision that are poorly understood. In particular, the behavior of colliding continental crust and lithosphere during collision remains an outstanding issue during the mountain-building process.

This problem is drawn into particularly sharp focus at the Taiwan arc–continent collision, where there has been much debate over the importance of thin-skinned versus thick-skinned structural styles. Suppe (1981) used topographic profiles and the geometry of a basal décollement in the Western Foothills foreland fold-and-thrust belt to argue Taiwan behaves as a steady-state thin-skinned critical wedge. In this model, mountain belts, like accretionary wedges, are described as a deforming wedge of granular media separated by a basal décollement from crust passively subducting below (Davis et al., 1983). Many subsequent studies have expanded on this model by incorporating the effects of erosion, sedimentation, thermal effects and rheological heterogeneity (Morley, 2007; Willett et al., 1993; Willett, 1999) or sought to justify its application beyond the foreland fold-and-thrust belt of Taiwan (Carena et al., 2002; Willett et al., 2003).

However, there are a number of first-order observations that suggest that basement is involved to a significant degree in the mountain-building process in Taiwan, particularly in the Central Range metamorphic hinterland, where pre-Tertiary basement of the southern Chinese continental margin has been exhumed and exposed at the surface (Ho, 1986). Several studies have argued that Taiwan may be described as a thick-skinned wedge driven primarily by underplating rather than frontal accretion (Beyssac et al., 2007; Fuller et al., 2006; Simoes et al., 2007). This model explains the incorporation of crustal material as a down-stepping of the basal décollement into continental

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crust, shaving off slivers of crust into the overlying wedge as the thick, buoyant continental shelf attempts to subduct eastward beneath the Philippine Sea plate.

A fundamental implication of these models is that the exposed basement rocks of the Central Range are a consequence of steady-state subduction of the southern Chinese continental shelf, a requirement not obviously supported by seismicity and regional tomography velocity models (Kuo-Chen et al., 2012). Additionally, numerous studies of rifted continental margins around the world have revealed a wide-range of complex structural and compositional styles (Menzies et al., 2002; Reston, 2009) that may influence the collision process in different ways (Afonso and Zlotnik, 2011; Beltrando et al., 2010; Manatschal, 2004; Reston and Manatschal, 2011). Recently, McIntosh et al. (in press) argued Taiwan is the result of a multi-stage collision in which thin, highly extended continental crust is subducted and structurally underplated to the accretionary prism in advance of the encroaching continental shelf, and then subsequently uplifted and exhumed to the surface during collision with the shelf.

The key drivers of this model include (1) the identification of a wide zone of thin crust outboard of the southern Chinese continental shelf near Taiwan that contains faulted blocks of highly extended continental crust; and (2) identification of high-velocity material beneath the metamorphosed sediments of the Central Range near Hengchun Peninsula in southern Taiwan taken to be accreted and exhuming crust from the distal margin. In this model, the exposed continental basement rocks of the Central Range originate from the distal continental margin at the earliest stages of collision, rather than steady-state collision with the thick continental shelf.

We investigate this possibility with coincident multi-channel seismic (MCS) reflection data and wide-angle ocean-bottom seismometer (OBS) data from offshore southern Taiwan that constrain the crustal structure of the incipient mountain belt at the early stages of collision. These data reveal a fast seismic velocity anomaly that is suggestive of crustal material structurally underplating the accretionary prism at the early stages of mountain-building. Our new observations support a multi-stage collision in Taiwan and indicate the crustal accretion process is presently occurring at the Manila trench subduction zone south of Taiwan and southeast of the southern Chinese continental shelf.

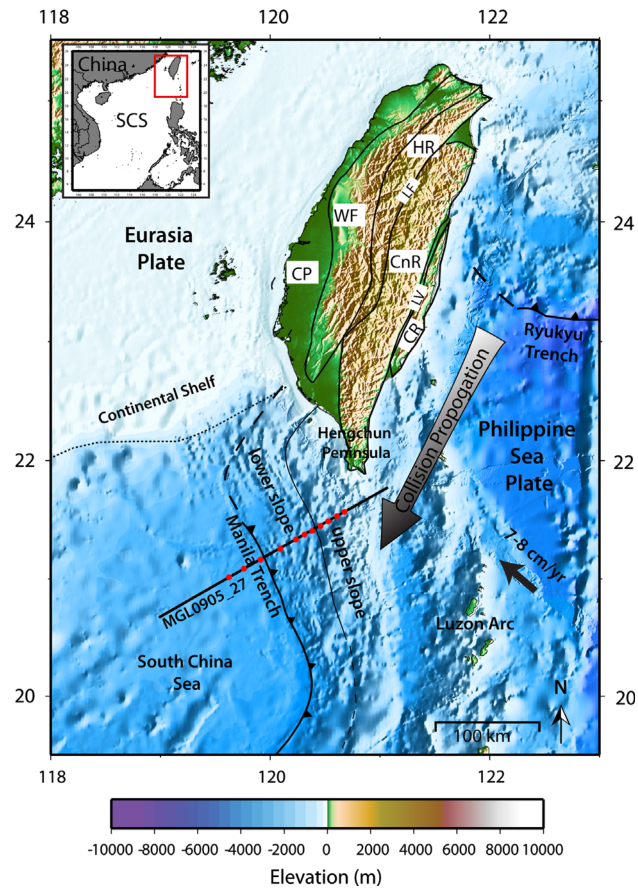

Fig. 1. Onshore Taiwan consists of five tectonostratigraphic terranes: CP – Coastal Plain foreland basin; WF – Western Foothills fold-and-thrust belt; HR – Hsuehshan Range inverted Tertiary rift basin; CnR – Central Range metamorphic hinterland; CR – Coastal Range accreted arc complex. LF – Lishan fault; and LV – Longitudinal Valley. Although the plate convergence is NW–SE at 7–8 cm/yr, the collision is propagating to the southwest due to the obliquely oriented continental shelf and subduction zone. The collision is older in central-northern Taiwan, but just beginning offshore southern Taiwan. MCS reflection data (solid black line) and wide-angle OBS data (red circles) were acquired along MGL0905-27 across the Manila trench and accretionary wedge to constrain crustal structure of the early stage arc–continent collision. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Tectonic background

The Taiwan arc–continent collision is the culmination of a complete Wilson cycle that began by rifting of South China in the late Cretaceous, forming the southern Chinese continental margin and conjugate margin (Ru and Pigott, 1986). Rifting eventually led to continental break-up in the early Oligocene followed by the opening of the South China Sea (SCS) ocean basin by seafloor spreading from early Oligocene–mid-Miocene (Briais et al., 1993). SCS ocean crust began subducting eastward beneath the Philippine Sea plate at the Manila trench starting in the early to mid-Miocene (Hall, 2002), consuming the ocean crust and in the northern SCS, bringing the Luzon arc of the Philippine Sea plate into collision with the southern Chinese continental margin of the Eurasia plate (Fig. 1). Because of the oblique geometry of the collision, the Taiwan arc–continent collision began in central-northern Taiwan ~5–7 Ma (Huang et al., 2006) and has been actively propagating southward (Byrne and Liu, 2002; Lee et al., 2006; Suppe, 1984).

Previous researchers have exploited this geometry by interpreting different spatial transects across Taiwan as different temporal stages in the collision process. In northern Taiwan, post-collisional processes dominate, but may be complicated by the opening of the Okinawa trough and roll-back of the Ryukyu trench east and north of Taiwan (Clift et al., 2008; Teng, 1996). Southern Taiwan and immediately offshore southern Taiwan is in the early stage of mountain building (Huang et al., 2000), while further offshore south and southwest of Taiwan likely represents the 'pre-collision' conditions of the southern Chinese margin and Manila trench subduction system (Byrne and Liu, 2002).

The Taiwan orogen is frequently discussed in terms of five tectonostratigraphic domains (Ho, 1986; Huang et al., 1997). From west to east, they are the Coastal Plain foreland basin; Western Foothills foreland fold-and-thrust belt; Hsuehshan Range in northern Taiwan, an inverted Paleogene rift basin of the southern Chinese margin; the Central Range metamorphic hinterland; and the Coastal Range accreted Luzon arc complex. While much of the Central Range is metamorphosed and highly deformed sedimentary strata from the southern Chinese passive margin, the eastern Central Range also contains exhumed blocks of pre-Tertiary continental margin metamorphic and igneous basement (Beyssac et al., 2007; Ho, 1986). The Central Range extends south towards Hengchun peninsula and its offshore equivalent, the Hengchun ridge. Morphologically, the Hengchun ridge continues southward into the accretionary prism along the Manila trench, suggesting a genetic link between the Central Range and the Manila trench accretionary wedge.

Numerous geophysical studies have focused on the Manila trench south of Taiwan in the context of arc–continent collision