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Three-dimensional density structures of Taiwan and tectonic implications based on the analysis of gravity data

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ABSTRACT

Taiwan is located in a collision and subduction area and has a complex tectonic history. To better understand the complicated structure beneath Taiwan, gravity studies, in addition to seismic and geological studies, provide useful geophysical information for studying shallow depths. Previous gravity studies of Taiwan in the last 30 years focused on local regionalized explanations and 2-D profile modeling. This study is the first to complete a 3-D gravity inversion of Taiwan, and it provides a more comprehensive and large-scale tectonic analysis.

Following 3-D gravity inversion using the least squares method, we sliced horizontal and vertical profiles from the 3-D density model to visualize tectonic changes. The low Bouguer anomaly was caused by thick sediment and crust layers. The high-density layers are located in special tectonic areas such as the Peikang and Kuanying basement highs. The deepest Moho depth beneath the middle of the Central Range is 45–50 km. The high gradient changes of the eastern section of the Moho relief are shown by the complex mechanism of plate collision. The geometry of plate subduction is apparent in northeastern Taiwan, and the oceanic crust is observable under eastern Taiwan, showing arc-collision boundaries.

Our 3-D density model, when combined with updated gravity data and seismic tomography, offers better resolution for deep structures than the previous 2-D forward results and serves as a physical property reference to better understand the tectonic structure beneath Taiwan.

1. Introduction

Taiwan is located at a complex juncture between the Eurasian and Philippine Sea plates, as shown in the plate-tectonic framework and geological units in Fig. 1. The mountains in Taiwan are young from a geological perspective, and formed because of the collision between an island arc system and the Asian continental margin (Wu, 1978; Ho, 1982; Tsai, 1986). The orogeny commenced at approximately 5 Million Years Before Present (Teng, 1987) and continues to this day. The mechanics of the orogeny and the details of its geometry are debatable. As a young and active orogen, Taiwan is a valuable site for studying the processes of mountain building, collision between plates, and tectonic structures in the region.

Over the last 30 years, various tectonic models have been proposed to characterize Taiwan's orogeny based on differing constraints and approaches. The "thin-skinned" model (Suppe, 1981) explains Taiwan's orogeny as analogous to a wedge of soil being driven forward by a bulldozer over an underlying basal detachment. Lallemand et al. (2001) created a 3-D mountain-building model that featured a steep eastward subduction with a tear at the ocean-continent boundary. Lin et al. (1998) suggested that the high velocities and extensional mechanisms in the eastern Central Range are the results of an ongoing exhumation of previously subducted continental crust. Lin (2000) also presented a thermal model of continental subduction and exhumation to explain the high heat flow observed on the surface and in the aseismic zone within the upper crust. The "thick-skinned" model (Wu et al., 1997) argued that subduction has not been identified from the distribution of earthquake hypocenters.

Therefore, Kim et al. (2004) proposed an alternative "lithospheric collision" model, which asserts that deformation is related to the lithosphere in the Taiwan orogeny. A preliminary study that used the receiver function method demonstrated the ability of the "thin-skinned" deformation model to explain the crustal deformation and tectonic evolution of the Western Foothills and western Coastal Plain (Fig. 1). The "thick-skinned" and "lithospheric collision" models should be capable of explaining the development of the Central Range.

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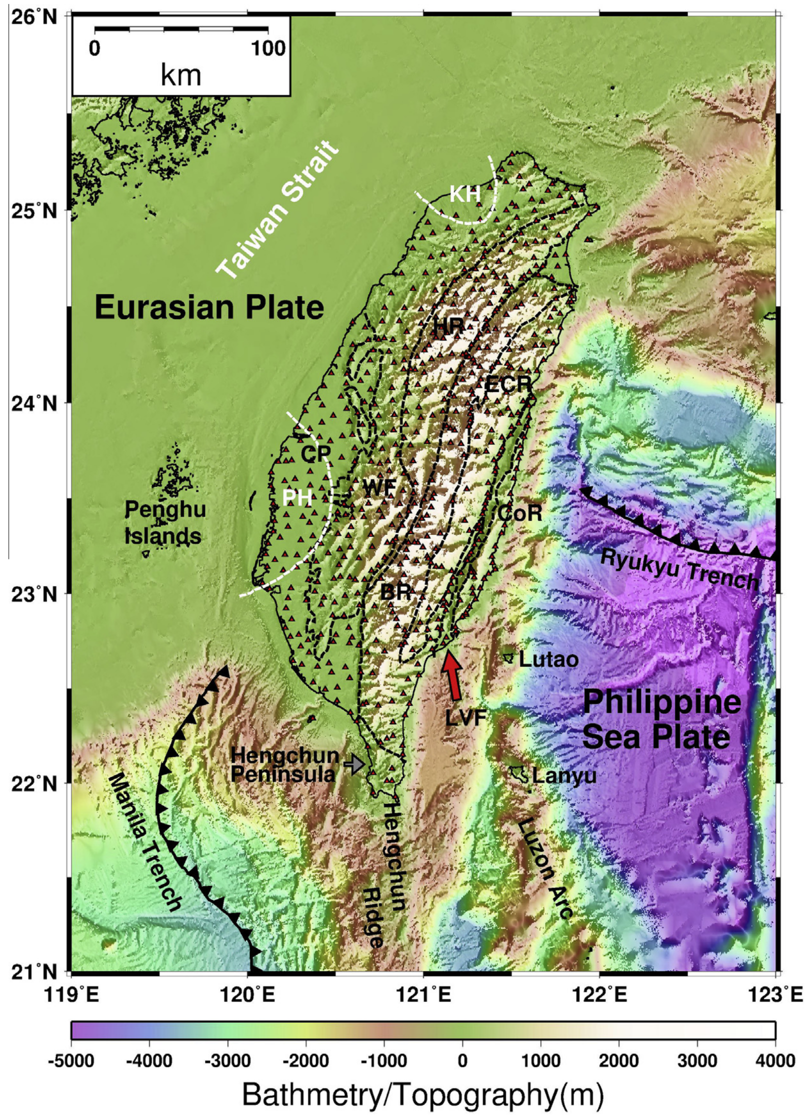

Fig. 1. Topography and geological subdivisions of the Taiwan region. CP: Coastal Plain; WF: Western Foothills; HR: Hsuehshan Range; BR: Backbone Range; ECR: Eastern Central Range; CoR: Coastal Range; LVF: Longitudinal Valley Fault; PH: Peikang High (a geometric basement high); KH: Kuanying High (a geometric basement high). The Manila and Rykukyu Trenches are drawn on the basis of bathymetry only.

Many seismic tomographic studies have examined subsurface structures and tectonic problems related to seismic velocities (e.g., Roecker et al., 1987; Shin and Chen, 1988; Rau and Wu, 1995; Ma et al., 1996; Kim et al., 2005; Wu et al., 2007; Kuo-Chen et al., 2012). These studies have created differing 3-D velocity structures for Taiwan because of their dissimilar assumptions and initial models, different approaches to inversion, or because of their use of different seismic databases. The seismic-tectonic features of Taiwan are not well understood. Using receiver function analysis to analyze teleseismic data observed by digital broadband seismic stations is a common method for determining crustal thickness beneath selected areas (Tomfohrde and Nowack, 2000; Kim et al., 2004; Ai et al., 2007; H.L. Wang et al., 2010). However, because of the limited number and coverage of broadband seismic stations, the exact geometry of local crustal structures beneath Taiwan cannot be elucidated. The use of a common conversion point stacking method for receiver functions suggests that the Philippine Sea plate is probably subducting beneath the Eurasian plate near central and northern Taiwan.

Several 2-D images of the crustal structures of Taiwan have been depicted using geophysical data. The 2-D density profiles modeling by the gravity data (Yen et al., 1998) across the major structural trends of Taiwan are consistent with the average continental Moho depths of 26 km for the Coastal Plain and the Western Foothills, 28 km for the Coastal Range in eastern Taiwan, and 33 km for the Central Range (Yen et al., 1998). Based on magnetotelluric observations, Chen et al. (1998) proposed that the depth of the Moho discontinuity is 20–30 km beneath the Central Range. Modeling and interpretations of the wide-angle seismic profile along the central cross-island highway from the Taicrust experience have revealed that the crustal thickness beneath the eastern section of the Central Range is approximately 45 km (Shih et al., 1998). The thickest crustal section is 50 km beneath the Coastal Range, along the southern cross-island highway (Yeh et al., 1998). The recent active seismic experiments conducted by the Taiwan Integrated Geodynamics Research (TAIGER) project have determined a Moho depth of 33–37 km along northern Taiwan and a depth of 36–44 km for southern Taiwan (Okaya et al.,