Magnetotelluric evidence for thick-skinned tectonics in central Taiwan

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ABSTRACT

Taiwan is the type example of an arc-continent collision. Numerous tectonic models have been proposed for this orogen, and include both thin-skinned and thick-skinned lithospheric deformation. These models predict very different structures at middle and lower crustal depths, but insufficient geophysical data exist to unequivocally distinguish between them. Long-period magnetotelluric (MT) data were collected in central Taiwan in 2006–2007 to constrain the crustal resistivity structure. A two-dimensional inversion of these MT data revealed a prominent electrical conductor that extends across the décollement predicted by the thin-skinned model. This feature is interpreted to be due to 1%–2% saline fluids, and is inconsistent with the thin-skinned model. In contrast, the thick-skinned model predicts this feature since fluids are generated in the crustal root through metamorphism. Quantitative correlation of the resistivity and seismic velocity models supports small-volume, high-salinity fluids in a thickened crust as the cause of this conductor.

INTRODUCTION

Arc-continent collisions are a fundamental tectonic process and contribute to continental growth. In ancient collisions, postorogenic geological events obscure the orogenic processes, thus studies of active collisions are needed. The oblique convergence between the Luzon Volcanic Arc and the passive margin of the Eurasian plate represents the best example of an active arc-continent collision. Since the late Miocene, convergence has produced a mature orogen in northern Taiwan, the collision becoming younger to the south (Byrne and Liu, 2002). Several models have been proposed to explain the collision tectonics of central Taiwan, and these models form a spectrum between two end members: (1) thin-skinned tectonics, and (2) thick-skinned lithospheric deformation.

In the thin-skinned model, a shallow décollement dips east within the upper continental crust. Deformation is localized above this surface while the Eurasian continental lithosphere subducts below. The thin-skinned model was motivated by geological and shallow seismic exploration in the Western Foothills fold-and-thrust belt (Suppe, 1981). Near-surface deformation in the Western Foothills (Yue et al., 2005) and surface heat flow (Bahr and Dahlen, 1990) are consistent with predictions from critical wedge theory employing a shallow décollement. In addition, earthquake hypocenters have been moved under certain assumptions to infer that a band of seismicity exists at 8–10 km depth from the Western Foothills to the Coastal Range, which is interpreted to be the décollement (Carena et al., 2002).

In contrast, the thick-skinned model predicts continuous deformation throughout the lithosphere, with prograde metamorphism occurring within a thickened crust beneath the Central Ranges (Wu et al., 1997). This model is supported by observation of a crustal root in seismic tomography models (Wu et al., 2007) and by precisely relocated hypocenters (Wu et al., 2004). Receiver function analysis (Kim et al., 2004), TAICRUST active source seismic data (McIntosh et al., 2005), shear wave splitting (Rau et al., 2000), and gravity data (Yen et al., 1998) also support the thick-skinned model.

Existing geophysical data could not distinguish between these end-member models beneath the Central Ranges, thus additional data were needed. As part of the Taiwan Integrated Geodynamics Research (TAIGER) project, the first long-period (10–10000 s) MT data were collected in Taiwan. MT measurements image subsurface electrical resistivity and can provide constraints on lithospheric composition and strength (Unsworth et al., 2005). This paper describes the collection and interpretation of the TAIGER MT data in central Taiwan.

MAGNETOTELLURIC DATA COLLECTION AND ANALYSIS

MT measurements use natural electromagnetic (EM) fields to image subsurface resistivity structure. The penetration depth of these signals increases with period (Simpson and Bahr, 2005). In 2006–2007, long-period MT data were recorded at 21 stations in central Taiwan and at a remote reference station on the Penghu archipelago to reduce cultural EM noise (Fig. 1). The study area is located in a region of complex geology and

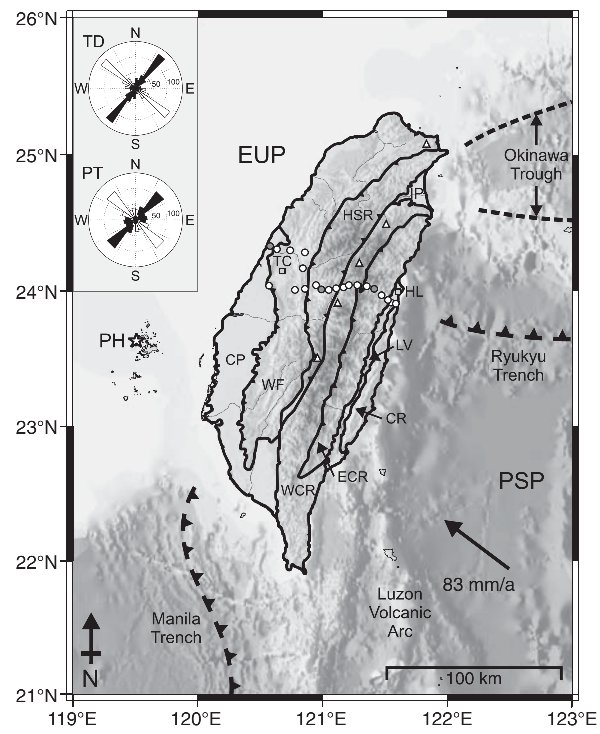


Figure 1. Regional geologic and tectonic map of Taiwan. White circles denote long-period magnetotelluric stations; gray circles indicate where only magnetic field data were analyzed; white triangles show locations of Au-Cu deposits. Star marks remote reference station on Penghu (PH) archipelago. EUP—Eurasian plate; PSP—Philippine Sea plate. Geological provinces: CP—Coastal Plain; WF—Western Foothills; HSR—Hseuhshan Range; WCR—West Central Range; ECR—East Central Range; LV—Longitudinal Valley; CR—Coastal Range; IP—Ilan Plain. Cities: TC—Taichung; HL—Hualien. Rose diagrams show geoelectric strike direction computed from tensor decomposition (TD) and phase tensor (PT) analysis for periods 10–3000 s. Black and white sectors are equivalent, as there is inherent 90° ambiguity in strike direction determined by these methods.

is surrounded by ocean with variable water depths. These factors require careful data analysis to determine if a two-dimensional (2-D) or three-dimensional (3-D) interpretation is appropriate. The dimensionality and geoelectric strike direction were investigated using both tensor decomposition (McNeice and Jones, 2001) and phase tensor analysis (Caldwell et al., 2004). These techniques found a consistent strike direction (N37°E) that is parallel to the major geological boundaries (Fig. 1; Fig. DR1 in the GSA Data Repository[1]). Induction vectors can also determine the dimensionality (Simpson and Bahr, 2005). Within the period band 10–100 s the induction vectors are predominantly perpendicular to the geoelectric strike, indicating 2-D conductivity structure (Fig. DR2). EM signals at these periods are sensitive to mid-crustal depths, where major differences are predicted between the end-member models. At periods >1000 s, the induction vectors point east due to the large conductance of the Philippine Sea. For periods 100–1000 s, induction vectors in eastern Taiwan mainly point northeast, indicating 3-D conductivity structure. Despite this 3-D evidence, the well-defined strike direction and the 2-D nature of the induction vectors at periods most sensitive to the upper and middle crust justify a 2-D analysis. The 2-D inversion algorithm of Rodi and Mackie (2001) was used to generate smooth resistivity models. An inversion of the MT impedances and induction vector data produced a model that fits the observations (Fig. 2A). MT data showing high levels of distortion and/or noise were excluded to allow a good fit by the inversion (root mean square misfit = 1.3; Figs. DR3 and DR4).

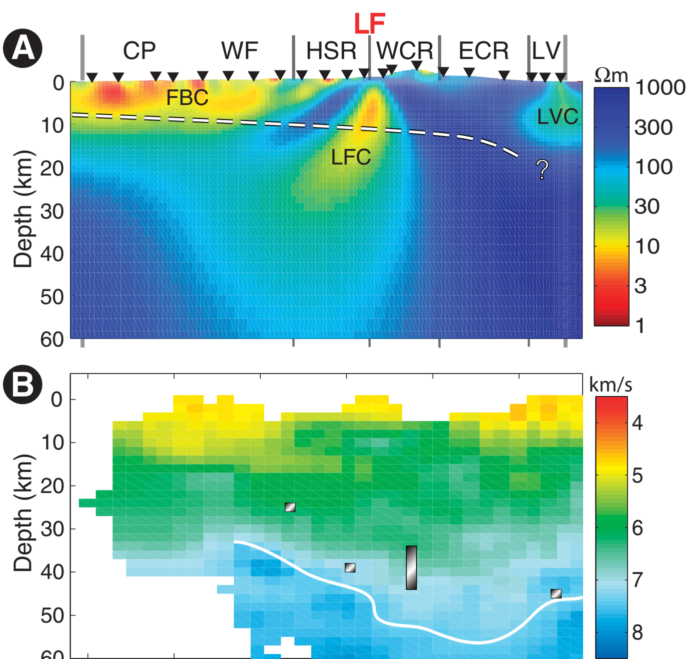
INTERPRETATION

Resistivity Model

Conductive (low resistivity) sedimentary rocks are imaged in the foreland basin of western Taiwan (FBC in Fig. 2A). East of this zone, resistivity increases where the sedimentary rocks contact the metamorphic rocks of the Hseuhshan Range. While limited in near-surface resolution, this model does not support underthrusting of the conductive Western Foothills rocks beneath the Hseuhshan Range. The steep contact imaged between these provinces favors the thick-skinned tectonic model. The boundary between the Hseuhshan Range and West Central Range coincides with the west-dipping Lishan fault, suggested to border the eastern edge of an Oligocene half-graben (Clark et al., 1993).

In eastern Taiwan, a near-surface conductor (LVC in Fig. 2A) that may be related to fluids coincides with the Longitudinal Valley fault (Yu and Kuo, 2001, their figure 2). This active, high-angle oblique thrust fault overlies the suture zone between the Eurasian plate and the Philippine Sea plate (Yu and Kuo, 2001). However, this model feature is poorly resolved, owing to its location near the end of the profile and the insensitivity of long-period MT data to near surface structure.

A prominent feature of the resistivity model is the mid-crustal conductor (LFC in Fig. 2A) located beneath the Lishan fault. Partial melts and/or aqueous fluids have been proposed to explain similar crustal conductors elsewhere (Wannamaker et al., 2002; Unsworth et al., 2005).



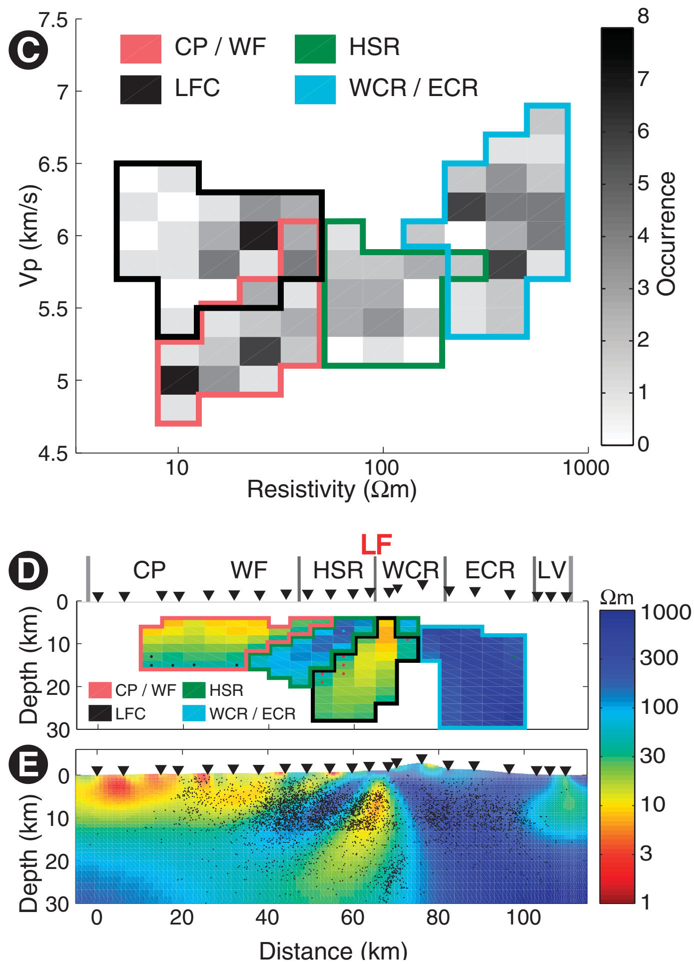


Figure 2. A: Joint transverse electric, transverse magnetic, and tipper inversion model. FBC—Foreland Basin conductor; LFC—Lishan fault conductor; LVC—Longitudinal Valley conductor; CP—Coastal Plain; WF—Western Foothills; HSR—Hseuhshan Range; LF—Lishan fault; WCR—West Central Range; ECR—East Central Range; LV—Longitudinal Valley. Dashed line shows décollement from Carena et al. (2002). B: Tomographic P-wave velocity model with contour v_p = 7.3 km/s. Vertical bars show Moho depth (Kim et al., 2004). C: Crossplot of P-wave velocity and electrical resistivity for models shown in A and B. D: Resistivity model indicating spatial regions giving rise to zones in C. E: Resistivity model showing hypocenters within 20 km of the profile.

[1]GSA Data Repository item 2009171, supplemental information and figures, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Given the relatively shallow depth and thermal conditions of the Lishan fault, a distributed zone of saline fluids in the middle to lower crust is the most likely cause of the low resistivity.

The Lishan fault conductor appears to cross the location of the décollement proposed by Carena et al. (2002). If the Lishan fault conductor is caused by a zone of interconnected aqueous fluids, then this is significant in terms of the depth extent of deformation in central Taiwan. The presence of such a feature is consistent with a thick-skinned model since interconnected fluids would be released below 10–15 km depth as the crust is thickened. A feature similar to the Lishan fault conductor was observed in an MT study of the South Island of New Zealand (Wannamaker et al., 2002) and was attributed to fluids released from prograde metamorphism within a thickened crust. The presence of the Lishan fault conductor presents two challenges to the thin-skinned model. First, with minimal deformation below the décollement, it is difficult to envision a mechanism to generate fluids at shallow depths within the subducting Eurasian plate. Second, if a décollement were present, it might be expected to disrupt upward fluid migration.

Identifying whether the Lishan fault conductor extends into the mid-crust has significant tectonic implications. However, resolving the depth extent presents a challenge, since MT data are primarily sensitive to the depth to the top of a conductor. Smooth inversions often smear conductive features to depth, thus a series of constrained inversions were implemented with models fixed to be resistive below a given depth. The fit to the observed tipper data (ratio of vertical to horizontal magnetic fields) adjacent to the Lishan fault is illustrated in Figure 3. Note that these inversions also fit the MT impedances; however, only the tipper responses are shown as these data are most sensitive to vertical structure (Unsworth et al., 2000). Progressively decreasing the depth to the resistive basement causes an increase in the data misfit; the depth at which this occurs corresponds to the shallowest conductor permitted by the data (Li et al., 2003). The F30 model fits the measured data very well (Fig. 3). The misfit is higher in the F20 model, but is still acceptable. In contrast, the F10 model does not adequately fit the measured data, indicating that the Lishan fault conductor extends beyond a depth of 10 km. Conductance plots of these constrained inversions also indicate a poor fit to the F10 model (Figs. DR5 and DR6).

The presence of a conductive feature extending across the depth of the inferred décollement is difficult to reconcile with a thin-skinned model and is interpreted as support for the thick-skinned lithospheric deformation model of Wu et al. (1997).

Correlation of Resistivity and Seismic Velocity

Integration of independent geophysical data was implemented by comparing a seismic velocity model and relocated earthquake hypocenters with the resistivity model. The tomographic model consists of P-wave velocity estimates on an x = y = 5, z = 2 km grid, and incorporates first-arrival data from TAIGER active seismic transects in 2007–2008. Hypocenter locations for M > 2 events from 1993 to 2002 were obtained using the double-difference relocation method (Wu et al., 2004).

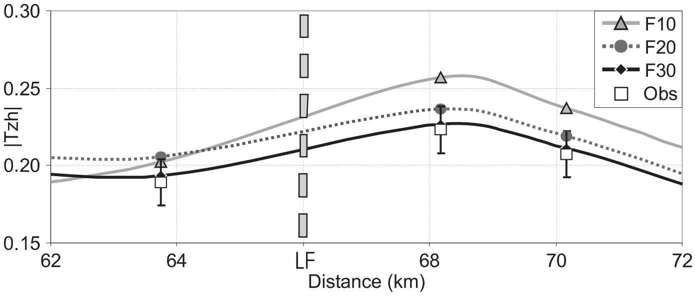


Figure 3. Tipper data projected parallel to profile at period of 100 s for stations adjacent to the Lishan fault (LF). Open squares (Obs) denote measured data with absolute error floor of 0.03. Smooth curves are responses of constrained inversion models with resistive (300 Ωm) basement fixed at depths 10, 20, and 30 km (models F10, F20, and F30, respectively).

The resistivity and velocity models (Figs. 2A and 2B) are clearly correlated. For example, both models have their lowest values in the upper 10 km beneath the Coastal Plain and Western Foothills. However, a quantitative approach is required to determine the degree to which these parameters are related. The method of Bedrosian et al. (2004) was used to determine distinct model domains that are defined by ranges of velocity and resistivity. The resistivity model was first interpolated onto the same grid as the velocity model, and poorly resolved areas of the models were masked to avoid correlation of unconstrained parameter estimates. For example, conductors are smeared to depth by the regularized inversion, thus cells beneath large conductors were excluded from the analysis. Model edges were also masked where features are poorly resolved. A histogram of the occurrence of resistivity and velocity combinations for each model cell was then generated (Fig. 2C). Distinct domains within this histogram are identified and mapped back onto the resistivity model (Fig. 2D).

No universal relationship between resistivity and velocity has been reported for crustal-scale studies (Bedrosian et al., 2007). In general, porosity provides a link between electrical resistivity and seismic velocity (Hacikoylu et al., 2006), since as porosity decreases, both resistivity and velocity increase. Metamorphic grade increases eastward across Taiwan, thus an associated increase in electrical resistivity and seismic velocity is expected. Four distinct domains are observed in the histogram, and three of these (Coastal Plain/Western Foothills, Hseuhshan Range, and West Central Range/East Central Range) define a trend of increasing velocity and resistivity with metamorphic grade. However, the Lishan fault conductor domain is not on this trend.

The Lishan fault conductor domain is characterized by an area of anomalously low resistivity and only moderately low velocity. Fluids generated by prograde metamorphism within a thickened crust are the most likely explanation for this conductor. Evidence for extensive fluid circulation in this area comes from a number of sulfide deposits adjacent to the Lishan fault (Fig. 1). Tectonically driven hydrothermal fluid circulation is often associated with mesothermal gold mineralization in young or active orogens (Craw et al., 2002, their table 1). Thus, it is necessary to show that fluids can account for the low resistivities in this domain, without causing a decrease in velocity. At the pressure-temperature conditions present in the middle to lower crust, saline fluid is expected to have a resistivity of ρ_w ~0.01–0.05 Ωm (Nesbitt, 1993). Assuming a cementation factor of m = 1.5, Archie's law (Archie, 1942) requires porosity values of 1%–2% to explain a bulk resistivity of 15 Ωm. This result is not critically dependent on the values of the parameters used in Archie's Law (Fig. DR7). Laboratory measurements indicate little change in P-wave velocity with varying pore-fluid salinity (Jones et al., 1998). Thus, a porosity of a few percent saturated with saline fluid is consistent with both the velocity and resistivity constraints on the Lishan fault conductor.

Correlation of Resistivity and Hypocenter Locations

Links between resistivity and seismicity have been noted in previous studies (Chen et al., 2007; Ogawa et al., 2001). Of interest in central Taiwan is a cluster of deep (20–30 km) seismicity located near the eastern edge of the Lishan fault conductor (Fig. 2E). Focal mechanisms suggest that these epicenters are associated with a thrust fault, with the Central Ranges on the footwall side (Wu et al., 2004). Gourley et al. (2007) recognized this and other evidence for deep vertical faults within the Central Ranges that would contribute to building a crustal root. The location adjacent to the Lishan fault conductor suggests that this fault may act as a conduit for fluid migration toward the surface.

CONCLUSIONS

A resistivity model of the first long-period MT data collected in central Taiwan reveals a major conductor located beneath the Lishan fault that extends from the near surface to beyond 10 km depth. The shallow décollement predicted by the thin-skinned tectonic model is consistent with the MT data in western Taiwan, but not with the Lishan fault conductor in central Taiwan. Quantitative correlation between the resistivity and a tomographic velocity model indicates that aqueous fluids with 1%–2% porosity can account for the Lishan fault conductor. The thick-skinned lithospheric deformation model is consistent with these observations, with the fluids being produced in the lower crust by prograde metamorphism.

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