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Electrical structures of the source area of the 1999 Chi-Chi, Taiwan, earthquake: Spatial correlation between crustal conductors and aftershocks ☆

Chien-Chih Chen [a,*], Sung-Ching Chi [a], Chow-Son Chen [a], Chieh-Hou Yang [b]

[a] Institute of Geophysics, National Central University, Chungli, 320 Taiwan, ROC
[b] Department of Civil Engineering, Ching Yun University, Chung-Li, 320 Taiwan, ROC

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Abstract

Wide-band magnetotelluric (MT) data were collected on an east–west profile, approximately perpendicular to the local strike of the Chelungpu thrust, through the hypocentral area of the Chi-Chi earthquake for imaging the seismogenic structure. MT data were then inverted for two-dimensional resistivity models plus best-fitting static shift parameters using a nonlinear conjugate gradient algorithm that minimizes the sum of the normalized data misfits and the smoothness of the model. As shown in the inverted 2D resistivity models presented in this paper, an electrical conductor beside the hypocenter of the Chi-Chi earthquake indicates that deep-crustal fluids may participate in the rupture process of the Chi-Chi earthquake. A striking spatial correlation between the crustal conductor and occurrence of aftershocks beneath the Chelungpu fault suggests a postseismic pore pressure adjustment ongoing after the mainshock. Additionally, the hypocenter exhibits an electrical resistive zone, consistent very well with a predicted compact zone from a crustal deformation and transient fluid flow modeling.

Keywords: Magnetotellurics; Electrical structures; Chi-Chi earthquake; Taiwan; Crustal fluids; Crustal conductors

1. Introduction

Large-magnitude earthquakes are rare events but are often dangerous and costly, killing hundreds of people and destroying millions of dollars of property. An Mw 7.6 earthquake on Sep. 20, 1999 (early morning of Sep. 21, local time), the most powerful and devastating inland earthquake in the recorded seismological history of Taiwan, struck central Taiwan near Chi-Chi town and shocked the whole island. It resulted in more than 2400 causalities and tens of billions of dollars in property loss. The destructive Chi-Chi earthquake also brought on extensive surface ruptures for about 80 km in length along the range-bounding Chelungpu thrust (Fig. 1).

A growing body of evidence suggests that fluids are intimately linked to a variety of faulting processes (e.g. Hickman et al., 1995). When fluid migrates in the crust and weakens some parts of fault zones, the fluid pressure rises and the elastohydrodynamic lubrication comes to reduce friction for large events relative to small ones (Kanamori and Brodsky, 2001). Such elastohydrodynamic lubrication is recently proposed to explain the

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* Corresponding author. Tel.: +886 3 4227151 65653; fax: +886 3 4222044.
E-mail address: chencc@ncu.edu.tw (C.-C. Chen).

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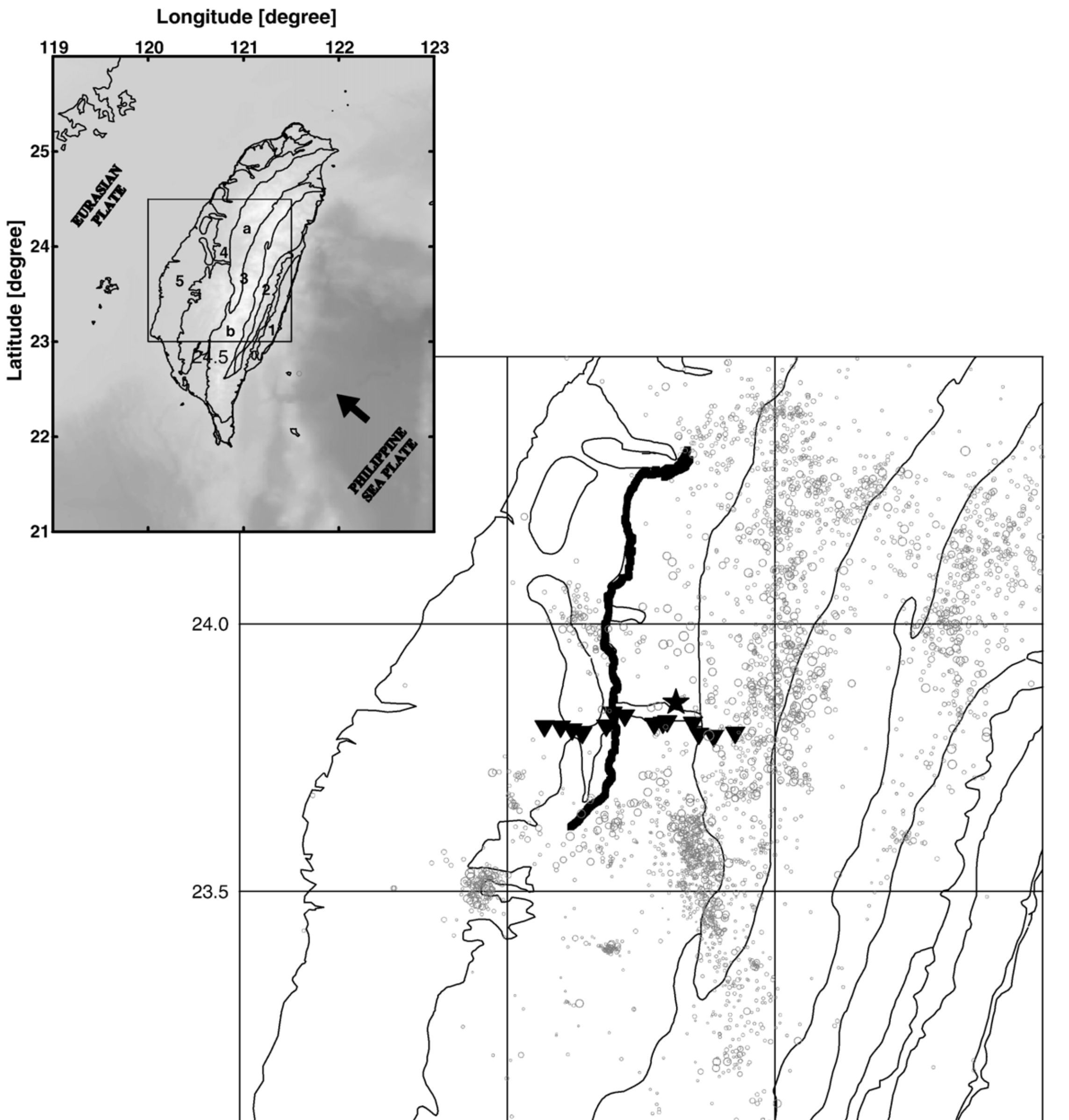

Fig. 1. Map of the study area showing locations of MT sites (inverse triangles) and the epicenter of the 1999 Chi-Chi, Taiwan, earthquake (star). Also shown are epicenters of aftershocks (open gray circles) occurred between Sep. and Oct. 1999. The bold line indicates the surface break of Chelungpu thrust. On the left-upper inset map of the geological units of Taiwan are: (1) Coastal Range; (2) eastern Central Range; (3) western Central Range: (a) Hsuehshan Range and (b) Backbone Range; (4) Western Foothills; (5) Coastal Plains. Thick arrow indicates the relative direction of plate motion.

extremely large ground-motion velocity observed in the Chi-Chi earthquake, but with minor short-period acceleration (Ma et al., 2000; Kanamori and Brodsky, 2001). There are many factors determining the occurrence of fault lubrication, such as the effective permeability in the fault zone. Faults either aid in or inhibit fluid migration. It is thus important to study what roles faults play in distributing fluids in the crust and in altering pressure domains.

Very recently, Lee et al. (submitted for publication) used integrated crustal deformation and transient fluid flow modeling techniques to investigate the response of crustal fluids to the Chi-Chi earthquake. Their results show that the negative compact volumetric strains tend to concentrate near the tips of the Chelungpu thrust, either near the surface or close to the focus at depth. The model also predicts that dilatations occur to both the west and the east of the Chelungpu fault. The volume increase in a dilatation zone could cause a coseismic decrease in pore fluid pressure and, in contrast, pore fluid pressures rise in the contractional zone. As a result, after the mainshock, crustal fluids tend to migrate from the areas of overpressure, i.e. the compressional zones, to the areas of underpressure, i.e. the dilatational zones. Tracking the crustal fluids is thus crucial to verify the concept of postseismic pore pressure adjustment and their theoretical model.

Electromagnetic (EM) methods can be used to image the crustal fluids that are more conductive than the host rocks. One distinct advantage of using EM methods is that they are highly sensitive to conductive materials in the crust. In this work MT method, that uses Earth's natural time-varying EM fields as the sources, was conducted to delineate the subsurface electrical structures of the surface-breaking extension and around the hypocentral area of the Chi-Chi earthquake. We attempt to examine whether a conductor indicating fluids exists around the source area of the Chi-Chi earthquake. Parts of MT soundings used in this paper and their 1D inversion models were reported in our previous paper (Chen and Chen, 2000). It should be noticed that approximately 1D electrical models presented in Chen and Chen (2000) may give good qualitative results of subsurface structures, the resolution in depth, however, could be quantitatively poor (Jones et al., 1992). We thus present and describe our two-dimensional interpretation of inverted electrical structures in this study. New MT soundings conducted after the publication of our previous paper (Chen and Chen, 2000) are also included in the present work.

2. MT methodology and data representation

MT method resolves subsurface electrical resistivity by measuring the electric and magnetic field strengths of naturally occurring EM waves incident on the earth's surfaces. Since the penetrating depth of EM waves is proportional to period, measuring the MT response for a range of periods gives the depth sounding of the earth's resistivities. For a homogeneous halfspace, the MT apparent resistivities are equal to the true resistivity of the earth and the MT phases have the constant value of 45° at all the sampling frequencies. If the earth has a two-dimensional (2D) resistivity structure, say invariant in the north–south direction, then two independent polarizations of the electric field must be considered. In the transverse electric (TE) mode, electric current flows parallel to the N–S direction (i.e. the so-called strike direction); in the transverse magnetic (TM) mode, it flows perpendicular to the strike direction.

The MT transect was chosen to be perpendicular to the approximately north–south trending structures of the Chelungpu thrust and the fold-and-thrust belt in the middle of Taiwan (Fig. 1). Fourteen MT soundings (Fig. 1) across the hypocentral area of Chi-Chi earthquake were recorded using commercial MT V5-16 and MTU-5 systems developed by Phoenix Geophysics Ltd., Canada. The soundings were acquired during a time span from October 1999, soon after the Chi-Chi earthquake, to May 2001. Originally only an old type of MT V5-16 system, which is quite difficult to implement the MT remote-reference technique (Gamble et al., 1979), was equipped for MT research in Taiwan before 2001 and the new commercial MTU-5 system were introduced into Taiwan in January 2001. Therefore the remote-reference technique for enhancing the data quality was used at those MT soundings conducted after 2001. A remote-reference MT site was placed in Taoyuan county in northern Taiwan, where it is about 100 km far from the study area.

The statistically robust routine (Method 6 described in Jones et al., 1989) had been implemented to process MT time-series data and to give estimates of apparent resistivity and phase for periods 0.0026–1820 s. In Fig. 2 we show the apparent resistivity and phase curves for all the MT sites used in this study. The estimates of the apparent resistivity and phase data are presented in an axial system rotated to the N–S direction, which corresponds to the tectonic strike around the study area (see below). In the period band from 1 to 10 s, the so-called MT dead-band, the natural signal level is lowest and the existence of coherent noise has much more serious effect upon the impedance estimates. Generally speaking, the data quality for the resistivity is better than the phase and TM mode (diamonds) is better than TE mode (crosses). Although the MT data is noisy at some sites (e.g. MT6 and MT11), for most sites the MT curves are smooth enough to fit well using a 2D electrical model (solid lines). It is also worth mentioning that the trends of MT response functions vary quite gently site-by-site from west to east and that similar trends in data can be usually found at neighboring sites.

The observations can be also introduced in the form of pseudosections, which are contour plots of MT response functions with log period as the ordinate and distance along the profile as the abscissa (Fig. 3A and C). Pseudosections are useful for summarizing the general trends in data concisely and for highlighting the strongest anomalies along the entire profile. For comparison, the

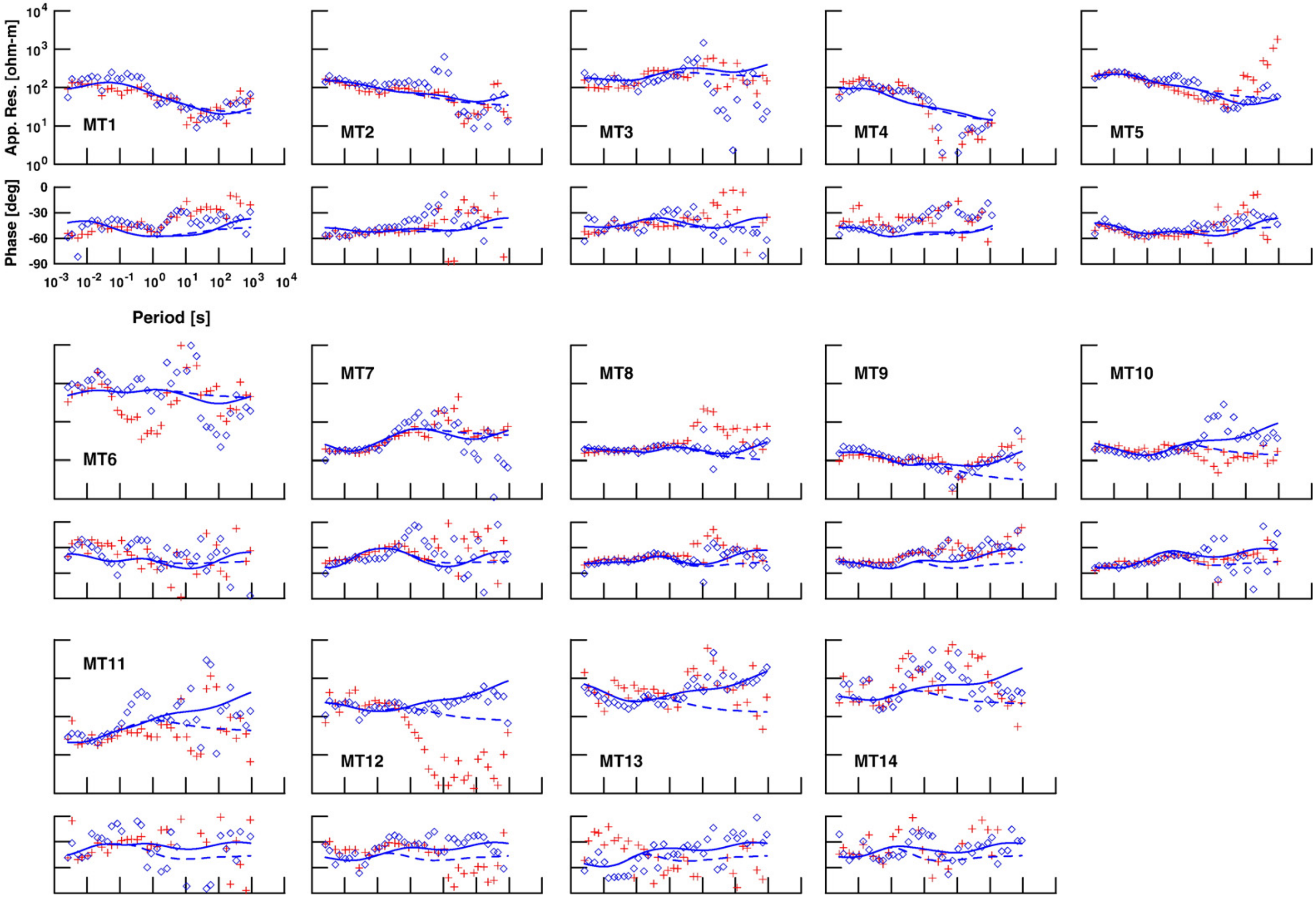

Fig. 2. Sounding curves at 14 MT sites used in this study. Sites from MT1 to MT14 are named in the order from the west to the east (Fig. 1). Crosses represent the TE mode responses and diamonds for the TM mode. For clarity uncertainties are not shown. Solid lines are the response functions from the best fitted model (Fig. 5) and dash lines from another competing model without C1 and R1 in Fig. 5. The plotting scale at every site is the same and only shows for MT1.

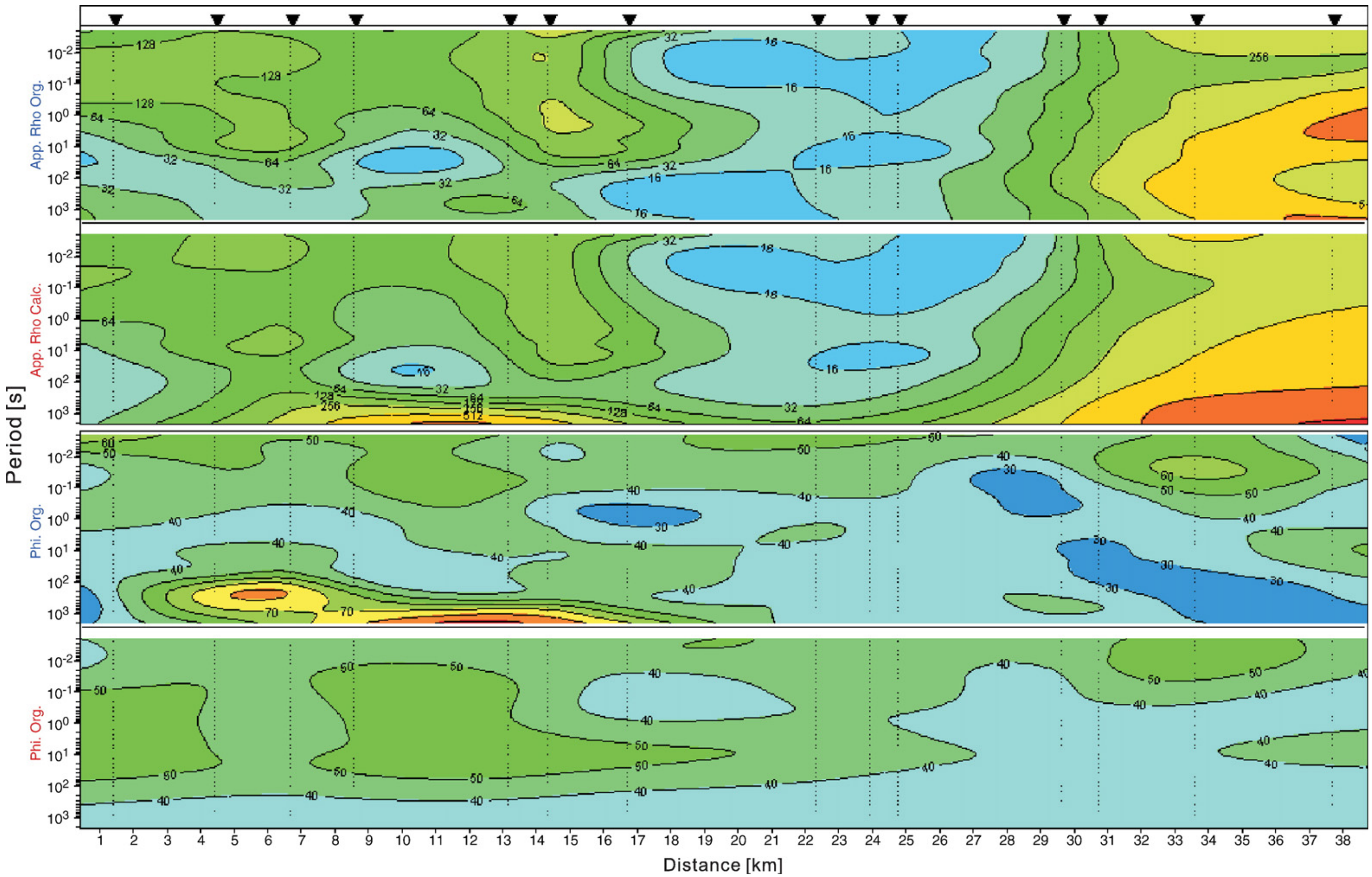

Fig. 3. Pseudosections for (A) observed apparent resistivity of TM mode, (B) calculated apparent resistivity of TM mode from the 2D model shown in Fig. 5, (C) observed phase of TM mode, and (D) calculated phase of TM mode from the 2D model shown in Fig. 5. Dots show the sampling period points of MT response at each site.

predicted resistivity (Fig. 3B) and phase (Fig. 3D) pseudosections of TM mode from the best fitted 2D model are also shown.

3. Regional electrical strike for MT data

For two-dimensional modeling, we need first to establish a regional strike direction for our MT dataset. Several lines of evidence (e.g. Ho, 1986; Rau and Wu, 1995) suggest that within the study area structural variations along the north–south direction are small enough to justify a 2D interpretation. Geologically, as shown in Fig. 1, three major geological units, Coastal Plains, Western Foothills and Hsuehshan Range, are all aligned with the N–S trends, as well as many stratigraphic formations and faults including the Chelungpu thrust (Ho, 1986). In addition, seismic wave tomography (Rau and Wu, 1995) also reveals that subsurface structures in middle Taiwan vary mostly along the east–west direction instead of the N–S.

In the context of MT methodology, the strikes computed from MT data itself (Fig. 4) at most frequency bands for each site are consistent with the north–south direction. Shown in Fig. 4 is the regional strike calculated from Groom and Bailey's decomposition technique (Groom and Bailey, 1989) for our MT dataset. In the sophisticated MT data analyses, it is often assumed that the structure is approximated by a three-dimensional local anomaly superposed on a regional two-dimensional structure. Then the technique of MT tensor decomposition (Groom and Bailey, 1989) could be applicable to extract the regional 2D strike direction. According to the methodology of Groom et al. (1993) an electrical strike of 90° along the E–W direction (Fig. 4), which also indicates another perpendicular direction of the N–S due to the mathematical operation of tensor rotation, was found to be optimal for doing 2D inversion. With the regional strike of the N–S direction the resulting shear and twist parameters of tensor decomposition model are in general frequency-independent for the shorter and longer period bands at all sites, indicating the validity of 2D parameterization for our MT dataset. Thus we have chosen a strike direction along the N–S direction for the following 2D inversion.

4. Two-dimensional inversion of MT data

A smooth inversion routine using a regularized inverse algorithm minimizes the sum of the chi-squared measure of data misfit and the squared norm of the Laplacian of the model function (Mackie et al., 1997). The inversion algorithm would determine the static shift parameters at each site, accompanying with solving for the subsurface resistivity structures. To prevent the inversion from being dominated by those data with unrealistically small variances, particularly in the high band data, a noise floor of 5% in the complex impedance was used. The starting model for inversion was a homogeneous half-space model with a resistivity of 100 Ω-meters. No topography was included in the

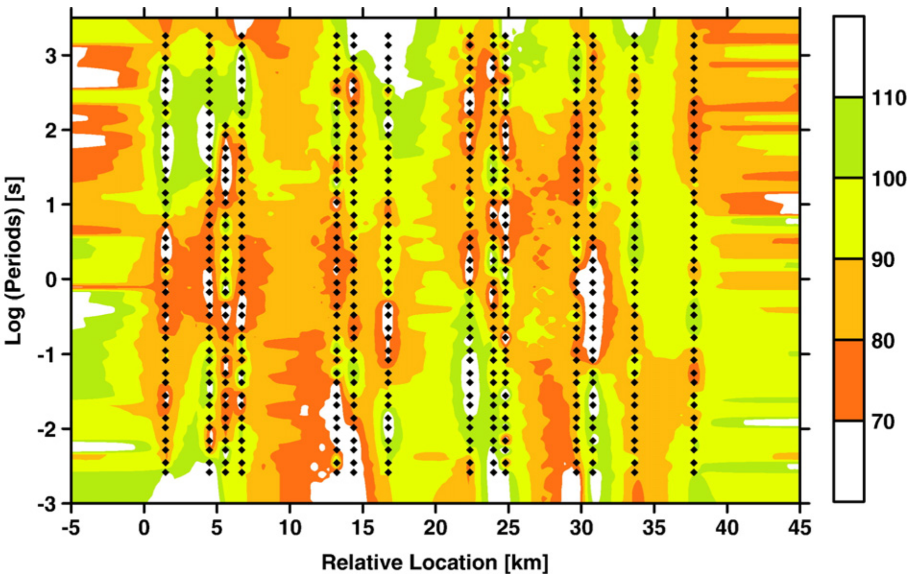

Fig. 4. Regional strikes calculated from MT tensor decomposition technique for each period at each site. For most period bands and MT sites an strike of around 90° (from light orange to yellow) is obtained, which indicates an electrical strike along the E–W or N–S direction.

inversion since the relief for all MT sites, from the elevation of 60 m to 370 m, is relatively flat.

There are many inverse strategies proposed to recover the subsurface structures using different polarizations of MT data. In general, the TM data are emphasized in the 2D inversion because experiments demonstrate that they are more insensitive to 3D effects (e.g. Wannamaker et al., 1991). For our MT dataset, while joint TM and TE modes inversions resulted in models with RMS errors of about 6.0, with most of those misfits occurring in the long periods TE data, inversions of only the TM mode data (Fig. 5) were able to fit the data to a reduced RMS of 3.3. A higher value of RMS is necessary in order to obtain the minimum structure model. A less RMS can be obtained after a few more iterations. However, the norm of the model increases significantly when the data is fitted better. Most features of those two models from joint TE/TM and TM only inversions are the same as each other, except for that the conductive zones appeared sharper and clearer in the former model than the latter.

Considering that the misfit of TE data is high as described above and that data in the TE mode might be distorted sensitively by 3D heterogeneity (Fig. 2), we focus primarily the geological interpretation on the inverted 2D model from TM data only. Despite the mismatch for the long period (>100 s) phase data at four sites in the west, the best fitted model predicts well the overall observed TM data, as it can be seen from Fig. 3. Thus, TM mode in our Chi-Chi MT dataset seems to be much less influenced by anomalous 3D local bodies.

We reproduce the geological cross-section shown in Fig. 3 of Kao and Chen (2000) to superpose our electrical model for understanding seismogenic structures. In the shallow, above the depth of 4 km, the Chelungpu thrust is marked by a significant resistivity contrast with the green, conductive hanging wall and the blue, resistive footwall (Fig. 5). The geometry of this contrast is highly coincident with the fault plane determined by the seismological data. Such resistivity contrast should resulted from the variation in lithostratigraphical units from

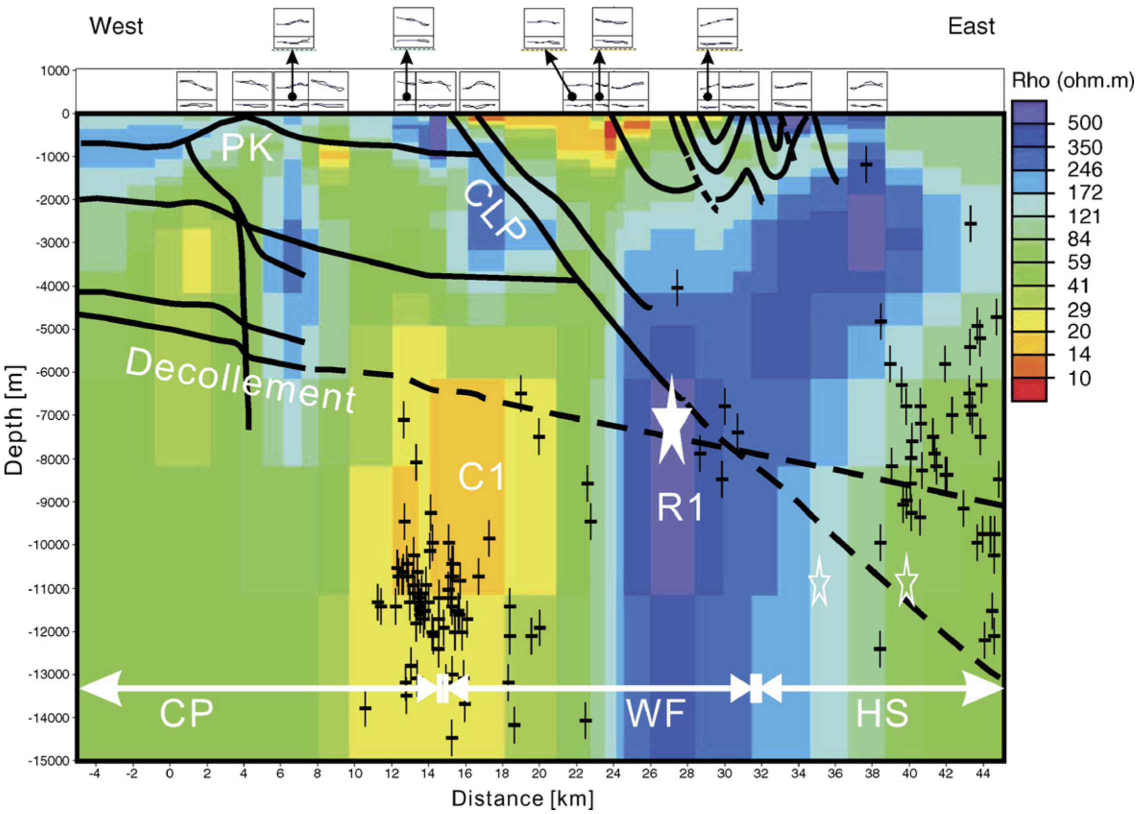

Fig. 5. Resistivity model from TM mode inversion superposed by the geological cross-section redrawn from Kao and Chen (2000). MT site locations are indicated by the small figures of apparent resistivity and phase curves (blue = calculated; black = observed). Those MT responses at five sites are redrawn above for their completeness. Solid star represents the Chi-Chi mainshock. Open stars and crosses denote two major aftershocks and a group of aftershocks occurred in the middle segment of Chelungpu fault, respectively. C1 = Conductive zone; R1 = Resistive zone. HS = Hsuehshan Range; WF = Western Foothills; CP = Coastal Plains; CLP = Chelungpu thrust; PK = Pakuashan anticline.

Pleistocene gravel (Toukoshan formation) to Pliocene shale and sandstone (Chinshui and Cholan formations). A significant high resistive zone (R1) located at the hypocenter is required to fit the upwards of the MT apparent resistivities for the long period bands at five sites to the east (see Fig. 2 and insets in the Fig. 5). Beside this resistive hypocentral area this model displays a definite electrical conductor (C1), indicating crustal fluids. Additionally, in the Coastal Plains, an important feature beneath the Pakuashan anticline is a high-angle normal fault (Fig. 5) also characterized as a distinct resistivity change in the electrical model.

Because C1 and R1 are two important features in our electrical model from MT, which are related to the source area of the Chi-Chi mainshock, we further carry out a sensitivity check to them. We can simply *mute* the C1 and R1 from our electrical model shown in Fig. 5 and re-calculate the MT responses for comparing with the observed sounding curves. We have shown new MT responses of an electrical model without C1 and R1 in Fig. 2 (dash lines). Obviously the electrical model without C1 and R1 fails to fit satisfactorily the observations, particularly for the data in the low frequency bands for several MT sites in the east.

5. Spatial correlation between crustal electrical conductors and aftershocks

In this section we will concentrate our focus on the interpretation of the electrical structures C1 and R1 around the source area, which were revealed by our MT analysis. There is no evidence to conclude that the hypocentral area is electrically resistive *before* the Chi-Chi earthquake; all the MT soundings were collected after the mainshock. Such statement is quite important for the concept of postseismic pore pressure adjustment. Since both C1 and R1 around the source area are almost located beneath the Miocene or Palaeogene decollement (Suppe, 1980), it should be not possible to possess such a large contrast in resistivity. It turns out that the Chi-Chi earthquake probably induces these electrical conductive and resistive materials.

Porosity of less than 1% is required for the common resistivity of ~100 Ω-meters for the materials at the depth of hypocenter. It is noted under such small starting porosity in crust even few compression in porosity would raise one to two orders of magnitude in the increase of resistivity (Hyndman et al., 1993). A straightforward scenario, following the calculated volumetric strain fields induced from the Chi-Chi earthquake (Lee et al., submitted for publication), is that the compact volumetric strains reduce porosity and enhance resistivity in the source area of the Chi-Chi earthquake. Coseismic dilatational strain causes initial pore pressure drops beside the hypocenter and then subsequent rise of pore pressure, due to overpressure expulsion of crustal fluids from the compressional zone of the hypocenter, could weaken the rock and lead to mechanic failures. A striking spatial correlation between the predicted dilatational zones and occurrence of the Chi-Chi aftershocks provides direct evidence (Lee et al., submitted for publication). Fractured rocks with deep-crustal fluids enhance the interconnectivity of pore spaces and reduce the resistivity in the C1 zone. Thus, we may also find the striking spatial correlation between the locations of aftershocks and C1 conductors (Fig. 5). A broad, rather than a ‘planar trending’, group of aftershocks residing within dilatational zones more likely reflects strong influence from crustal fluid flow (Lee et al., submitted for publication).

6. Discussion and conclusion

While Ma et al. (2000) based on teleseismic waveform inversion, proposed that fluid pressurization may reduce the dynamic friction resulted in large amount of slip during the Chelungpu’s rupturing, our MT work presented here provides an indicator of crustal conductors for fluids participating in the source area of the Chi-Chi earthquake. The possible causes for deep-crustal conductors are related to the presence of conductive minerals, melt or fluids. One trivial interpretation for crustal electrical conductors is the metal deposits, which provide an electronic conducting path within the rock. The large-scaled mutual connectivity of deposits could, however, fail in a young orogenic belt such as Taiwan, where the active mountain-building processes probably destroyed the connections between conducting paths. Also there is no evidence of any abnormal heat flow around our study area (Ho, 1986). Abnormal geothermal gradient may cause good electrical conductors in the crust as depth increases to more than 10 km. However, the temperature elevation at the depth of 9 km beneath the Western foothills of Taiwan is only 300 °C more or less based on recent geothermal modeling (Lin, 2000). This temperature rise is not sufficient to produce a distinct high conductivity anomaly. The candidate of crustal conducting mechanism for C1 thus invokes crustal fluids of utilizing aqueous electrolytic conduction.

To our knowledge, so far, there is no any direct measurement that can detect the flow pattern of fluids in the deep crust. The geophysical techniques, like seismic tomography (e.g. Zhao et al., 1996; Chen et al., 2001) and MT (e.g. Gupta et al., 1996), are probably the available ways to image *indirectly* the signature of deep-crustal fluids. Very recently 3D velocity structure around the source area of the Chi-Chi earthquake was derived by means of seismic tomographic inversion in Chen et al. (2001). They have found a substantial change in Vp/Vs after the Chi-Chi earthquake that may reflect an outward shift of the fluid-filled fractured source region. Therefore, the scenario proposed in the previous section could be highly plausible based on two independent MT and seismic approaches.

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