

Sanyi-Puli conductivity anomaly in NW Taiwan and its implication for the tectonics of the 1999 Chi-Chi earthquake

Chien-chih Chen and Chow-son Chen

Institute of Geophysics, National Central University, Chung-li, Taiwan, ROC

Received 6 August 2001; revised 14 November 2001; accepted 24 January 2002; published 16 April 2002.

[1] Based on tensor decomposition technique, we have analyzed the dimensionality of magnetotelluric (MT) data and propose a 2-D electrical model characterized by a high conductive anomaly beneath Sanyi-Puli seismic zone, a distinct NW-SE trending linear seismic zone in the fold-thrust belt of NW Taiwan. Fluid pressurization indicated by the highly conductive anomaly may result in the active seismicity in Sanyi-Puli seismic zone and, particularly, may also induce the large slip associated with high static stress drop in the northern part of the fault rupture process for the 1999 Chi-Chi, Taiwan, earthquake. *INDEX TERMS:* 7230 Seismology: Seismicity and seismotectonics; 8045 Structural Geology: Role of fluids; 8100 Tectonophysics

1. Introduction

[2] The Mw 7.6 Chi-Chi earthquake on September 20, 1999 (early morning of September 21, local time) is the most powerful and devastating inland earthquake that had ever recorded in the seismological history in Taiwan. This event severely damaged central Taiwan near the small town of Chi-Chi and shocked the whole island. Afterwards a huge amount of investigations into this earthquake exhausted the small population of geoscientists in Taiwan, but excited their minds. The Chi-Chi earthquake produced an extensive surface rupture of about 80 km in length along Chelungpu thrust, which marks the eastern boundary of the foreland basin in the orogenic belt of Taiwan. Field investigations show that the Chelungpu thrust itself has bent toward the northeast and migrated toward the east hinterland (Figure 1). At its northern end, the surface rupture was truncated by Sanyi-Puli seismic zone, a distinct NW-SE trending linear seismic zone with a length of about 100 km and a width of 15 ~ 20 km in NW Taiwan. Sanyi-Puli seismic zone, as a free boundary of Chelungpu thrusting, probably controls the morphological bending at the northern end of Chelungpu thrust (J.C. Lee, personal communication, 2001).

[3] MT soundings across Sanyi-Puli seismic zone, as part of an integrated project of seismotectonic investigations in NW Taiwan, had been conducted before the Chi-Chi earthquake during 1998 and 1999. Sanyi-Puli conductivity anomaly (SPCA) in a preliminary 1-D interpretation of MT data was reported previously [Chen and Chen, 2000] and a dehydration triggering mechanism was proposed to explain the abundant seismicity in this area. It should be noticed that the previous 1-D electrical model based on Bostick inversion of determinant MT responses gives a good qualitative result, however, the resolution in depth could be quantitatively poor [Jones *et al.*, 1992]. Full interpretation of MT data requires a detailed analysis of possible distortions in MT data combined with at least a 2-D modeling/inversion. One of the major objectives in this paper is to implement a 2-D analysis of Sanyi-Puli MT dataset and, consequently, to examine the previous electrical model. An interesting impli-

cation for the rupture dynamics of Chi-Chi earthquake will be given in the discussion then.

2. Magnetotelluric Data Analysis

[4] Eight MT soundings (Figure 1) across Sanyi-Puli seismic zone were recorded with a real-time MT V5-16 system (Phoenix Geophysics Ltd., Canada) over the period range between 0.0026 and 1820 seconds. A robust routine had been implemented to process the MT time-series data and to reduce the variances of the off-diagonal MT impedance tensor. More details about the principles and data processing for MT method could be found in the literatures [e.g. Jones, 1992]. Apparent resistivity and phase curves had been published in our previous paper [Chen and Chen, 2000].

[5] Before modeling the results of MT soundings one must determine if the structure is significantly three-dimensionality within the errors of the data, and to what extent the 3-D may affect the validity of 1-D or 2-D models of the MT responses. 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. The technique of MT tensor decomposition [Groom and Bailey, 1989] could be applicable to extract the regional 2-D strike direction. The regional electrical strike directions were estimated from Sanyi-Puli MT dataset using simultaneously electric and magnetic galvanic distortion tensor decomposition method [Chave and Smith, 1994]. According to the methodology of Groom *et al.* [1993], an electrical strike of N30°W/N60°E was found to be optimal in the following 2D inversion for this dataset. With the regional strike of N30°W/N60°E 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. When constraining the regional strike to other directions, the decomposition parameters vary substantially with frequency and thus the decomposition model is inappropriate to describe the behavior of MT data. There might be another strike direction suitable for the sites 88, 89 and 90. However, based on the chi-square test, N30°W/N60°E is acceptable to be the strike direction along the entire profile.

[6] Both TM (currents along N60°E) and TE (currents along N30°W) modes apparent resistivities and phases were inverted for 2-D electric models accompanying with the static shift parameters on a logarithmic scale by the reduced basis Occam's inversion algorithm [Siripunvaraporn and Egbert, 2000]. The static shift parameters estimated by the inversion suggest that the severest distortion with a multiplicative factor of about 1.2 occurred in the apparent resistivity curve of TE mode at site 90. Other static shift factors clustered around -0.5 ~ 0.5 for both modes at all sites.

[7] Different initial models, one with a homogeneous half-space of 100 ohm-m and others with a layered structure, were examined during the inversions to test the robustness of the obtained models. All the models obtained exhibit a common feature of the midcrustal conductor. Shown in Figure 2a is the best-fitting one among these similar subsurface resistivity models.

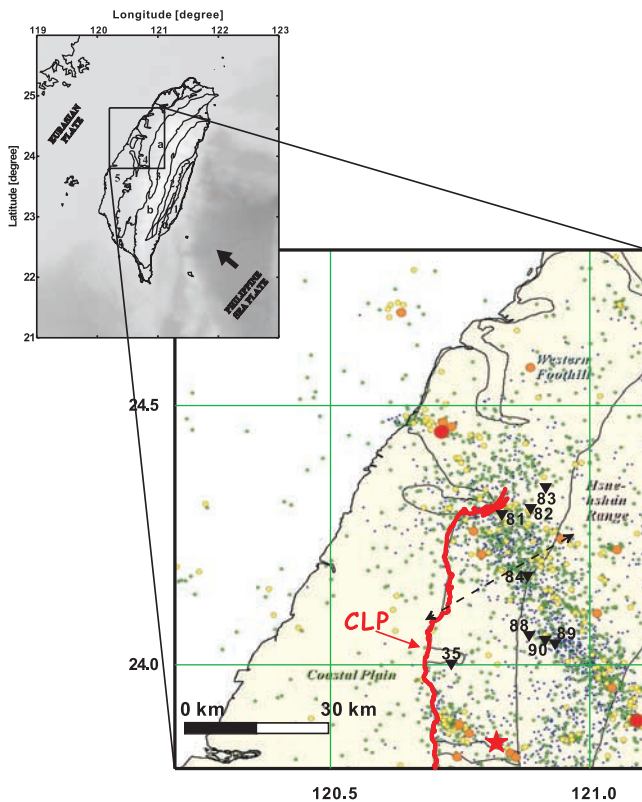


Figure 1

Figure 1. Map of the Sanyi-Puli seismic zone showing locations of MT soundings (inverse triangles) and the epicenter of the 1999 Chi-Chi earthquake (star). The dashed line of N60°E with end-arrows denotes MT 2-D profile; all the MT soundings are projected onto this profile. Epicenters of earthquakes (solid color circles) with $M_L < 5.3$ occurred between 1991 and 1997 delineate a distinct NW-SE trending linearity. CLP = Chelungpu thrust. On the left-upper inset map of the tectonic and geological structure of Taiwan are: (1) Coastal Range; (2) eastern Central Range; (3) western Central Range: (a) Hsuehshan Range and (b) Backbone Range; (4) Western Foothill; (5) Coastal Plain. Thick arrow indicates the relative direction of plate motion.

Its overall RMS misfit is about 2.9 with assuming the error floor of 5% in impedance. A higher value of the misfit was necessary in order to obtain the minimum structure model [Siripunvaraporn and Egbert, 2000]. A better misfit could be obtained after a few more iterations. However, the norm of the model increased significantly when the data was fit better. The decomposed observations of phase data and the predicted phases for two modes are shown in Figure 2b. The major behaviors of TE apparent resistivity [see Figure 4 in Chen and Chen, 2000] and phase data could be modeled satisfactorily along the entire profile. Comparing to that, in the eastern part of the profile there is a significant discrepancy between the observations and predictions for TM phases in the period range of 1 ~ 100 s, but not for TM apparent resistivities. We attribute this discrepancy to two possibilities: either the failure of tensor decomposition or the anisotropy in the middle crust.

[8] It is interesting that strong 3-D effects probably result in the misfit of TM phases. Some experimental and numerical tests suggest that TE mode is more affected by 3-D structures, rather than TM mode [e.g. Wannamaker et al., 1991]. Considering the modeling results of Sanyi-Puli dataset and BC87 dataset [Jones et al., 1993; Chave and Jones, 1997] as well, this issue is still

under debating. Strong 3-D effects could cause sites 88, 89 and 90 to fail in implementing the tensor decomposition technique. According to the methodology of Groom et al. [1993], there is another candidate of the regional 2-D strike for these sites, i.e. N20°E. This strike direction is approximately parallel with the trend of Hsuehshan Range. On the other hand, Jones et al. [1993] introduced a layer with the different resistivities along two directions of the polarizations into their 2-D modeling. Such an anisotropy produces the parallel phase responses in two modes, and suggests making the above discrepant fit of TM phases in Sanyi-Puli MT dataset. As shown in Figure 2b both modes of the observed phases possess the parallel values lower than the predictions in the eastern part of MT profile.

[9] The significant feature of the inverted model shown in Figure 2a is the midcrustal conductor at the depth of 13 ~ 20 km with a resistivity less than 30 ohm-m beneath the Sanyi-Puli seismic zone. Despite the modeling misfit as discussed above Sanyi-Puli MT dataset are unequivocal about the existence of the high electrical conductivity along N30°W, a direction similar to the trend of Sanyi-Puli seismic zone. While both the previous 1-D model [Chen and Chen, 2000] and the 2-D model presented here confirm the existence of SPCA, the latter provides a clear image with a better resolution in depth. On the contrary there is little conclusion about whether the conductor becomes shallower in the

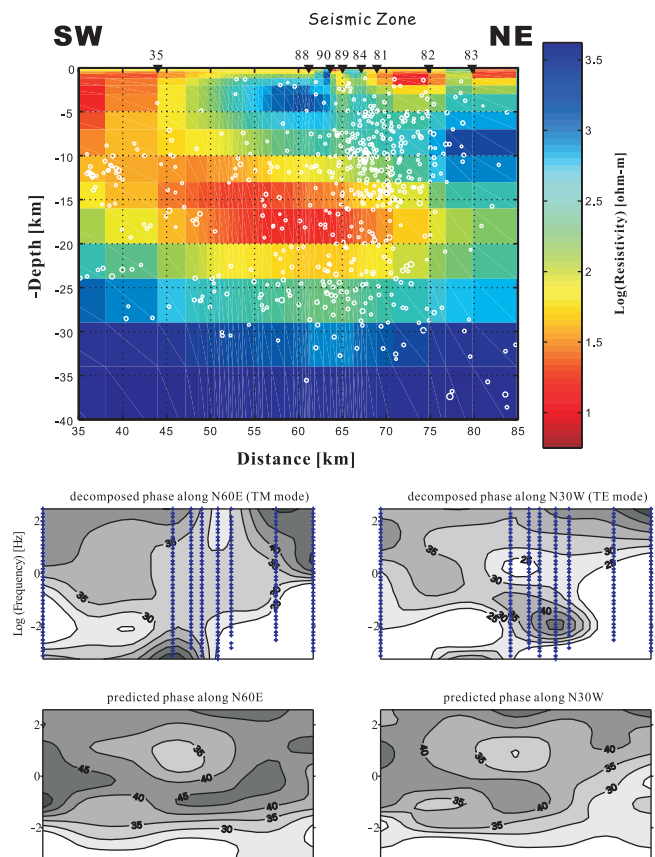


Figure 2

Figure 2. (a) Upper panel: inverted 2D model of the Sanyi-Puli MT dataset. This model extends 115 km and 8 MT stations are centrally located. Hypocenters of earthquakes (open circles) occurred in 1997 are also projected onto this profile. (b) Lower panel: decomposed phase data and predictions by the 2D model in (a). The unit of contour lines is in degree. Pluses on the upper two plots are the frequency-sampling points.

southwestern part of the profile, because of the two sparse MT soundings 88 and 35.

3. Discussion and Implication for the Tectonics of the 1999 Chi-Chi Earthquake

[10] For the Sanyi-Puli seismic zone, there are two seismogenic layers which occur mainly at depth ranges around 5 ~ 13 km and 20 ~ 33 km respectively beneath the Western Foothills [Rau *et al.*, 1998]. Many issues concerned with the dehydration mechanism triggering the active seismicity in this area are not possible to be addressed in the previous phase without the depth resolution quantitatively and precisely [Chen and Chen, 2000]. Whether the depth of SPCA is deeper than the upper seismogenic layer beneath this seismic zone becomes the key that should be resolved in detail. Comparable with the 2-D electrical model of Figure 2a, it is very clear that SPCA is exactly located at the base of the upper seismogenic layer. In this case SPCA indicates a brittle-ductile transition of the middle crust filled with high-pressure fluids.

[11] Fluids in the deep crust migrate very rapidly upwards and accumulate around the brittle-ductile transition [Bailey, 1990]. The rapid evolution of porosity allows the fluid to transport below this transition, however, in the cooler crust above this transition such a mechanism weakens immediately. As a consequence, a horizontally extensive reservoir with high horizontal permeability develops around the brittle-ductile transition and reduces the resistivities of the rocks. An anisotropic conductive layer might form due to the growing of the connected fluids along some preferred directions. Whether fluids keep penetrating into the crust above the brittle-ductile transition depends on the permeability of the rock above this level. It is plausible that the less permeability above the transition makes the upward infiltration slow down, rather than cease. Continuing upward fluid infiltration then results in the elevated pore pressures above this level [Bailey, 1990], and the following fractures and frequently seismic events [Ague *et al.*, 1998]. Abnormal pore-fluid pressures existing below about 5 km in NW Taiwan have been reported by Suppe and Wittke [1977] but the bottoms of which remain suspect and unknown.

[12] Rau *et al.* [1998] proposed a lithospheric-scale model that is characterized by a transition from a thrust regime in the Central Range to an escape regime toward the Western Foothills in the foreland belt of NW Taiwan. They suggested that a localizing shear stress concentration provoked by the tectonic escape process in the region could explain the mechanism of the Sanyi-Puli seismic zone. Although their model describes satisfactorily the mechanical behavior in the Taiwan foreland belt, the electrical structure presented here raises the important possibility that metamorphic dehydration may itself be one of the inducements causing the Sanyi-Puli seismic zone. Besides, existence of a highly electrical conductive fluid-filled zone would also enhance stress concentration in the upper brittle part of the crust leading mechanical failure [Gupta *et al.*, 1996].

[13] Several lines of evidence suggest that high-pressure fluids in fault zones may play a critical role in controlling the rupture dynamics of earthquakes [e.g. Zhao *et al.*, 1996; Gudmundsson, 1999]. The slip distribution of the Chi-Chi earthquake determined from the teleseismic waveform inversion [Ma *et al.*, 2000] shows that the maximum slip within the fault zone is about 8 m located at about 45 km to the north of epicenter, very close to the Sanyi-Puli seismic zone. The static stress drop in the large slip region is of 11 MPa, which is much higher than the average one of 1.1 MPa for this earthquake. Consequently Ma *et al.* [2000] suggested that melting/fluid pressurization may reduce the dynamic friction resulted in the large amount of slip. High conductivity in the crust could be induced by many causes, including both the presence of melting and fluid. Although there is no data available to rule out the melting hypothesis yet it is unnecessary when the fluids pre-

exist beneath the Sanyi-Puli seismic zone, based on Occam's razor. We thus suggest that fluid pressurization needs to be taken into account when modeling the rupture dynamics of Chi-Chi earthquake at the northern end.

[14] **Acknowledgments.** This manuscript is greatly improved by Dr. S. J. Mackwell and two anonymous reviewers. Drs. A. D. Chave, R. L. Mackie and W. Siripunvaraporn are especially thanked to provide the source codes for MT tensor decomposition and 2-D inversion. The authors are indebted to Drs. J. Ledo, K. F. Ma, J. Parker, M. Unsworth, and R. Van der Voo for useful suggestions in an early manuscript. Thanks are also extended to T. L. Tseng and M. W. Huang for plotting these figures. This work was supported by a research grant (NSC 90-2116-M-008-007) from National Sciences Council, ROC.

References

- Ague, J. J., J. Park, and D. M. Rye, Regional metamorphic dehydration and seismic hazard, *Geophys. Res. Letts.*, 25, 4221–4224, 1998.
- Bailey, R. C., Trapping of aqueous fluids in the deep crust, *Geophys. Res. Letts.*, 17, 1129–1132, 1990.
- Chave, A. D., and A. G. Jones, Electric and magnetic field galvanic distortion decomposition of BC87 data, *J. Geomag. Geoelectr.*, 49, 767–789, 1997.
- Chave, A. D., and J. T. Smith, On electric and magnetic galvanic distortion tensor decompositions, *J. Geophys. Res.*, 99, 4669–4682, 1994.
- Chen, C. C., and C. S. Chen, Preliminary report on the Sanyi-Puli seismic zone conductivity anomaly and its correlation with velocity structure and seismicity in the Northwestern Taiwan, *Earth Planets Space*, 52, 377–381, 2000.
- Groom, R. W., and R. C. Bailey, Decomposition of magnetotelluric impedance tensor in the presence of local three-dimensional galvanic distortion, *J. Geophys. Res.*, 94, 1913–1925, 1989.
- Groom, R. W., R. D. Kurtz, A. G. Jones, and D. E. Boerner, A quantitative methodology for determining the dimensionality of conductivity structure and the extraction of regional impedance responses from magnetotelluric data, *Geophys. J. Int.*, 115, 1095–1118, 1993.
- Gudmundsson, A., Fluid overpressure and stress drop in fault zones, *Geophys. Res. Letts.*, 26, 115–118, 1999.
- Gupta, H. K., S. V. S. Sarma, T. Harinarayana, and G. Virupakshi, Fluids below the hypocentral region of Latur earthquake, India: geophysical indicators, *Geophys. Res. Letts.*, 23, 1569–1572, 1996.
- Jones, A. G., Electrical conductivity of the continental lower crust, in *Continental lower crust*, edited by D. M. Fountain, R. J. Arculus, and R. W. Kay, Elsevier, New York, 1992.
- Jones, A. G., D. I. Gough, R. D. Kurtz, J. M. DeLaurier, D. E. Boerner, J. A. Craven, R. G. Ellis, and G. W. McNeice, Electromagnetic images of regional structure in the southern Canadian cordillera, *Geophys. Res. Letts.*, 12, 2373–2376, 1992.
- Jones, A. G., R. W. Groom, and R. D. Kurtz, Decomposition and modelling of the BC87 dataset, *J. Geomag. Geoelectr.*, 45, 1127–1150, 1993.
- Ma, K. F., T. R. A. Song, S. J. Lee, and H. I. Wu, Spatial slip distribution of the September 20, 1999, Chi-Chi, Taiwan, Earthquake (Mw 7.6) — inverted from teleseismic data, *Geophys. Res. Letts.*, 27, 3417–3420, 2000.
- Rau, R. J., J. C. Lee, H. Kao, and H. T. Chu, Transition from convergence to escape: inferences from seismic tomography, seismicity, and focal mechanisms in the foreland belt of central-western Taiwan, submitted to *J. Geophys. Res.*, 1998.
- Siripunvaraporn, W., and G. Egbert, An efficient data-subspace inversion for 2-D magnetotelluric data, *Geophysics*, 65, 791–803, 2000.
- Suppe, J., and J. H. Wittke, Abnormal pore-fluid pressures in relation to stratigraphy and structure in the active fold-and-thrust belt of northwestern Taiwan, *Petrol. Geol. Taiwan*, 14, 11–24, 1977.
- Wannamaker, P. E., P. M. Wright, Z. X. Zhou, X. B. Li, and J. X. Zhao, Magnetotelluric transect of Long Valley caldera: resistivity cross-section, structural implications, and the limits of a 2-D analysis, *Geophysics*, 56, 926–940, 1991.
- Zhao, D., H. Kanamori, H. Negishi, and D. Wiens, Tomography of the source area of the 1995 Kobe earthquake: evidence for fluids at the hypocenter?, *Science*, 274, 1891–1894, 1996.