The Possible Causes of the Crustal Low Resistive Zone for the Western Foothills, Taiwan

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ABSTRACT

This study attempts to discuss the possible causes of the crustal low resistive zone based on the magnetotelluric observations in the Western Foothills, Taiwan. The depth and resistivity of this low resistive zone (LRZ) have the values, on the average, of 9 km and 30 ohm-meters. According to the independently geological data, the possible causes of the LRZ are related to the high CO_2 activity in Taiwan and the dehydration reactions. The existence of a significant amount of HCO_3^- in crustal fluid would produce a consequent impact on resistivity.

(Key words: Magnetotelluric method, Electrical structure, Dehydration, Carbon dioxide, Western foothills)

1. INTRODUCTION

The Island of Taiwan is located in the active boundary between the Philippine Sea plate and the Eurasian plate. The relative plate velocity between the Philippine Sea plate and the Eurasian plate is at about 7.1 cm/yr and in the direction of about N50°W (Seno et al., 1993). The overall plate configuration in the vicinity of Taiwan is well defined by seismicity (Tsai, 1986). While the Philippine Sea plate is subducting northwestward from the Ryukyu Trench in the northeast of Taiwan, the Eurasian plate is subducting beneath the Philippine Sea plate along the Manila Trench in the south of Taiwan. Thus, Taiwan lies on the region in which the polarity of subduction changes. The rapid arc-continental collision is responsible for the complex geological setting and the rugged topography. The geology and tectonics of Taiwan can be found detailedly in the two book-length introductions of Ho (1982, 1986).

Due to the rarity of arc-continent collisions among the active orogenic belts in the world, Taiwan possesses tectonically a unique position. Because of its interest as a typical example of an active arc-continental collision, the structure of the active Taiwan mountain belt always catches the scientists' attentions. The readers are referred to the special issue on TECTONOPHYSICS (Lallemand and Tsien, 1997) for a recent progress of the studies on the active collision in Taiwan. Many geophysical investigations, including the analysis of seismicity (Wang et al., 1994), the gravity measurement (Yen, 1991), the seismic tomography

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(Rau and Wu, 1995), the seismic reflection profiling (Shih *et al.*, 1997) and, the most recently, the deep electrical sounding (Chen and Chen, 1998; Chen *et al.*, 1998), had been conducted to give a detail figure beneath Taiwan during the last decade. This study, which attempts to discuss the possible causes of the crustal low resistive zone based on the magnetotelluric observations, is a supplement for the previous paper by the authors (Chen and Chen, 1998).

2. THE LOW RESISTIVE ZONE FROM MAGNETOTELLURIC OBSERVATIONS

As an important property of the Earth's interior, the deep electric resistivity had been investigated actively by the magnetotelluric (MT) method in the Taiwan orogen during the last two years (Chen *et al.*, 1996, 1997; Chen and Chen, 1998; Chen *et al.*, 1998). The MT technique makes use of naturally-occurring electromagnetic (EM) wave fields as sources for exploring the deep electric resistivity structure (Vozoff, 1991). These EM waves propagate diffusively into the earth, and so the penetration depths of the signals increase with period and resistivity. A tensor MT survey has been carried out in the field. The measurements of EM fields were made using 5 components, including 2 orthogonal electric field components (Ex and Ey) and 3 magnetic field components (Hx, Hy and Hz), at a MT site. A remote reference by using 2 additional magnetic components (Rx and Ry) was used to suppress EM noise at some sites. The data were recorded by a real-time MT V5-16 system, Phoenix Geophysics Ltd. (Canada), with a capability of measuring the broad band EM signals ranging from 384 to 0.00055 Hz.

To account for the unpredictable natural changes in EM source field strength over time, the observed electric field is normalized by the orthogonal magnetic field at each frequency. The resulting quantity, e.g. $Zyx = Ey/Hx$, has units of ohms and is called the impedance of the earth. Practitioners of MT generally convert impedance values to apparent resistivity. Apparent resistivity vs. frequency usually resembles a smoothed version of the true resistivity over increasing depths below the measurement site. Another complementary to apparent resistivity is the phase of the impedance. More details about the principles and data processing for MT method can be found in the published literatures (e.g. Vozoff, 1972).

The important results from MT observations (Chen and Chen, 1998) have concluded that there exists a low resistive zone at the depths of 10-20 km beneath Taiwan. Beneath the Western Foothills, the depth and resistivity of this low resistive zone (LRZ) have the values, on the average, of 9 km and 30 ohm-meters. These values are significantly different from those beneath the Central Range, which are 20 km and 80 ohm-meters (Chen and Chen, 1998). Figure 1 shows the electrical models beneath two MT sites located on the Western Foothills. The solid and dashed lines represent the electrical models obtained respectively from sites TST and MLI (Chen and Chen, 1998). Here we consider the static shift effect in MT measurements. In its simplest form for data from either 1D or 2D earth models, this effect manifests itself as a shift of the apparent resistivities by a frequency independent multiplicative constant without affecting the phases. A 1D interpretation of the shifted apparent resistivity curve would lead to an erroneous model with both resistivities and depths of the layers have been shifted away from the true earth. As shown in Figure 1, the thin-dashed line is the affected model and the thick-dashed line is the recovered (suggested) model at site MLI. After shifting the model of
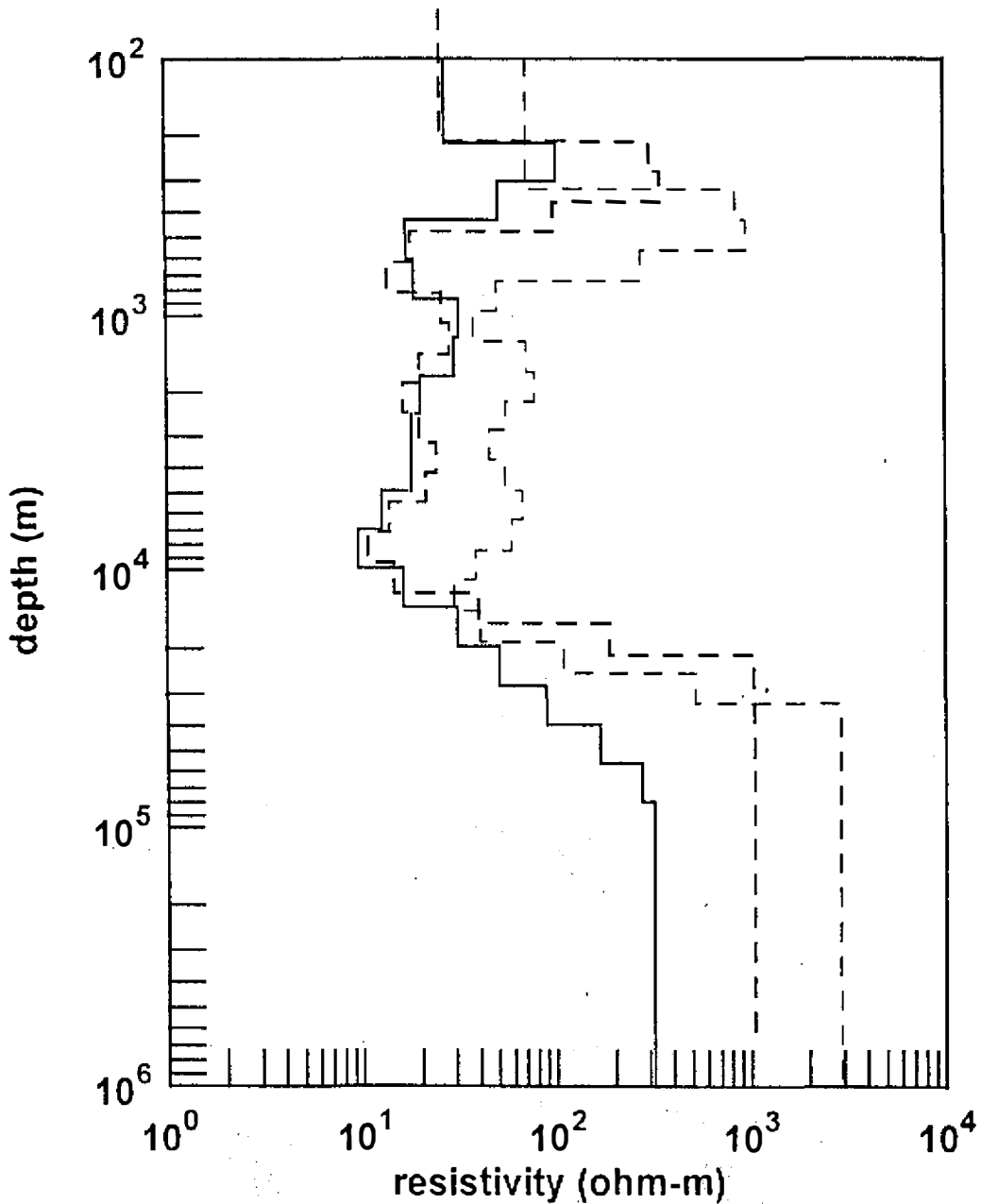
Fig. 1. The electrical models beneath two MT sites located on the Western Foot-
hills (after Chen and Chen, 1998). The solid and dashed lines represent
the electrical models obtained respectively from sites TST and MLI whose
locations are shown in Figure 2. The thin-dashed line is the affected model
and the thick-dashed line is the recovered model at site MLI.

MLI, a common LRZ, with a resistivity about 10 ohm-meters and a depth ranging from 7 to 10 km, appears at the two sites.

3. CAUSES OF THE LRZ

The resistivity is sensitive to the existence of small amounts of fluid, melt, or conductive minerals, and can vary over many orders of magnitude, e.g. from 0.01 ohm-m to 1,000,000 ohm-m (Jones, 1992). The actual resistivity of rock is usually controlled, not only by the matrix host rock resistivity itself, but also by the connection in the rock matrix of typically a fluid (ionic conduction) or solid (electronic conduction) phase. Thus, the bulk resistivity value reflects the pore fluid resistivity and the rock porosity, and is a function of temperature, pressure, and ion content of the fluid. Besides fluids, the resistivity of rock is also sensitive to the presence of conductive minerals, such as graphite, sulfide, and magnetite (Jones, 1992). Detailed interpretation of the electrical structure will require independent data from geology or from geophysics. This section is an attempt to interpret the possible causes of the above LRZ, according to the independently geological data (Chou *et al.*, 1989; Liou, 1981). Due to the two
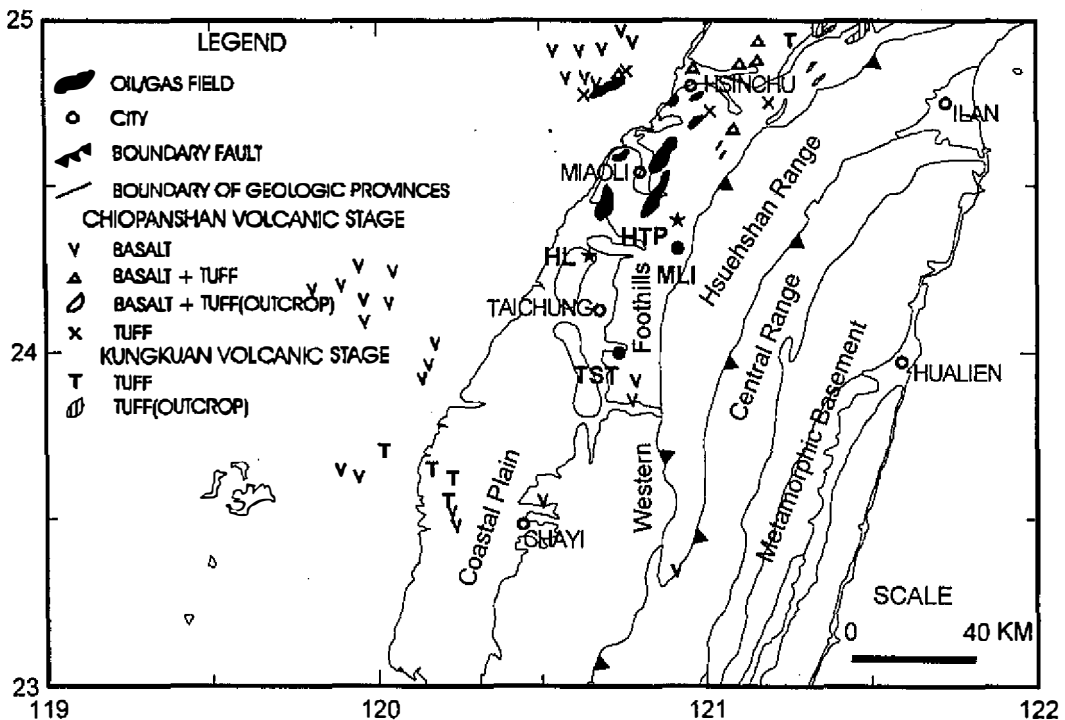

Fig. 2. The locations of the two MT sites, TST and MLI (solid circles), and two exploration wells, HTP and HL (stars). Included are also the volcanic rock distribution and the oil-gas fields in western Taiwan (after Chou *et al.*, 1989).

selected MT soundings and the available geological data are mainly concentrated on the Western Foothills (Figure 2), this attempt will be restricted in this area, in particularly the middle-western Taiwan.

The locations of the above two MT sites, i.e. TST and MLI, are shown in Figure 2. Also included in Fig. 2 are the volcanic rock distribution and the oil-gas fields in western Taiwan. A high content of CO_2 in natural gas produced in these oil-gas fields had been reported by Chou *et al.* (1989). The CO_2 is mainly trapped under the sealing Piling Shale to charge the reserviors of the Mushan Formation and the Wuchihshan Formation in the several onshore and offshore gas-oil fields. The evidence indicating high CO_2 activity in Taiwan includes not only the high CO_2 content of natural gases in the Western Foothills but also high CO_2 content of thermal waters in metamorphic and sedimental terranes, and high concentration of carbonate minerals in mafic and pelitic rocks of the Central Range and the Western Foothills (Liou, 1981).

CO_2 is excluded as a conductive candidate because it is an insulating liquid and a non-polar gas, and thus has little or no effect on electrical properties (Olheft, 1981). However, as a major dissolved component in aqueous fluids of the crust, CO_2 in aqueous solutions is, at upper and mid crustal temperatures, largely in the form of CO_2(aqueous) with a lesser amount of H_2CO_3 (Fein and Walther, 1987). In solution, two dissociation reactions can occur:

$$CO_{2(aq)} + H_2O \Leftrightarrow HCO_3^- + H^+$$

$$HCO_3^- \Leftrightarrow CO_3^{2-} + H^+$$
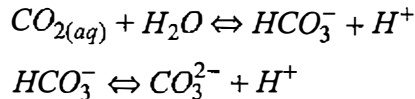
The existence of a significant amount of HCO_3^- in crustal fluid is probable, with a consequent impact on resistivity. In addition, the concentration of HCO_3^- is extremely sensitive to pH changes (Nesbitt, 1993). Thermal waters from the metamorphic and sedimental terranes in Taiwan are indeed characterized by pH values of 7-10 and high concentrations of $NaHCO_3$ and HCO_3^- (Liou, 1981).

What is the source of the aqueous fluids in the crust? It had been expected by Suppe (1981) that the dehydration reactions are taking place at lower temperature about 220°C at depth of 7 km in the Western Foothills due to the drop in fluid pressure-solid pressure ratio. Thus, the dehydration reactions may offer these fluids in the crust.

4. DISCUSSIONS AND CONCLUSIONS

The origin of the high content of CO_2 in natural gas is attributed to the deep foreign inorganic sources which are associated with the crust or mantle (Chou *et al.*, 1989). CO_2 migrated from the CO_2-pool derived by the magma from the mantle. Beneath the Western Foothills, the foreign deep CO_2 migrated upwards along the fractures and faults originated by igneous activity and orogeny. Therefore, the CO_2 was sealed under the Piling Shale to charge the reservoirs of the Mushan and Wuchihshan Formation.

Subsurface geologic reports, paleontological data and stratigraphic correlation studies of the 88 onshore and offshore exploration wells in the western Taiwan Basin were incorporated

by Shaw (1996). While the top for the Mushan Formation at HTP (Figure 2) is approximately at the depth of 2.5 km (Dr. M.T. Lu, pers. commun.), the evaluated depth at HL (Figure 2) is about 5.2 km (Figure3 in Shaw, 1996). **Not only** the strata were disturbed during the mountain building in Taiwan, **but** the Mushan Formation **thrust** upward in the Western Foothills (Suppe, 1981).

While the resistivity of the whole upper crust maintains the value below 50 ohm-m, a minimum value appears at the depth of about 8 km. A simplest explanation for the relatively low resistivity in the upper crust of the Western Foothills is the thick sediments presented there, which may contain water and/or other fluids (Dr. R.J. Rau, pers. commun.). What are the fluids made of? Should carbon dioxide be required to lower the resistivity? Should the resistivity of the whole upper crust be dominated by the CO_2-H_2O-salt solutions? In addition, should the layer with a minimum resistivity indicate the deep CO_2-pool as suggested by Chou *et al.* (1989)? More precise electrical structure of MT observations and other relevant data, such as conductivity studies of CO_2-H_2O-salt solutions at higher temperature, pressure and CO_2-salt concentrations, are needed to confirm our concept and to provide the physicochemical states beneath Taiwan.

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