Three–dimensional Magnetotelluric Characterization of the Guangdong Xinzhou Geothermal field (China)

Xiangyun Hu*, Shan Xu, Qi Han, Sijing Liu
Institute of Geophysics & Geomatics, China University of Geosciences, Wuhan, China
*Corresponding author: Email: xyhu@cug.edu.cn

Summary
Broadband magnetotelluric (MT) data and controlled source audio–frequency magnetotelluric (CSAMT) data were recorded from an array of measurements crossing Xinzhou geothermal field and its surrounding area. CSAMT measurements were conducted first with the aim of investigating the electrical discontinuities in order to sketch out shallow part of the geothermal reservoir. MT 3–D inversion are used to delineate a detailed resistivity structure and location of electrical discontinuities. A 3–D geological model is constructed to simulate the shape of hydrothermal reservoir, hot saline brine and alteration zone. The 3–D inversion results of MT data show the subsurface resistivity structure correlated to the distribution of geothermal reservoir (such as faults and fractured granite) and investigate mechanisms by which the high heat flux of Xinzhou geothermal field is transported to the surface. Power generation is feasible in this hydrothermal system.

Keywords: magnetotelluric, hydrothermal system, electrical conductivity, subsurface structure, 3–D modeling

1. Introduction
Guangdong is located on the southeast margin of Eurasian continent, which is one of the most active geothermal regions in China. Under the interaction of Pacific Plate, Philippine Plate and Indo–Australian Plate, this area has an outstanding level of geothermal resources, with many geothermal manifestations such as hot springs, fumaroles and hydrothermal alteration zones at the surface. Xinzhou geothermal field is one of the most active hydrothermal systems in Guangdong. Five wells (ZK1, ZK2, ZK3, ZK4, ZK5) with depth of 300 meters were drilled during 1983 to 1984, the temperature of which was above 85°C. Since then, hot spring in ZK3 (>95°C) keeps pouring out, as a result, the locals built a tower for water storage. However, geothermal energy is currently limited to depths of 300 meters. To maintain and increase this level of energy development in the long term, production from depth>1km is required where temperature may approach 200°C.

2. Experiment
Our team has conducted a serious of investigations in Yangjiang in recent years. In the first phase, Five CSAMT survey lines, in the operating frequency of 1Hz to 9600Hz, were conducted in the year 2012 around the well heads of the geothermal field. In the second phase, Broadband MT array (0.000 3–320Hz) were collected after CSAMT survey in the year 2013 extending from the west geothermal field to the east coastline: 42 sites spaced 10km and 40 more closely–spaced sites at ~5km intervals (red dot lines in Fig. 1.a).

The distance between the two profiles is 37km. Induction vectors are plotted according to convention of Parkinson [1]. Their real parts point to conductors in a 2–D setting, indicating the influence of seawater. For frequency=0.005 5 the impact of the conductive seawater of South China Sea is clear at all sites of the array (Fig. 1.b). In the third phase, a dense grid of 196 magnetotelluric sites with broadband has been acquired over the Xinzhou geothermal field and its surrounding area in 2015 summer (Fig. 1.c).

We calculate the phase tensor following the rule proposed by Caldwell [2] to analyze underlying characteristic for the 196 sites without any previous assumption. Phase tensor ellipse at T=1.33 s from this survey are shown in Figure 4 superimposed on xy and yx mode apparent resistivity map of the region respectively. The skew angle is filled in ellipse at every MT site, the southwest part of our research area has big absolute value, the reason may be that the intrusive see water from Beijing Harbor makes the conductivity distribution complicated. Fig. 4 also refers that in the middle of our research area where the MT sites are dense, the major axis of ellipse are E–W direction and converge to middle, here is the place around the Xinzhou hot spring. Another attractive characteristic is that some phase tensor points to the northeast which shows very high conductivity compared to other place. It is interesting and needs further discussion. Although the small value of skew angle is shown in the middle of Fig. 4, it is not necessarily a good indication of the nearness of the conductivity structure to 2–D. Much more reliable criteria for two–dimensionality are the constancy of the direction of the principal axes of the phase tensor with period and with location along strike.

3. 2D Inversion results
2–D inversion of CSAMT TM mode is used to outline the shallow part of geothermal reservoir (Fig. 2.a), using smooth inversion algorithm[3]. Error floors were set to 5% for the apparent resistivity and phase. All the five sections show a conductive zone from surface to the depth of 650–800m. The low–resistivity region is consistent with the location of thermal spring, which may suggest a shallow channel of hot water. Due to the geological setting, many faults of different trends and ages affect the geothermal reservoir. Clastic rock and breccia found in the core samples suggest the main structural element governing the hydrology and hydrogeology of this region is F9 fault which trends nearly NE and forms the conduits for fluids. As a result nearly all current thermal springs and anomalously thermal wells are distributed along the fault zone.

None–linear conjugate gradient algorithm[4] is employed in 2–D MT inversion for line 100 and line 200 (Fig. 2.b). The model achieved acceptable normalized root mean square (r.m.s) missfit 1.793. In general, 2–D MT model shows discontinuous low–resistivity (1~50Qm) of different size to the depth of 40km across both of the profiles, interpreted to be channels connecting the surface geothermal field to deeper conductive regions. A large resistive zone, which is visible from the middle of L100 profile to the east margin, probably indicates the ancient residual oceanic crust due to ancient subducting of...
Philippine Plate and Pacific Plate. Geochemical data shows a Na–Cl type of thermal water with mineralization >2.8g/L. As a consequence, thermal water probably has its origin from the sea.

---

**Figure 1:**

a) MT and CSAMT array in Xinzhou geothermal field. Red triangle is the location of Xinzhou geothermal field in China. Red dots show MT sites with interval of 10km; Red line denotes MT sites with space of 5km; Five CSAMT lines shown by blue dots, intersecting MT profile L100, were deployed in the rectangular area with dashed lines.

Boreholes are shown by five colored stars: green star – ZK1, black star – ZK2, yellow star – ZK3, blue star – ZK4, and red star – ZK5.

b) Real part of induction vector arrow for frequency 1.02Hz, 0.032Hz, 0.005 5Hz and 0.000 3Hz.

c) Elevation map of the study area, black dots present MT sites and red dot is the hot spring.

---

**Figure 2.**

a) CSAMT profiles and thermal wells. Hot well ZK4 is located 15m east from CSAMT line L4, near number 17 and 18 site; Three hot wells–ZK1, ZK2 and ZK3 are close to line L5, with distance 15m, 35m and 10m to the east respectively. ZK5 is near line L8, the distance from which is 40m.

b) 2−D resistivity inversion models of the two MT profiles, L100 and L200.

c) 3−D resistivity inversion models of the two MT profiles, L100 and L200.

---

**4. 3D inversion result**

To validate the main resistivity structures seen in the 2−D models, 3−D MT inversion algorithm ModEM\(^5\) was used to model the MT grid data, it has been used in many magnetotelluric prospecting\(^6−9\) because of the advantage of fast convergence and time saving. The input data used for inversions were the apparent resistivity and phase angle with 32 periods (0.001~100s) from 196 MT soundings at locations in Fig 1.c. The prefer inversion result (RMS reduced to 3.29 after 87 iterations) took the 1D layer model\(^10\) as the starting model with a fine mesh (86×84×50 cells) on it. The final 3D inversion result exhibits a panorama of the subsurface resistivity distribution in Fig. 2.b. For the convenience of description, we have identified some significant anomaly areas. At the surface (Fig. 3. a), the inversion result shows four obvious abnormalities, R1 and R2 are resistance bodies in the northwest and southeast respectively, R2 belongs to Cretaceous granite which is large−scale exposure in the southeast. The conductivity anomaly C1 and C2 is located in the southwest and northeast of our research area.

The regional hydrology survey displayed that underground hot water has a high salinity\(^11, 12\). Under this circumstance, C1 may result from seawater intrusion and depict the path how the sea water inflow the Xinzhou geothermal field. The composition of C2 is more complex and it basically disappears at the depth 3 000m in Fig. 3.b. Quaternary strata, consist of clay, leads to the low resistivity in C2 at shallow depth.
Depending on the depth to which C2 extends downwards and its intersection with geothermal field, we can believe that C2 also functions as water storage in terms of the good permeability of overlying strata. R1 becomes more and more obvious as the depth increases (Fig. 3.c and d), it is a huge complete Jurassic granite bedrock under geothermal field and may extends deeper but exceed our inversion range. R3 appears between 2 500m (Fig. 3.b) and 9 000m (Fig. 3.d), R2 and R3 may be a whole granite and intrude slopingly into stratum. R2, as a front end, is exposed and eroded on the surface, while R3 is still buried in the ground.

Figure 3. Depth slices of the inversion model at a) 0 m b) 3 000 m c) 6 000 m d) 9 000 m depth respectively. The red dots present the location of MT sites.

5. Conclusion

Models from MT and CSAMT inversion agree well with the tectonic features of Xinzhou geothermal field. In 2−D CSAMT inversion result, a conductive zone to depth of 800m extends through the five CSAMT profiles, consistent with the distribution of F9 fault in this area. In 2−D MT inversion result, discontinuous highly conductive anomaly of small scale, obtained at 10km depth, shows shallow fracture acting as conduits of thermal spring. Large−scale conductive permeability is visible at depth of 10km to 40km, possibly indicating deep faults transporting upwellung thermal fluids. Thermal water originates as sea waters, heated by deep circulation and moving westwards via fractures and faults into shallow aquifer. High−resistivity zone is revealed in both 2−D and 3−D models. One hypothesis is that this resistive zone suggests residual oceanic crust due to complex tectonic activities of Eurasian continent and Philippine plate. Mantle upwelling and underplating, revealed by moderate conductivity, can provide steady heat source. As a result, power generation is feasible in this hydrothermal system.

Acknowledgement

This work was performed with financial support from China Geological Survey project (1212011220014) and Natural Science Foundation of China (41630317).

References