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CONDUCTIVITY STRUCTURE OF CRUST AND UPPER MANTLE BENEATH THE NORTHERN TIBETAN PLATEAU: RESULTS OF SUPER-WIDE BAND MAGNETOTELLURIC SOUNDING

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Abstract To study the conductivity structure of crust and upper mantle as well as the thermal regime of lithosphere beneath the northern Tibetan Plateau, the project INDEPTH (III)-MT completed super-broadband magnetotelluric (MT) sounding along Deqing-Longweicuo (line 500) and Naqu-Germu (line 600) in northern and central Tibet in 1998 and 1999. The result shows that the conductivity structure of crust and upper mantle is quite different across the Kunlun Mountains. North to the mountains the crust and upper mantle is relatively highly resistive. South to the mountains, the conductivity structure of crust and upper mantle is of obvious stratification as described following. The upper crust is dominated by discontinuous high-resistivity bodies with intercalated low-resistivity anomalies. And the electric structure of the upper crust in NS direction looks like complicated with discontinuous and block-shaped features. Meanwhile the intermediate and lower crust are characterized by large-scale high conductivity anomalies, indicated by separated high-conductivity bodies of big sizes and differing shapes with resistivity less than 4Ωm. Beneath the Bangong-Nujiang and Jinshajiang River sutures, the high-conductivity bodies in the crust tend to extend toward the upper mantle, implying existence of a low-resistivity conduit between crust and mantle. Based on the observed electric structure of crust and mantle beneath the northern and central Tibetan Plateau, we infer that there are extensive partial melt and thermal fluids there like southern Tibet. Their origin is associated with thermal exchange between crust and mantle beneath the Bangong-Nujiang and Jinshajiang River sutures which occurred in their own conduits. The thermal exchange conduit below the Bangong-Nujiang River suture was formed earlier than that beneath the Jinshajiang River suture. Therefore the thermal activity of crust and mantle beneath the study area began from south and west, then spread toward north and east, leading to the current heat flow distribution in middle and northern Tibet which becomes larger from west to east and from south to north.

Key words INDEPTH-MT, Magnetotelluric sounding, High-conductivity body in crust, Thermal exchange between crust and mantle

1 INTRODUCTION

About 40∼50 millions years ago, the Indian continent collided with the Asian continent and began to underthrust beneath the Tibetan plate, leading to gradual uplift of the Tibetan Plateau. It involves an extremely complicated tectonic history of collision orogene. To explain the cause of the plateau formation, in 1924 Argand proposed that there is double-crust in Tibet[1]. The following several tens years have witnessed various kinds of hypotheses about the Tibetan Plateau, such as subduction[2], compression and thickening[2], and lateral extrusion[3]. They lack, however, sufficient supportive evidence or have differing contradictions. It becomes clear that the whole plateau, in particular the northern plateau, should be studied for understanding the evolution processes of the Tibetan Plateau. Knowledge of the tectonics and structure of crust and upper mantle

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beneath the northern plateau is critical to the studies of the relationship between the India and Asian continents after the plate collision as well as the dynamic mechanisms of formation and evolution of the plateau. But the early previous work were focused on the Himalayas and southern Tibet. Later some studies were made on the northern margin of the plateau. Deep geophysical exploration is little in northern Tibet.

Previous studies indicate that the Tibetan Plateau has a thickened crust which is thicker in the south and becomes thinner in the north[5], while the lithospheric thickness increases from south to north[6]. Data of heat flow and velocity structure show that in southern Tibet the crust is hot with low velocity and the mantle is cold with high velocity, and both are just contrary in northern Tibet[7]. Therefore it has been suggested that southern Tibet has hot crust and cold mantle, and northern Tibet has cold crust and hot mantle.

Nevertheless the relevant studies of recent years have yields different conclusions. It has been suggested that the Qiangtang area, which is located in middle Tibet, is characterized by thinner crust, low Pn velocity, lack of Sn velocity, and large-scale high-conductivity bodies which may extend downward to mantle, likely implying upwelling of hot mantle material produced local melt in crust[8,10∼13,20∼25]. The models to interpret this phenomenon claim that it is related with subduction-delamination of the Indian plate or compression-thickening-delamination of lithosphere of northern Tibet, both can cause lithospheric mantle convection-asthenospheric upwelling, leading to local melt in crust[10,11,26,27]. It is obvious that the interpretations above represent two differing dynamic models. To verify these models requires more precise geophysical observations and inversions as well as deep analysis and discussion.

This paper presents new study results based on the super-broadband magnetotelluric sounding data which were acquired in central and northern Tibet in 1998 and 1999 (project INDEPTH(III)-MT).

2 FIELD EXPERIMENTS

INDEPTH(III)-MT is part of the third stage of the project INDEPTH, which was a cooperative program of China University of Geosciences (Beijing), Washington University of US (Seattle), and Geological Survey of Canada. This project used modern advance super-broadband magnetotelluric (MT) technology to explore structure of crust and mantle in middle and northern Tibet. Its field experiments were made in two years.

2.1 Layout of Survey Lines

As shown in Fig. 1, INDEPTH(III)-MT has designed two survey lines in Tibet. One is the Deqing-Longwei line (line 500) finished in 1998 and the other is the Naqu-Germu line (line 600) ended in 1999. Because of large relief of topography and poor communication, the MT site spacing is not equal, and all less than 15km. The line 500 is about 380km long, along which 58 measurement sites were set, including 26 sites of long-period (LIMS), with average spacing 6∼7km. The line 600 is about 600km long with 43 sites, including 20 LIMS sites, and their average spacing is 13∼14km. To locate precisely, GPS was used to determine geographical coordinates of all sites. In general the site error is less than 100m.

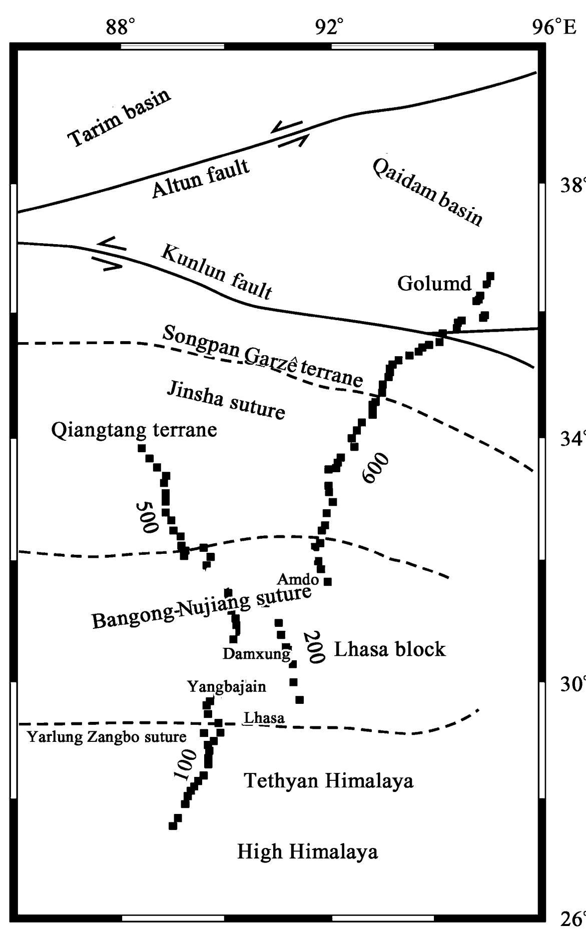

Fig. 1 Map showing INDEPTH-MT sites
Numbers indicate the name of each

2.2 Instrument and Equipment

In previous MT measurements of China, the lowest frequency of observed signal is usually 0.0005Hz, i.e. period 2000s. For the study of Tibet with a thick crust, it cannot reach the expected depth of exploration. Hence MT signal of periods as long as several tens thousands seconds should be collected. Besides, the Tibet region has very complicated deep and shallow structures produced by special tectonic evolution. To suppress distortion of shallow local structure and heterogeneous electricity, MT signal of frequency as high as millions Hz is also required. But at present the domestic MT instruments of any type have no such a wide band of frequency. Therefore we have chosen the MT system of local network type MT-24NS of EMI Co. of US, matched by the long-period intelligence MT system (LIMS). Currently this is the most advanced MT instrument. MT-24NS collects wide-band signal of $3.2\times10^2 \sim 4.6\times10^{-4}$Hz. And LIMS records long-period signal of $0.1\sim 3\times10^{-5}$Hz. At the same site, both the instruments were used for measurements. Linking their data yielded super-broadband MT records.

2.3 Measurement Method

As mentioned above, to collect MT data on super-broadband it is necessary to combine the broadband MT-24NS with the long-period LIMS system. It means that the two systems are used for measurements at the same site and their records are linked to yield MT data of very wide frequency band. When employing this measurement method, it is required that the results of the two systems can be compared each other at the same frequency point, implying that the data quality must be very high. Hence site selection, station layout, and data collection must be carried out strictly following the relevant technical codes.

Since the dominate trends of tectonics in Tibet are nearly east-west, we defined the X axis pointing to north and Y axis to east. When using MT-24NS and LIMS simultaneously at one site for measurements, the same electrode system was used as much as possible. Meanwhile the electrodes, their intervals and surrounding conditions kept constant. When fixing an LIMS station, the main frame was installed at the center of the station. The three-component magnetic detector was buried 3∼5m away from the main frame. And the buried depth was larger than 0.5m. For the detector it was also defined that the X axis was pointed to north and Y axis to east. At each site of the survey lines, MT-24NS was used to collect broadband MT data with measurement time 20∼24h. In general, the LIMS station was fixed at every other broadband MT site to collect super-long-period MT data with observational time 7 days or more. Then the broadband data and super-long-period data from these two systems were linked by using the Rhoplus analysis method[28]. The resulting data have a frequency range 320∼1/20000Hz, as shown in Fig. 2. To ensure the quality of measurements, the technology of "remote reference track" was used for all sites. In general the magnetic field is utilized as the reference when considering the actual effect.

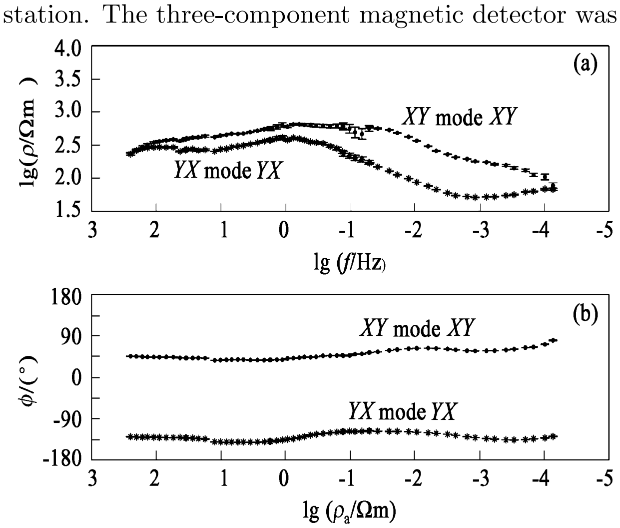

Fig. 2 Super-wide band MT sounding curve of site Tbt-573 (MT-24&LIMS

The technical requirement of layout of the "remote reference site" is close to that for the "original observational site". The data collection between these two sites is performed by GPS. When the interval is larger than 5km, the expected effect can be achieved. Therefore, the neighboring sites can be used as "references" each other to realize the "remote reference track" technology so that work efficiency can be enhanced.

3 DATA PROCESSING AND INVERSION

With developments of modern MT sounding methods, there have been a series of advanced technology of MT data processing and inversion, such as Robust processing for time sequence of MT field components[29], Rhoplus analysis[28], decomposition of complex impedance tensors[30], 2-D MT rapid relaxed inversion (RRI)[31], 2-D MT Occam inversion[32,33], 2-D conjugate gradient (CG) inversion[34].

In the 2-D inversion of the super-broadband MT data for the line 500 and line 600 of this work, we have used three 2-D MT data inversion methods separately, RRI, Occam, and CG, and single-mode and double-mode repeatedly. Based on known geological features and geophysical data of the study area, we analyzed and compared similarities of structural frames of models from different inversions and rationality of fine structures, and finally determined the acceptable inversion results of the two profiles (Fig. 3). They are models of electricity structure from inversion of the TM (H polarity) mode[35] data by using the conjugate gradient method.

Figure 3(a,b) are models of electric structure of the Deqing-Longwei profile (line 500) and Naqu-Germu profile (line 600), respectively. In the figures, measurement site positions are marked on the horizontal axis, and contours are logarithmic values of electric resistivity, of which red color means low resistivity and blue color denotes high resistivity.

Figure 4(A,B) displays theoretical responses of apparent resistivity and impedance of 2-D inversion models and their comparison with observed results for the line 500 and line 600, respectively. It indicates that the inversion models and observed ones of MT responses are roughly consistent, implying that the two profiles of 2-D MT inversion can represent the real subsurface distribution of electric conductivity. Comparatively, the results of middle and northern Tibet are relatively accurate and more reliable.

Suppose that the average electric resistivity of the crust in Tibet is 10Ωm. According to the expression of "penetration depth (H)" of a plane wave field in a homogeneous and isotropic crust[36]: $H = \frac{1}{2\pi}\sqrt{10\rho T}$, it is estimated that for a MT signal of 20000s the value of H will exceed 225km, which means that the maximum exploration depth of MT sounding in Tibet is likely 225km. Considering the reliability of survey results in Tibet, our attention is focused on the inversion results of uppermost 100km in the crust and mantle when discussing the electric structure models of the northern Tibetan Plateau.

4 CONDUCTIVITY STRUCTURE OF CRUST AND UPPER MANTLE IN NORTHERN TIBETAN PLATEAU

4.1 Deqing-Longweicuo Profile (Line 500)

As shown in Fig. 3a, there is a set of gentle gradient zones of electricity at depths 20∼30km on the profile Deqing-Longweicuo. However, these zones are concave downward obviously between sites 532∼546, 555∼566, and 575∼583 on the profile. For instance, the concave gradient zone at the middle portion of the profile (532∼546) is 70km deep.

At subsurface depths 50∼70km, there exists the second set of gentle gradient zones extending along the profile, which seems in negative relation with the first one in the feature of relief. As a whole, both sets of gradient zones dip toward slightly north. By these two sets of zones the uppermost 100km portion of subsurface is divided into upper, middle, and lower parts. In comparison with the seismic exploration results of Xu et al.[37] and Zheng et al.[38], the upper and middle parts are in the crust and the lower part belongs to the upper mantle.

The upper part mentioned above, i.e. the upper crust, is dominated by highly resistive bodies with resistivity values mostly more than 1000Ωm. There are, however, some exceptions there. For instance, between sites 530 and 536 appears a northward dipping zone of low resistivity extending to depth 20km. A nearly vertical low-resistivity zone exists between sites 587 and 595, which continues downward to link with the conductive middle crust. Besides, local low-resistivity bodies are also found at sites 544∼546, and 577∼581, of which the values of resistivity are about 10∼40Wm. Along the profile the electric structure of the upper crust looks like complicated, exhibiting a remarkable feature of lateral block-division.

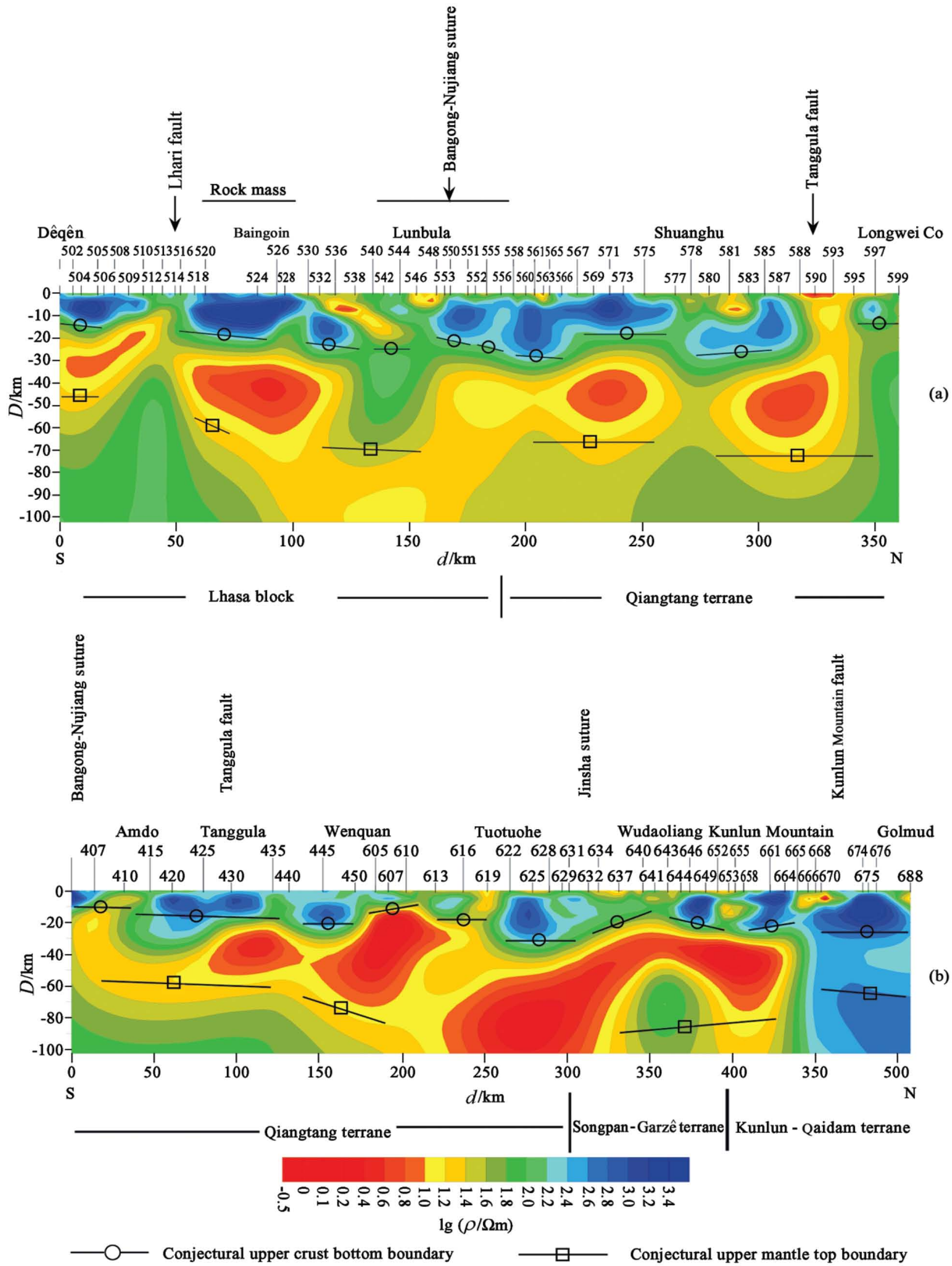

Fig. 3 Conductivity structure model of crust and upper mantle beneath the northern Tibetan plateau

(a) Resistivity model from MT 2D inversion of 500-line; (b) Resistivity model from MT 2D inversion of 600-line.

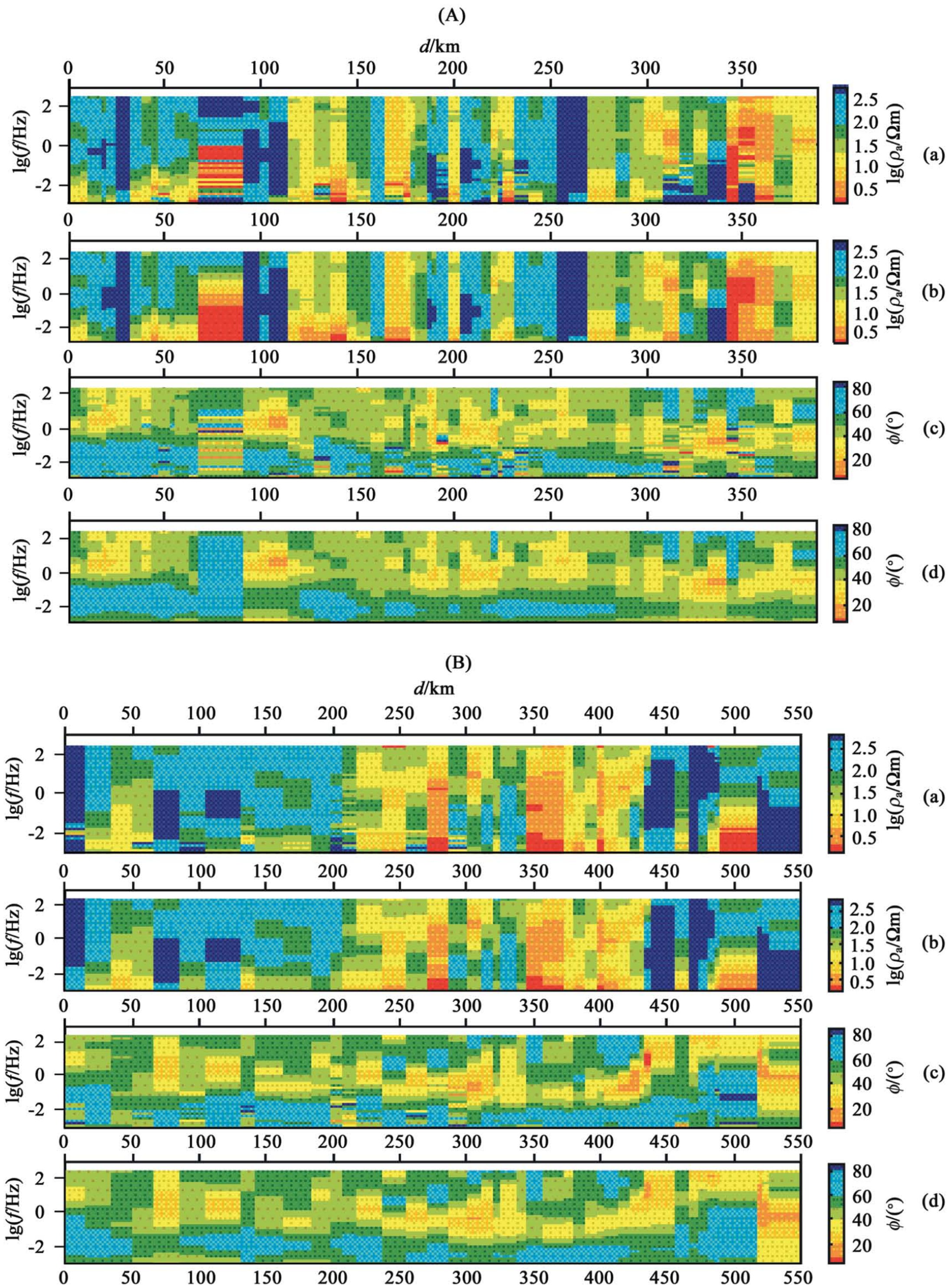

Fig. 4 Comparison of theoretical response of 2-D inverse and real data of 500-line (A) and 600-line (B)

(a) Real apparent resistivity contour diagram of imitative section; (b) Theoretical apparent resistivity contour diagram of imitative section; (c) Real impedance phase contour diagram of imitative section; (d) Theoretical impedance phase contour diagram of imitative section.

The middle portion, middle and lower crust, is characterized by high conductivity with resistivity values less than 10Ωm. Along the profile there are 4 sets of high-conductivity bodies which are of large scales. The high-conductivity bodies beneath Deqing located at the southern end of the profile, beneath Longweicuo at the northern end of the profile, tend to dip toward south. And the high-conductivity bodies in the middle of the profile look like fairly flat in geometry.

The lower portion of the exploration area, the uppermost mantle, has a uniform and simple distribution of electric property. Both the ends of the profile are of intermediate conductivity with resistivity values about 60∼160Ωm. In the middle of the profile a low-resistivity body extends downward steeply into the mantle with resistivity values about 10∼16Ωm.

On the cross section, the contours of electric resistivity indicate the existence of many horizontal gradient zones of electricity in the upper crust, some of which dip toward south, extending to depths less than 20km. While beneath the sites 512, 514, 540, 550, 565, 595, and 599, these gradient zones stretch downward into the middle and lower crust, linking their horizontal gradient zones together. Their extending depths do not exceed 70km in general. Except that the gradient zone beneath site 512 dips to north, other zones dip toward south.

4.2 Naqu-Germu Profile (Line 600)

Along the Nqu-Germu profile (line 600) MT sounding was carried on 43 sites. As shown in Fig. 3b, the contours of resistivity on the cross section reveal the existence of a set of gradient zones of electricity at depths 10∼40km. They extend along the profile like a wave with large fluctuation. Between sites 410∼430, and 619∼632, the gradient zone is as deep as 40km. While between sites 407∼415, and 450∼613, the gradient zone is merely 10km deep.

Similar to the line 500, at depths 50∼70km there is also the second set of gradient zones of electricity. As a whole, it looks like flat with little fluctuation, except an uplift of 50km depth between sites 637∼649. Meanwhile, these two sets of gradient zones separate the cross section into upper, middle, and lower parts. The upper part is the upper crust, the middle part is the middle and lower crust, and the lower part belongs to the uppermost mantle.

Figure 3b indicates that the upper crust along the Naqu-Germu profile is largely of high resistivity with values more than 1000Ωm. In comparison with the Deqing-Longweicuo profile (line 500), the high-resistivity bodies have a lower boundary of large relief and big thickness. Besides, local low-resistivity bodies appear between sites 410, 619, 634∼644, 652∼658, and 665∼670 with values of about 15∼40Ωm. Among them, the bodies beneath the sites 410 at the southern end and 619 at the middle of the profile tilt toward south, and link the anomalous area of high conductivity in the middle and lower crust. These demonstrate that the electric structure of the upper crust along the profile is characterized by discontinuity and block-division.

Figure 3b also shows that the middle and lower crust south to the site 665 is a large-scale anomalous area of high-conductivity with resistivity values less than 15Ωm. In this area there are 4 separated big bodies of high- conductivity with differing shapes, of which the resistivity values are less than 4Ωm. Among them the biggest body of high-conductivity lies in the middle of the profile (between sites 616∼637). It has a top at depth of about 25∼50km, dips toward south, and its bottom extends to the upper mantle, forming a path of high-conductivity between the crust and upper mantle. This high-conductivity body stretches toward north, conjoining with another north dipping high-conductivity body between sites 644∼664 located in the north of the profile, forming an asymmetric high-conductivity body of anticline shape. In the middle and south portion of the profile, there is a high-conductivity body between sites 605∼616, dipping south with top depth as shallow as 10km and bottom depth about 70km. The high-conductivity body between sites 425∼440 has the smallest scale and flat occurrence with top depth about 25km and bottom depth 50km.

At the northern end of the profile, north to site 665, the middle and lower crust is of high resistivity with values from 160Ωm to 400Ωm.

The lower part of the cross section is the uppermost mantle, which has a relatively simple structure of electricity. Its southern portion has intermediate resistivity values of 60∼100Ωm, while its northern portion is of high-resistivity with values 400∼2500Ωm. In the middle portion these also exists a steep path of high-conductivity with resistivity values 4∼16Ωm extending downward into the mantle.

The contours of resistivity in Fig. 3b shows that there are many lateral gradient zone s of electricity in the upper crust, implying a similarity between the Deqing-Longweicuo profile and Nq-Germu profile. Most of these zones also tilt toward south, extending downward to depths less than 20km. Beneath sites 435, 605, 619, 643, and 668, these gradient zones stretch into the middle and lower crust to link the lateral gradient zones of electricity there, which all dip to south with the largest depth less than 70km.

5 HIGH-CONDUCTIVITY BODIES IN CRUST AND UPPER MANTLE BENEATH THE MIDDLE AND NORTHERN TIBETAN PLATEAU

As shown in Fig. 1, the middle and northern Tibetan Plateau is composed of a series of tectonic units, including the Gangdisi-Lasha terrane, Qaingtang terrane, Songpan-Ganzi-Kekexili terrane, and Kunlun-Qaidamu terrane.

The survey line 500 starts in south from Deqing in the middle part of the Gangdisi-Lasha terrane, crossing in northwest direction through the Bange batholith and Bangong-Nujiang suture, and enters the Qiangtang terrane. Then the survey line traverses the southern Qaingtang basin across the axis of complex anticline in Qiangtang, reaching Longweicuo at the northern Qaingtang basin. Located east to the line 500, the line 600 starts in south from Naqu at the northern Gangdisi-Lasha terrane, extending northward across through the Bangong-Nujiang suture, entering Anduo at the southern edge of the Qiangtang terane. Then it turns toward northeast across the Tanggula Mountains, through the Jinshajiang suture and Kunlun fault zone, traversing the Qiangtang terrane and Songpan-Ganzi-Kekexili terrane, entering the Kunlun-Qaidamu terrane, finally arriving Germu (see Fig. 1). Apparently, these two survey lines pass through the tectonic deformation area of the middle and northern Tibetan Plateau (along Deqing-Germu), which is one of the most significant areas for the study of dynamics of formation and evolution of the Tibetan Plateau. Detection of structure of crust and upper mantle of this area will provide new evidence for further understanding deep processes of collision between the India and Eurasian plates and plateau uplift as well as coupling effects between shallow and deep structures.

The features of electric structure in Fig. 3 shows clearly that there exist widespread high-conductivity bodies at depths 20∼30km in the crust beneath the middle and northern Tibetan Plateau, which are of differing sizes and not linked each other, with resistivity values less than 10Ωm. These bodies of high-conductivity extend northward to the Kunlun fault zone and southward to the Gangdisi-Lasha terrane. Between them, below the Songpan-Ganzi-Kekexili terrane the bodies of hogh-conductivity are relatively thinner and confined within the middle crust, exhibiting distribution of a “anticline” shape. The axis of this “anicline lies in the Wudaoliang area, and its southern flank links with the body of high-conductivity found at the Jinshajiang suture, which has the largest size and highest conductivity. The model of electric structure along the line 600 indicates that the body of high-conductivity beneath the Jinshajiang suture located in the northern Qiangtang terrane tends to extend downward into the uppermantle (Fig. 3b). Meanwhile beneath the middle and southern Qiangtang terrane, sizes of bodies of high-conductivity in the crust decrease. Between the Tuotuo River and Wenquan the body of high-conductivity has the smallest depth from its top.

Comparing the models of electric structure for the lines 600 and 500 suggests that the sizes of high-conductivity bodies in the crust increase from west to east beneath the Qiangtang terrane, meanwhile their resistivity values decrease. South to the Bangong-Nujiang suture (northern Gangdisi-Lasha terrane) there is also bodies of high-conductivity in the crust which extends to upper mantle, but with resistivity notably higher than those beneath the Jinshajiang suture. The model of electric structure for the line 500 also indicates that the high-conductivity bodies in the middle crust beneath then Gangdisi-Lasha terrane has small thickness and small sizes, tending to overthrust and superpose from south to north below the Jiali fault.

On the whole, south to the Kunlun Mountains in middle and northern Tibat, the high-conductivity bodies in the crust have decreasing sizes and slightly growing resistivity values from north to south and from east to west. Meanwhile their buried depths become shallow from west to east. The biggest body with the highest conductivity is located in the norhern Qiangtang terrane about 34.5°N. Beneath the Bangong-Nujiang suture the high-conductivity bodies in the crust all tend to extend to the upper mantle constituting low-resistivity paths between the crust and mantle. While such paths beneath the Bangong-Nujiang suture have obviously larger resistivity with respective to those below the Jinshajiang suture.

It can be found that the high-conductivity bodies in the crust beneath the Tethyan Himalayas in southern Tibet and the Gangdisi-Lasha tectonic zone have good analogy in their resistivity values, buried depths, and space distributions. There have been many discussions on the cause of high-conductivity bodies in the crust of southern Tibet. Various kinds of evidence suggest that these bodies are associated with temperature, very likely produced by partial melt, linked thermal fluids or liquid hydrated material[20,40]. We infer that the high-conductivity bodies in the crust found in middle and northern Tibet are much possibly formed also by the same causes mentioned above.

In fact it has long been recognized that the temperature grows with increasing depth in the earth, hence dry rock in crust and upper mantle becomes more conductive. Studies demonstrate that temperature has large influence on the conductivity of rock in the deep crust and uppermost mantle in continents. Because increase of temperature can cause chemical reaction of rock in deep crust and uppermost mantle, making chemically bound water in rock-forming mineral be given off, leading to local melt, hence reducing electric resistivity of rock. It implies that resistivity of lithosphere is generally related with temperature. To a large extent its electric structure depends upon the subsurface thermal regime[41]. Therefore, the deep anomalies of electric conductivity found in middle and northern Tibet reflect very likely partial melt beneath this area. This conclusion has been supported by seismic sounding results.

Based on the analysis to the PASSCAL data, Owens and Zandt[10] suggested that beneath the Qiangtang and Songpan-Ganzi-Kekexili terranes there exist low-velocity zones in the lower crust and S wave attenuation in the upper mantle. This special anomalous area of wave velocity extends from the Bangong-Nujiang suture to the Kunlun fault zone. It implies that there exist likely partial melt bodies in the lower crust and upper mantle beneath the Qiangtang and Songpan-Ganzi-Kekexili terranes. A great number of experiments on physical properties at high temperature and pressure show that the existence of local melt in crust and upper mantle will cause high conductivity, low seismic velocity, and S wave attenuation. Owens and Zandt[10] also concluded that the crust of the Songpan-Ganzi-Kekexili terrane is very thin with low velocity of seismic waves. These conclusions are roughly in agreement with MT sounding results in the northern Tibetan Plateau. The difference between these two aspects is that the location with lowest electric resistivity (highest degree of melt) from MT sounding is below the northern Qiangtang terrane, rather than beneath the Songpan-Ganzi-Kekexili terrane. But this obvious difference has been removed by a fine analysis to the PASSCAL data by Vergne[42].

In fact, the structural images of the upper mantle beneath northern Tibet from other seismic observations are in accordance with our MT results. For example, the broad-band seismic P wave tomography images of Zhou[8] indicate the a velocity body lies between depths 35km and 310km beneath middle and northern Tibet (85°E∼93°E, 30°N∼36°N), which is comparable with the distribution of high-conductivity bodies beneath the Bangong-Nujiang and Jinshajiang sutures.

It can be concluded that there exist indeed widespread partial melt bodies in the crust beneath middle and northern Tibet. The observed deep anomalies of electric conductivity are primarily associated with the thermal structure and material state of the lithosphere in the study area. Currently, the models to explain this phenomenon suggest that it is related thickening-delamination of the lithosphere in northern Tibet, which can cause mantle convection-asthenosphere upwelling leading to local melt in the crust[20,43].

As mentioned above, the electric structures on cross sections of the Bangong-Nujinag suture and Jinshajiang suture are very similar (see Fig. 3). Since electric structure of crust and mantle is closely related with thermal structure, it seems likely that there exist thermal paths connecting the crust and upper mantle beneath these two sutures and its surroundings. The high-conductivity bodies beneath these areas should be resulted from upwelling of thermal material from the upper mantle. Studies of volcanic rock in the Tibetan Plateau[44] and broad-band seismic tomography results[8] also provide evidence for this inference to some extent.

All thermal effects in crust and upper mantle are function of time. Hence mantle convection, asthenosphere upwelling, and rock melt are accompanied by thermal responses with time.

If we think that the high-conductivity bodies in the crust beneath middle and northern Tibetan Plateau are primarily related with local melt of rock, the evolution of these bodies should be thermal response processes with time. We can suppose that the fast ascent of thermal material of asthenosphere produced local melt in crust at early time of the evolution. The thermal paths fomed by this process had high temperature, behaving as plastic state, hence left obvious trace of low-resistivity paths in electric structure. Meanwhile those local melt bodies around thermal paths in crust were characterized by large range, high temperature, and strong plasticity, as indicated by appearance of large-scale high-conductivity anomalies. When it is far away from the thermal paths, however, the quantity of heat in these local melt bodies dissipated gradually, leading to decrease of sizes of the high-conductivity anomalies as well as drop of their electric conductivity.

With time elapsing, the speed of ascending thermal material in the asthenosphere would decline, causing gradual cool of the thermal paths and weakening of plasticity. It resulted in poor electric conductivity and increased resistivity of rock. Correspondingly, the sizes of high-conductivity anomaly bodies indicative of local melt in crust also reduced, and they conductivity became small.

Of course, the realistic processes must be more complicated than the speculations stated above. Thermal conduct of subsurface medium, accumulation and loss of energy processes must be underway simultaneously. But whatever how these processes are complicated, they are associated with time. Under the precondition that we can verify that the formation of high-conductivity bodies and low-resistivity paths between crust and mantle is primarily related with subsurface thermal state, we infer that their volume sizes and values of electric resistivity are indirectly associated with time. Therefore it is plausible to study the evolution of subsurface thermal structure and thermal state based on observed electric structure of crust and mantle.

According to this idea, on the basis of studies on high-conductivity bodies in crust and upper mantle beneath the middle and northern Tibetan Plateau, as well as other relevant studies, such as petrology and geochemistry, we attempt to make further speculation described below.

The Bangong-Nujiang suture and Jinshajiang suture represent thermal exchange paths between crust and mantle which formed in two periods. Because they have very analogous electric structures, and beneath them exist high-conductivity bodies in the crust extending downward to the upper mantle, constituting low-resistivity zones linking crust and mantle.

By comparison, it is noted that the high-conductivity bodies and low-resistivity paths below the Jinshajiang suture have larger sizes, smaller buried depth of top, and lower resistivity with respect to those beneath the Bangong-Nujiang suture. Probably it implies that the Jinshajiang suture is still in a state of intense thermal activity at present. While below the Bangong-Nujiang suture, the thermal activity has been weakened, local melt bodies in the crust are cooling gradually and recrystallized. Therefore it is suggested that the crust-mantle thermal exchange process below the Bangong-Nujiang suture started earlier than that beneath the Jinshajiang suture. This is consistent with the study of petrology in Tibet by Zhao et al[44]. Their result shows that the magma activity in the Tibetan Plateau continued for a time period after the collision, while spread not in single direction in space. It occurred first in the Qiangtang area, then diffused toward south and north, migrated toward outside in a wave-like manner. It means that the thinning event of the lithosphere in this area is very likely characterized by multistage.

It can be speculated that the crust-mantle thermal activity started from south and west in the middle and northern Tibet. With time elapsing, it spread gradually toward north and east. Hence the current heat flow distribution in middle and northern Tibet should increase from west to east and from south to north.

6 CONCLUSIONS

The MT sounding result in the middle and northern Tibetan Plateau further indicates that the thermal regime and material state of the plateau are peculiar. It is of great significance for advancing studies on mechanisms of formation and evolution of the Tibetan Plateau.

The study result of this work shows that bounded by the Kunlun fault, the electric structure of crust and upper mantle beneath middle and northern Tibet is different in south and north. North to the Kunlun fault, the crust and upper mantle is of high resistivity, implying cold crust and cold mantle. While south to the Kunlun fault, layered structure characterizes the conductivity of the crust and upper mantle, described as follows. The upper crust is dominated by discontinuous high-resistivity bodies, interpenetrated by local low-resistivity anomalies. In north-south direction, the upper crust exhibits complex electric structure featured by discontinuity and block-division. But the middle and lower crust is a broad area of high-conductivity anomalies, with separated and large sized high-conductivity bodies of differing shapes, of which the resistivity values are less than 4Wm. Beneath the Bangong-Nujiang suture, the high-conductivity bodies in the crust tend to extend downward to the upper mantle, forming low-resistivity paths between crust and mantle. And the feature of electric structure is indicative of hot crust and hot mantle.

Based on the electric structure of crust and upper mantle beneath the middle and northern Tibetan Plateau, it can be speculated that there are widespread partial melt and thermal fluids there, like the case of southern Tibet. They are primarily associated with the thermal exchange between crust and mantle and thermal activity beneath the Bangong-Nujiang and Jinshajiang sutures, which are heat exchange paths between crust and mantle formed in two periods. The heat exchange path between crust and mantle beneath the Bangong-Nujiang suture was formed earlier than that below the Jinshajiang suture. Hence, the thermal activity started from south and west, then spread toward north and east, leading to the increasing of heat flow from west to east and from south to north.

If the heat exchange between crust and mantle and thermal activity indeed occurred in the study area with differing initial times, we should wonder whether these processes of two periods have the same mechanism of formation? What is the relationship between the earlier heat exchange path between crust and mantle (below the Bangong-Nujiang suture) and the subduction of the Indian plate? Is the later heat exchange path (beneath the Jinshajiang suture) related with the affection of the Asian plate? Is it possible that two periods of lithospheric compression and thickening-delamination-asthenosphere upwelling occurred in middle and northern Tibet?

To these questions we have not yet definite answers at present. Only these problems are really addressed, can we reach thorough understanding of the formation and evolution of the thermal regime of crust and upper mantle beneath middle and northern Tibet. This is just the goal of our further efforts.

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