

Crustal electrical structure of the eastern segment of the collision-related porphyry copper-polymetallic metallogenic belt in South Tibet and its constraints on fluid migration

Yue Sheng

sysansiro@126.com

China University of Geosciences Beijing <https://orcid.org/0000-0002-1517-6290>

Sheng Jin

Hebei GEO University <https://orcid.org/0000-0003-1274-8553>

Gaofeng Ye

China University of Geosciences Beijing

Letian Zhang

China University of Geosciences Beijing

Hao Dong

China University of Geosciences Beijing

Yaotian Yin

China University of Geosciences Beijing

Chengliang Xie

China University of Geosciences Beijing

Jian'en Jing

China University of Geosciences Beijing

Wenbo Wei

China University of Geosciences Beijing

Research Article

Keywords: South Tibet, Magnetotellurics, Collision-related copper-polymetallic metallogenic deposit, Ancient shared magma chamber, Fluid pathway

Posted Date: August 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10447750/v1>

Abstract

The Tibetan Plateau orogenic belt is one of the most active orogens with abundant mineral resources. In the collision-related Cu polymetallic belt in South Tibet, the Qulong and Jiama porphyry Copper (Cu)-polymetallic deposits attract the academic attention. However, it is remaining unclear whether the ore-bearing hydrothermal fluids of these two deposits originated from a shared deep-seated magma chamber at a certain depth and the characteristic of this magma chamber is. To address this, we present a new 3-D electrical resistivity model, derived from area-domain magnetotelluric (MT) data, to explore the crustal structure beneath the eastern segment of the collision-related Cu polymetallic belt in South Tibet. The model reveals three large-scale low-resistivity zones of the upper-middle crust at depths of 20–40 km, which are interpreted to be the ancient mixing magma chambers of ultrapotassic magma and adakite-like melt, with fluid exsolution in the top of magma chambers. Some localized low-resistivity features closely align with the Qulong, Jiama and Nuri deposits in the upper crust connect with the inferred ancient mixing magma chambers, likely representing pathways for the upward migration of the hydrothermal fluids of the Cu-dominated polymetallic deposits. What's, more, the Qulong and Jiama porphyry Cu-dominated polymetallic deposits are more likely to have a shared deep-seated magma chamber and the shared fluid pathways ranging of 40 km -10 km. In addition, the Cu-bearing hydrothermal fluids also migrated laterally to make the old crust reworking to release more Mo ions, forming the porphyry Mo-dominated polymetallic deposits. Integrating with geochemical and geological constraints, the MT results reveal the migration feature of the hydrothermal fluids between the Cu-dominated and Mo-dominated polymetallic deposits in the eastern segment of the collision-related Cu-polymetallic metallogenic belt.

1. Introduction

Material circulation among Earth's spheres sustains the dynamic equilibrium of the Earth system, in which the abnormal metal enrichment has resulted in the mineral resources that are essential for human society. Prior to the continental collision, the Tibetan Plateau orogenic belt has experienced multiple episodes of ocean–continent subduction, laying an initial material foundation for collision-related metallogenic theory. The India–Eurasia continental collision initiated at 65–60 Ma not only drove the subduction of the Indian continental slab, but also induced asthenospheric upwelling, lateral flow and thermal erosion beneath the Lhasa terrane because of variable subduction geometries. These processes triggered partial melting of the overlying lithosphere, variation of the crustal rheology, and interactions among the surface, crust and mantle, which resulted in the abnormal metal enrichment and formed a series of ore deposits related to the magmatic-hydrothermal evolution or fluid circulation. Accordingly, the Tibetan Plateau serves as a natural laboratory for investigating the geological processes mentioned above (Hou et al., 2015; Hou et al., 2020; Yin & Harrison, 2000; Tapponnier et al., 2001; Yin, 2006; Xu et al, 2016; Zhu et al., 2012, 2013).

The collision-related porphyry copper (Cu)- polymetallic metallogenic belt (CPCB), which is mainly located in the Lhasa terrane, has formed in the post-collision period of the Indian-Eurasian collision

process, including the Zhunuo, Jiru, Pusangguo, Bairong, Chongjiang, Gangjiang, Renqinze, Qulong, Jiama, Nuri, Bangpu and Tangbula deposits (Hou et al., 2015, 2023; Tang et al., 2014; Tang et al., 2021). Previous researchers have carried out extensive studies on giant to supergiant deposits in the collision-related porphyry Cu-polymetallic metallogenic belt, focusing on deposit geological characteristics, geochronology, lithogeochemistry, elemental distribution patterns, fluid geochemistry, and ore genesis (Hou et al., 2015, 2020, 2023; Lin et al., 2023; Tang et al., 2014, 2021; Tang et al., 2019; Wang et al., 2015, 2018, 2020, 2021; Yang & Fu, 2020; Xue et al., 2021; Yang et al., 2015; Zheng et al., 2018, 2020; Qi et al., 2025. etc.). Significant understandings have been achieved regarding a series of scientific issues, including regional geodynamic setting, origin of ore-forming magmas, evolution of magmatic-hydrothermal fluid systems, source and enrichment processes of ore-forming metals (Cu, Au, Mo), fluid source, and oxygen fugacity variations. Xu et al. (2023) further reported that the transcrustal mineral system including the magma source area of anatexis in the lower crust, partially molten zones in the mid-crust, and some multi-stage magma reservoirs at different depths in the upper crust. Geophysical studies have also reported the coupling relationship between some geophysical parameters (including bouguer gravity, magnetic susceptibility, velocity, resistivity) and distribution of the collision-related porphyry Cu polymetallic deposits (e.g., Wang, 2012; Huang et al., 2019; Sheng et al., 2024).

Specially, previous study has revealed that the Qulong and Jiama porphyry Cu-dominated polymetallic deposits in the eastern segment of the collision-related porphyry Cu-polymetallic metallogenic belt are geographically close to each other and separated by a nearly north–south striking fracture zone that generally extends along the Jiama Qu River; nevertheless, the metallogenic models of these porphyry Cu-polymetallic deposits are slightly different (Tang et al., 2021). Furthermore, previous studies reported that the hydrothermal fluids required for porphyry mineralization must be derived from the deep-seated area in the crust (Hou et al., 2015, 2023), and therefore, geochemical data further indicate that the ore-bearing hydrothermal fluids of these two deposits originated from a shared deep-seated magma chamber at a certain depth (Qu et al., 2007; Yang et al., 2016; Wang et al., 2018). However, it is doubtful whether a shared magma chamber is beneath the Qulong and Jiama porphyry Cu-dominated polymetallic deposits, and what the characteristic of this magma chamber is; these issues are lack of the geophysical imaging. The cross-shaped MT data array covering the vicinity of the Qulong-Jiama ore concentration district are used to briefly discuss the relationship of the large-scale crustal conductive zones and metallogenic system (Sheng et al., 2022). And Wu et al. (2023) also indicated that the high-velocity basic lower crust is lacking beneath the Qulong-Jiama ore concentration district, and the property of crust mainly show the felsic feature, which resulted from the delamination of the basic lower crust.

The magnetotelluric (MT) method is a passive geophysical method that explores the subsurface electrical structure by measuring the time variation of electromagnetic fields at the Earth's surface, and has a good probing effect on the presence of melts/fluids which show the conductive (that is, low-resistivity) features detected in the subsurface (Wei et al., 2001; Unsworth et al., 2005; Becken et al., 2011). In this study, based on the MT stations (Figure. 1; black dots) from Sheng et al. (2022), some new stations (Figure. 1; blue dots) are added in the blank region to construct an area-domain MT data set

covering the eastern segment of the collision-related porphyry Cu-polymetallic metallogenic belt. The electrical resistivity model obtained by the 3-D inversion is aiming at sketching crustal structure, and providing the geophysical evidence for the feature of the ancient magma chambers and pathways of the hydrothermal fluids in the upper-middle crust.

2. Geological background

The Lhasa terrane, which is the major tectonic unit of the Tibetan Plateau, is bounded by the Yarlung Tsangpo Suture Zone in the south and by the Bangong–Nujiang Suture Zone in the north (Zhu et al., 2011). During the Mesozoic, with the northward subduction of the Neo-Tethyan Ocean, the Lhasa terrane was driven to wedge into the southern margin of the Asian continent, and collided with the Indian lithospheric plate around 65 Ma (Mo et al., 2011). The Lhasa Terrane has experienced subduction-related lithospheric modification and crustal thickening triggered by the continent–continent collision (Hou et al., 2015; Xu et al., 2017; Zhang et al., 2015). With widespread Cenozoic magmatic activities, an approximately 1500 km-long east-west-trending magmatic belt is generated. This belt comprises the syn-collisional Gangdese Batholith, which hosts the ~ 5 km-thick Linzizong volcanic succession (64–41 Ma; Zhu et al., 2011; Hou et al., 2015), as well as the post-collisional ultrapotassic and potassic intrusions emplaced during the Miocene (Miller et al., 1999; Ding et al., 2003; Zhao et al., 2009; Xu et al., 2017). The collision-related porphyry Cu-polymetallic deposits are mainly located in the eastern segment of the southern Lhasa Terrane, having a tight relationship with the adakitic porphyry intrusions (20–12 Ma; Wang et al., 2015). Meanwhile, the Miocene ultrapotassic magmatic rocks (12–10 Ma; Xu et al., 2017) locally intrude in the Mesozoic volcanic-magmatic arc in southern margin of the Lhasa Terrane.

The study area is located in the east of the Lhasa terrane and is also the eastern segment of the collision-related porphyry Cu-polymetallic metallogenic belt, with geographic coordinates approximately ranging of latitude of 29°N to 30.5°N and longitude of 91°E to 92°E (Fig. 1). In this region, the Qulong, Jiama, Nuri deposits are the porphyry (-skarn) Cu-dominate polymetallic deposits (Hou et al., 2015), and Bangpu, Lakang'e are the porphyry (-skarn) Mo-dominate polymetallic deposits (Qi et al., 2025), while some Oligocene porphyry-skarn Mo-W-Cu deposits are also distributed in the southern boundary of this region and are closed to the IYS (Huang et al., 2020). Magmatic activities within this region have formed during the Mesozoic-Cenozoic period, developing the basic, intermediate-acid intrusive rocks and intermediate-acid volcanic rocks. The resulting tectono-magmatic belt is predominantly composed of Late Triassic–Jurassic granites, Cretaceous granites, Paleocene–Eocene granites, and Oligocene–Miocene granites (Zhu et al., 2011).

3. Data

3.1 Data collecting and processing

Based on the study of Sheng et al. (2022), some new MT data (Blue dots; Fig. 1a) are collected to create a new dataset of 76 MT stations covering the eastern boundary of the collision-related porphyry Cu-

polymetallic metallogenic belt (Figure. 1b). All the MT data were recorded with five components of the time-varying electromagnetic field (E_x , E_y , H_x , H_y , H_z , x , y and z are the South-North, East-West and vertical directions). After data collection, the original MT time series data were transformed into the frequency, and then processed with a standard remote reference (Gamble et al., 1979). At last, frequency dependent transfer function was computed using the statistically robust algorithm (Egbert, 1997). The high-quality MT data of most stations are obtained with the period range of 0.003s~3000s, while a few of the MT stations have the maximum period of 1000 s or 100 s.

Figure 2 shows the sounding curves of some typical stations from different parts of the profile, and the locations of these sites are marked as purple triangles in Figure.1. The apparent resistivity and phase show curves with a clear shape and good continuity, which indicates that the MT data are good quality (Fig. 2). Stations of P1~P3~P4~P5 and P6 are located in the southern Lhasa terrane, and the data show similar features of moderate-high resistivity in the shallow area and low resistivity in the deep area. The apparent resistivity curves of station P2 have the feature of an upward tail, which indicates a possible high-resistivity block in the deep area.

3.2 Data analyzing

Because the phase tensor of the MT data is not easily affected by distortion, it has been widely used for dimensional analysis. The results of the phase tensor can be represented by an ellipse, and the polarization direction of the phase tensor is the principal axis direction (Caldwell, 2004; Booker, 2014). The ellipse of the phase tensor can also be colored by the skew angle β . When the absolute value of the skew angle $|\beta|$ is equal to 0° and the lengths of the major and minor axes of the ellipse are similar (approximately circular), the MT data indicate a one-dimensional assumption is valid; when the absolute skew angle $|\beta|$ is equal to 0° and the lengths of the major and minor axes of the ellipse are unequal, the MT data indicate that a two-dimensional investigation is necessary; when the absolute skew angle $|\beta|$ is not equal to 0° , the MT data indicate that a full three-dimensional treatment is needed (Caldwell, 2004; Booker, 2014). The induction vector is calculated with the vertical component of the magnetic field, which is sensitive to the horizontal variation of resistivity and reverses direction above an electrical interface, boundary, or gradient. Under the Parkison convention, the arrows of the induction vector point to the direction of the current convergence (Parkinson., 1996). The open-source mtpy analysis data package (Krieger & Peacock, 2014) is used to plot the figures of the phase tensor results and induction vector results (Figure. 3).

In the high-period band (0.01 s- 0.1 s), the major and minor axes of ellipses are unequal, and the major axes of ellipses have no consistent of direction, and however, the absolute skew angles $|\beta|$ of most MT data are less than 3° (3° is a threshold value of the quasi-2D; referring to Booker et al., 2014); meanwhile, the arrows of the induction vector have no consistency of direction. In the middle-low (1 s-1000 s) period band, the major and minor axes of ellipses are unequal, and the major axes of ellipses have no consistent of direction, and the absolute skew angles $|\beta|$ of most MT data are more than 3° ; the arrows of the induction vector of the MT stations in the south point towards the IYS, and their orientations are

perpendicular to the strike of the IYS. In addition, in the periods of 1s- 100s, the arrows of the induction vector of the MT stations in the vicinity of the Qulong and Jiama porphyry Cu deposits point towards these two ore deposits, which indicates a conductive zone in the deep-seated area of the crust. The results above show that the MT data have the obvious 3-D feature. Combined with the distribution of the MT stations in an area, full 3-D modelling of the MT data is ideal and thus is carried out.

3.3 Data inversion

The 3-D inversion and modelling of the data is performed with the ModEM3D method (Egbert & Kelbert, 2012; Kelbert et al., 2014), and meanwhile, the CPU-GPU hybrid acceleration algorithm based on the regularized undispersed Curl-Curl equation is also used in our 3-D inversion (Dong et al., 2024). The size of the first vertical layer is 30 m and increases downward at a rate of 1.1 in the inner core area and 1.5 in the outer area. The 3-D inversion uses the total impedance tensor data and the tipper data over 45 frequencies (logarithmically spaced between 0.01-3,000 s, giving 8 frequencies per decade). For each impedance component, the error floors were set to 5% of $\sqrt{|Z_{xy} \cdot Z_{yx}|}$. An error of 5% on the impedance tensor is equivalent to approximately 2.86° on the phase components and 10% on the apparent resistivity components. Absolute error floors for the tipper data were set to 0.05 for T_x and T_y components (Tipper data).

To address the non-uniqueness problem of inversion, some necessary inversion experiments are carried out, and finally, the 1500 m×1500 m grid (one-fifth of the average station spacing), which can also model the possible galvanic distortion (Miensoopust, 2017), is the preferred mesh of the initial model. The mesh contains 97 (E-W direction), 99 (N-S direction), and 78 (vertical) cells, and also include 11 air layers. The starting model is a 100 $\Omega \cdot m$ half space. The smoothing parameters in the horizontal and vertical directions were chosen to be a constant value of 0.3. The normalized root-mean-square (nR.M.S.) misfit of the final model is 1.74, having been reduced from a starting value of 21.51 after 246 iterations. In order to evaluate the general resistivity features by 3-D inversion model, the horizontal slices with different depths and cross-sections with different profiles are shown in Fig. 4 and Fig. 5. The site-by-site nR.M.S. results in Figure. 5i show that the fit is not biased and that the obtained 3-D model fits the MT data.

Furthermore, a comparison of the observed/measured data and the 3-D model response of the resistivity and impedance phase in different frequency bands (0.1s, 9.85s and 955.85s; Figure S1) also illustrates the generally good agreement, although several sites have minor differences in the impedance phase. However, the fit of resistivity and impedance phase at the longest periods (e.g., 1000 s) is observed to be not as good as the shorter periods. This is likely because of the higher errors associated with the long-period data and reflects the reduced resolution of the model in the deep area. Additionally, both the site-by-site nR.M.S. of the tipper data (Figure. S2) and comparison of the observed/measured tipper data and the 3-D model response of the tipper data (Figure. S3) show that the tipper data also have the generally good agreement in the whole. In summary, the MT data have a good constraint on the preferred depth (≤ 45 km; the upper-middle crustal scale) of this study.

4. Result

4.1 Sensitivity test

It is reported that signals from the natural electro-magnetic (EM) field can easily penetrate high-resistivity bodies and are sensitive to conductive anomalies (e.g., Sheng et al., 2023). However, the physics of EM signal diffusion in the Earth means that MT data cannot accurately determine the lower boundary of a conductor. In order to constraint the electrical boundary of the conductive zones in the model, some new models are established in basis on the 3-D electrical resistivity model. After calculating the responses of each new model, the nR.M.S. misfit of the new forward model and the response curves of MT sites located near the corresponding conductive zones are discussed to verify whether the MT data have good constraints on the electrical resistivity model. The sensitivity test results represent that the conductive zones of C1, C2 and C3 are constrained by the MT data, and are distributed at depths of 20–40 km in the crust, and meanwhile, the conductive zone C1-1 and the resistive zone R2 underneath are both constrained by the MT data.

4.2 Electrical resistivity model

Below we summarize the electrical features of our model.

- (1) At depths of 20–40 km, there is a prominent conductive zone C1, which also has the trend of extending to the deep. The conductive zone C1 corresponds well with the Qulong and Jiama porphyry copper polymetallic deposits, and is located from the bottom of the upper crust to the middle crust beneath these two deposits (upper-middle crustal scale).
- (2) At depths of 20–25 km, the conductive zones C1, C2 and C5 show a relatively good connection; however, at depth of 15 km, these conductive zones are separated by some resistive zones with different scales. With the decrease of depth, the conductive zone C1 move northwards to connect with the conductive zone C1-1, which is located beneath the Bangpu porphyry Mo-Cu deposit.
- (3) Besides the conductive zone C1, the conductive zone C2 is adjacent to the IYS, and is located beneath the Nuri porphyry copper polymetallic deposit. The conductive zone C3 is distributed in the west, and shows a good connection with the conductive zone C4 at depths of 15–30 km.
- (4) At depths of 10 km and 5 km, the large-area resistive zones with resistivity of more than $1000 \Omega \cdot m$ are distributed in the study area, which represents the widely distributed Mesozoic–Cenozoic magmatic rocks (Zhu et al., 2012; Hou et al., 2015).
- (5) Some conductive zones with variable scales are scatted within these large-scale resistive zones at depths of less than 5 km, and the porphyry Cu polymetallic deposits are mainly distributed within and in the vicinity of these conductive zones.

4.3 Conductance of the special conductive zones

Besides the electrical resistivity modelled at various depths with the 3-D inversion algorithm, the conductance of a certain layer, in particular conductive ones, is also another parameter to sketch the electrical anomalies (Jones, 1992; Weidelt, 1985). On the other hand, the MT method is a method of volume exploration, and therefore, it is preferred to estimate the volume fractions of melts and fluids (and, by proxy, viscosity) through bulk conductivity derived from conductance (Le Pape et al., 2015; Rippe & Unsworth, 2010). According to the spatial distribution of the conductive zones (C1, C2, C3, C4, C5 and C1-1), the conductance at depths of 20–40 km and at depth of 10–30 km is obtained from the 3-D electrical resistivity model, respectively (Figure. 6a,b). The results show that the maximum conductance in the conductive zones C1, C2 and C3 can be 30000 S, 15000 S and 13500 S, while the minimum conductance in the conductive zones C4, C5 and C1-1 is far from 10000S. As conductance is the product of the bulk conductivity of a certain layer and the corresponding layer thickness, the corresponding bulk conductivity of the conductive zones C1, C2 and C3 is approximate 1.53 S/m, 0.76 S/m and 0.67 S/m, respectively.

5. Discussion

5.1 Contribution of the ultra-potassic melt on the conductive zones

Rocks within the crust are generally composed of various minerals and aggregates, the bulk electrical conductivity of which is controlled by the electrical conductivity, volume fraction, mass fraction and spatial distribution of each constituent mineral and aggregate. If these parameters are known, the bulk conductivity can be estimated using specific mixing models. Because of the uncertainties in the calculation of the bulk conductivity of the lithosphere, previous researchers have proposed a variety of numerical models to estimate rock bulk conductivity under different geometric configurations (e.g., Archie et al., 1942; Hashin & Shtrikman, 1962; Glover et al., 2000, 2010). Among these mixing models, the HS upper boundary model is employed to bridge the bulk conductivity of the conductive zones and volume fractions of melts/fluids in this study. The temperature model of Sun et al. (2022) shows that the temperature at depth of 20 km is more than 700°C and that at depth of 40 km is more than 1000°C. The water contents of aqueous melts can reach 8 wt % in Southern Tibet (Han et al., 2025). Therefore, the temperature and pressure at depths of 20-40km can meet the condition of the partial melting of rocks in the crust (referring to Sheng et al., 2023).

The ultra-potassic melts generated by the subducted Indian slab ponded and differentiated in the lower crust, and also induced the partial melting of the overlying crust to produce the granitic melts in the middle to upper crust (Han et al., 2025). However, Yang et al. (2015) also indicated that the mixing of ultrapotassic magma with adakite-like melt took place in both the lower and upper crust, and the ultrapotassic magma reservoir may be evolved at depths of 20–30 km. Geological and geochemical data report that the last large-scale magmatic activity (including ultrapotassic and adakitic magmatic activities) has occurred during the ~ 20 – 10 Ma (Summary of Bian et al., 2022). Therefore, the

contribution of the granitic melts and ultra-potassic melts to the conductive zone C1, C2 and C3 are preferred to be taken into consideration.

Under the condition of the average temperature ($\sim 900^{\circ}\text{C}$) and average pressure ($\sim 0.9\text{ GPa}$) at depths of 20–40 km, the conductivity of the aqueous granitic melts with the water contents of 8 wt% is 5.3 S/m (Guo et al., 2018), while that of the aqueous ultra-potassic melts with the water contents of 8 wt% is 9.6 S/m (Han et al., 2025). In the HS upper boundary model, the rock matrix conductivity can be taken to be the background value in the resistivity model, which can be estimated as $\sim 0.001\text{ S/m}$ with the equation proposed in Hashim et al. (2013), derived from laboratory experiments on leucogranite. Assuming the conductive zone C1 entirely results from the aqueous granitic melt, approximate 20% volume fractions of the aqueous granitic melt can produce the bulk conductivity. Assuming the conductive zone C1 entirely results from the aqueous ultra-potassic melt, more than 10% volume fractions of the aqueous ultra-potassic melt are needed. Therefore, if the partial melting of the crust is the main cause of the conductive zone C1, C2 and C3, the 10%-20% of volume fractions of melts are necessary to produce the bulk conductivity.

5.2 Implication of the crustal conductive zones

Besides the silicate melts, the alkali-bearing aqueous fluids with high salinity is another possible cause of the conductive zones in the upper-middle crust of the South Tibet, according the temperature and pressure condition in our region. Additionally, previous studies also indicated that the aqueous melts and alkali-bearing aqueous fluids are more likely to co-exist at depths of 20–40 km because of the immiscibility of the aqueous melts and alkali-bearing aqueous fluids (e.g., Sheng et al., 2023). Tang et al. (2019, 2024, 2025) reported that Mo was mainly partitioned into the F-rich magmatic-hydrothermal system released from the monzogranite porphyry, and Cu was mainly partitioned into the Cl-rich magmatic-hydrothermal system released from the diorite porphyry. Other studies have also highlighted that the alkali-bearing fluids (brine fluid) with high salinity played an essential role in the metal partition of the shallow magma chamber in the period of the collision-related porphyry Cu-polymetallic deposits (e.g., Qi et al., 2025; and reference therein).

Previous study report that the conductivity of the alkali-bearing aqueous fluids is ranging of 23.5 S/m–65.5 S/m under the condition of the average temperature ($\sim 900^{\circ}\text{C}$) and average pressure (0.9 GPa) (Guo & Klepper, 2019). If we assume that the conductive zones C1, C2 and C3 result from the alkali-bearing aqueous fluids, $\sim 3\%$ – 5% of volume fractions of the alkali-bearing aqueous fluids with the salinity of more than 3 wt% NaCl are needed for C1 and C3, and $\sim 5\%$ – 10% are needed for the conductive zone C2. When the alkali-bearing aqueous fluids is the salinity of 1 wt% NaCl, more than 10% of volume fractions are needed for these three conductive zones. The conductive zone C2 is close to the IYS and the mantle wedge related to the subduction of the Indian lithospheric plate, more alkali metals and magmatic volatiles may be stored in the conductive zone C2 (high salinity), which results in the higher conductivity.

Yang et al. (2015) reported that the quench textures (swallow-tail terminations) of the type II hornblende phenocrysts that formed at 20–25 km depth were more probably caused by fluid escape from mafic ultrapotassic magma, suggesting fluid saturation of the mafic ultrapotassic melt at 20–25 km depth. This implies that multistage H₂O addition resulted from the mixing of ultrapotassic magma with adakite-like melt, which took place in both the lower and upper crust. What's more, both the ultra-potassic rocks and adakite rocks are all exposed in this region (Han et al., 2015). Therefore, the conductive zones C1, C2 and C3 are more likely to be the ancient mixing magma chambers of ultrapotassic melt and adakite-like melt related to porphyry Cu polymetallic deposits, with fluid exsolution in the top of magma chambers.

In addition, the conductance of the conductive zones C1-1 and C4 are also high (more than 10000S). These three conductive zones also show a good connection with the conductive zones C1, C2 and C3 in the upper crust. Therefore, the conductive zones C1-1 and C4 are more likely to result from the alkali-bearing aqueous fluids with high salinity (including a small number of the silicate melts), and are indicated as the pathways of the hydrothermal fluids beneath the Mo-dominated polymetallic deposits in the eastern segment of the CPCB.

5.3 Fluid migration

Combined with the Hf isotope results (Hou et al., 2015, 2023), the lower crust beneath the conductive zones C1, C2, C3 has the feature of high value and low zircon Hf crustal model ages, representing the possible juvenile lower crust; the region beneath the conductive zone C4 shows the feature of middle resistivity, while the lower crust beneath the conductive zone C4 has the feature of high value and low zircon Hf crustal model ages, representing the possible juvenile crust; the resistive zone R2 is distributed at depths of more than 25 km beneath the conductive zone C1-1, and the lower crust beneath the resistive zone R2 has the feature of low value ($-1 \sim -4$) and high zircon Hf crustal model ages, representing the old crust.

The conductive zone C1, which is interpreted as the ancient mixing magma chambers of ultrapotassic magma and adakite-like melt, resulted from the upwelling of the Cu-bearing hydrothermal fluids related to the partial melting of the juvenile lower crust. This conductive zone is mainly located beneath the Qulong and Jiama porphyry Cu-dominated polymetallic deposits, and is more likely to be acted as a shared deep-seated magma chamber, which provides the ore-bearing hydrothermal fluids to these two deposits. The electrical channels from depth of 40 km to depth of 10 km correspond well with the low-velocity zones obtained by the broadband seismology (He et al., 2022; Wu et al., 2023), which can be interpreted as the shared fluid pathway, providing the hydrothermal source of the porphyry Cu-dominated polymetallic deposit.

Similarly, the conductive zone C2 is also indicated as the ancient mixing magma chambers of ultrapotassic magma and adakite-like melt related to the mineralization of the Nuri porphyry Cu-dominated polymetallic deposits, and the upward extension of the conductive zone C2 to the shallow area may be represented as the possible fluid pathway beneath the Nuri porphyry Cu-dominated polymetallic deposit. Furthermore, the small-scale conductive zones around the Qulong, Jiama and Nuri

porphyry Cu-dominated polymetallic deposits at depths of less than 10 km (Figure. 4a, b) are the possible secondary magma chambers in the porphyry metallogenic system (e.g., Siltoe, 2010).

The Lakang'e and Bangpu porphyry Mo-dominated polymetallic deposits are above the conductive zones C4 and C1-1 of the upper crust (Figure. 4, 6), respectively. Furthermore, the conductive zones C4 and C1-1 also connect well with the conductive zones C3 and C1 of the upper-middle crust at depths of 20–30 km, which indicates that the hydrothermal Cu-bearing fluids that resulted from the partial melting of the juvenile lower crust migrated laterally to make the old crust reworking to release more Mo ions. The Mo ions occupied the dominant position in the hydrothermal fluids in the Lakang'e and Bangpu deposits, forming the porphyry Mo-dominated polymetallic deposit.

As mentioned above, the difference of the electrical feature is interesting between the Cu-dominated polymetallic deposits and Mo-dominated polymetallic deposits. The large-scale conductive zones of the upper-middle crust (C1, C2) are beneath the Qulong, Jiama and Nuri Cu-dominated polymetallic deposits; in contrast, the conductive zones of the upper crust are mainly beneath the Lakang'e and Bangpu Mo-dominated polymetallic deposits, and these conductive zones of the upper crust connect with some adjacent conductive zones of the upper-middle crust (C1, C2). It is indicated that the Cu-bearing hydrothermal fluids derived from the juvenile lower crust moved upward to the middle to upper crust, evolving the multi-stage magma chambers and forming porphyry Cu-dominated polymetallic deposits in the shallow area, while the lateral migration of the Cu-bearing hydrothermal fluids resulted in the reworking of the old crust to release more Mo ions from the old crust, forming porphyry Mo-dominated polymetallic deposits in the shallow area.

6. Conclusion

We conducted a detailed investigation of the crustal architecture and mineralization processes in the eastern segment of the collision-related porphyry copper-polymetallic metallogenic belt. We utilized an area-domain of MT data in Southern Tibet to generate a 3D electrical resistivity model. The model reveals three obvious low-resistivity zone in the upper-middle crust at depths of 20–40 km. Integrating our results with geochemical and geological constraints, and these three conductive zones are indicated as the ancient mixing magma chambers of ultrapotassic magma and adakite-like melt, with fluid exsolution in the top of magma chambers. The electrical channels from depth of 40 km to depth of 10 km can be interpreted as the fluid pathway, providing the hydrothermal source of the porphyry Cu-dominated polymetallic (Cu-Mo) deposits Qulong, Jiama and Bangpu). Furthermore, the Qulong and Jiama porphyry Cu-dominated polymetallic deposits may have a shared deep-seated magma at depths of 20–40 km in and shared fluid pathways ranging of 40 km -10 km. In addition, the Cu-bearing hydrothermal fluids also migrated laterally to make the old crust reworked to release more Mo ions in the vicinity of the Lakang'e and Bangpu deposits, forming the porphyry Mo-dominated polymetallic (Mo-Cu) deposit.

Declarations

Acknowledge

Special thanks to the CUGB MT team. GMT software package (Wessel and Smith, 1998) was used for maps. This work was also supported by the High-performance Computing Platform of China University of Geosciences Beijing.

Ethics approval and consent to participate

Not applicable.

Funding

The study is funded by: China Magnetotelluric Array (Phase I), National Science and Technology Major Project (2024ZD1000202), National Natural Science Foundation of China (42304087), National Key R&D Program of China (2022YFF0800901) and Fundamental Research Funds for the Central Universities (2-9-2023-202)

Author contributions

Yue Sheng: Conceptualization, Writing-original draft, Writing-review & editing, Visualization, Funding acquisition; Sheng Jin: Project administration, Writing-original draft, Reviewing, Funding acquisition, Supervision; Gaofeng Ye, Letian Zhang, Hao Dong, Yaotian Yin, Chengliang Xie, Jian'en Jing and Wenbo Wei: Reviewing, Project administration and Supervision. All authors have read and approved the final manuscript.

Availability of data and materials

The MT data sets used in this study are available from the first author and corresponding author upon reasonable request.

References

1. Archie GE (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. *Trans Am Inst Mech Eng* 146:54–67
2. Bian S, Gong JF, Zuza AV, Yang R, Tian YT, Ji JQ, Chen HL, Xu QQ, Chen L, Lin XB, Chen XG, Tu JT, Xu XJ (2020) Late Pliocene onset of the Cona rift, eastern Himalaya, confirms eastward propagation of extension in Himalayan-Tibetan orogen. *Earth & Planetary Science Letters*, 116383. [10.1016/j.epsl.2020.116383](https://doi.org/10.1016/j.epsl.2020.116383)
3. Booker JR (2014) The magnetotelluric phase tensor: a critical review. *Surv Geophys* 35(1):7–40. [10.1007/s10712-013-9234-2](https://doi.org/10.1007/s10712-013-9234-2)

4. Caldwell TG, Bibby HM, Brown C (2004) The magnetotelluric phase tensor. *Geophys J Int* 158:457–469. 10.1111/j.1365-246X.2004.02281.x
5. Ding L, Kapp P, Zhong DL, Deng WM (2003) Cenozoic Volcanism in Tibet: Evidence for a Transition from Oceanic to Continental Subduction. *J Petrol* 44(10):1833–1865
6. Dong H, Sun K, Egbert G, Kelbert A, Meqbel N (2024) Hybrid CPU-GPU solution to regularized divergence-free curl-curl equations for electromagnetic inversion problems. *Comput Geosci* 184:105518. 10.1016/j.cageo.2024.105518
7. Egbert GD (1997) Robust multiple-station magnetotelluric data processing. *Geophys J R Astron Soc* 136(2):475–496. 10.1111/j.1365-246X.1997.tb05663.x
8. Egbert GD, Kelbert A (2012) Computational recipes for electromagnetic inverse problems. *Geophys J Int* 189(1):251–267. 10.1111/j.1365-246x.2011.05347.x
9. Gamble TD, Goubau WM, Clarke J (1979) Magnetotellurics with a remote reference. *Geophysics* 44:53–68
10. Glover PWJ, Hole MJ, Pous J (2000) A modified archie's law for two conducting phases. *Earth Planet Sci Lett* 180(3–4):369–383. 10.1016/S0012-821X(00)00168-0
11. Glover PWJ (2010) A generalized archie's law for n phases. *Geophysics* 75(6). 10.1190/1.3509781
12. Guo X, Zhang L, Su X (2018) Melting inside the Tibetan crust? Constraint from electrical conductivity of peraluminous granitic melt. *Geophys Res Lett* 45:3906–3913. 10.1029/2018GL077804
13. Han Z, Wang R, Guo X, Gaillard L, Ni HW (2026) Hydrous ultrapotassic melts and trans-lithospheric weakening of Himalayan-Tibetan orogenesis: *Geology*, v. XX, p. XXX–XXX. 10.1130/G54026.1
14. Hashin Z, Shtrikman S (1962) A variational approach to the theory of the effective magnetic permeability of multiphase materials. *J Appl Phys* 33(10):3125–3131. 10.1063/1.1728579
15. Hashim L, Gaillard F, Champallier R, Le Breton N, Arbaret L, Scaillet B (2013) Experimental assessment of the relationships between electrical resistivity, crustal melting and strain localization beneath the Himalayan-Tibetan Belt. *Earth Planet Sci Lett* 373:20–30. 10.1016/j.epsl.2013.04.026
16. Hou ZQ, Duan L, Lu Y, Zheng Y, Zhu D, Yang Z, Yang Z, Wang B, Pei Y, Zhao Z, McCuaig TC (2015) Lithospheric architecture of the Lhasa terrane and its control on ore deposits in the Himalayan-Tibetan orogen. *Econ Geol* 110:1541–1575. 10.2113/econgeo.110.6.1541
17. Hou ZQ, Yang ZM, Wang R, Zheng YC (2020) Further discussion on porphyry Cu-Mo-Au deposit formation in Chinese mainland. *Earth Sci Front* 27(2):020–044. 10.13745/j.esf.sf.202.3.8
18. Hou ZQ, Wang R, Zhang HJ, Zheng YC, Jin S, Thybo H, Weinber RF, Xu B, Yang ZM, Hao AW, Gao L, Zhang LT (2023) Formation of giant copper deposits in Tibet driven by tearing of the subducted. Indian plate *Earth Sci Reviews* 243:104482
19. Huang S, Yao Y, Lu H, Tian Z, Zheng X, Wang Y, Luo R, S., Feng JK (2020) High-Resolution 3-D shear wave velocity model of the Tibetan plateau: implications for crustal deformation and porphyry Cu deposit formation. *Journal of Geophysical Research: Solid Earth*, 125. 10.1029/2019JB019215

20. Huang WT, Liang HY, Zhang J, Chen XL, Lin SP, Zou YQ, Ren L, Wu J, Zhang LP (2022) Formation of the Cretaceous skarn Cu–Au deposits of the southern Gangdese belt, Tibet: Case studies of the Kelu and Sangbujiala deposits. *Ore Geol Rev* 122:103481
21. Jones AG (1992) Electrical conductivity of the continental lower crust. In: Fountain DM, Arculus RJ, Kay RW (eds) *Continental lower crust*. Elsevier B.V., Amsterdam, Netherlands, pp 81–143
22. Kapp P, Guynn JH (2004) Indian punch rifts Tibet *Geol* 32(11):993–996
23. Kelbert A, Meqbel N, Egbert GD, Tandon K (2014) ModEM: a modular system for inversion of electromagnetic geophysical data. *Comput Geosci* 66:40–53. 10.1016/j.cageo.2014.01.010
24. Krieger L, Peacock JR (2014) MTpy: A Python toolbox for magnetotellurics. *Comput Geosci* 72:167–175. 10.1016/j.cageo.2014.07.013
25. Lin B, Tang JX, Tang P, Zheng WB, Song Y, Li FQ, Leng QF, Wang ZC, Qi J, Sun M, Rodríguez JD (2023) B Geology, geochronology, and exploration of the Jiama giant porphyry copper deposit (11 Mt), Tibet, China: A review, *China Geology*, (6), 338–357
26. Liu BR, Dai JG, Shen J, Xu S, Han X (2021) Evidence for deep processes from the Miocene potassic rock: dynamic subsidence and uplift of the India-Asia suture zone. *Lithos*, pp 388–389. 10.1016/j.lithos.2021.106061
27. Le Pape F, Jones AG, Unsworth MJ, Vozar J, Wei W, Jin S, Ye GF, Jing JE, Dong H, Zhang LT, Xie CL (2015) Constraints on the evolution of crustal flow beneath northern Tibet. *Geochem Geophys Geosyst* 16(12):4237–4260. 10.1002/2015GC005828
28. Luo CH, Wang R, Weinberg RF, Hou ZQ (2022) Isotopic spatial-temporal evolution of magmatic rocks in the Gangdese belt: Implications for the origin of Miocene post-collisional giant porphyry deposits in southern Tibet. *Geol Soc Am Bull* 1/2134. 10.1130/B36018.1
29. Luo M, Wood JR, Cathles LM (1994) Prediction of thermal conductivity in reservoir rocks using fabric theory. *J Appl Geophys* 32:321–334. 10.1016/0926-9851(94)90031-0
30. Miensoopust MP (2017) Application of 3-D electromagnetic inversion in practice: challenges, pitfalls and solution approaches. *Surv Geophys* 38:869–933
31. Miller C, Schuster R, Kitzli U, Frank W, Purtscheller F (1999) Post-collisional potassic and ultrapotassic magmatism in SW Tibet: Geochemical and Sr-Nd-Pb-O isotopic constraints for mantle source characteristics and petrogenesis. *J Petrol* 40:1399–1424
32. Mo X (2011) Magmatism and Evolution of the Tibetan Plateau. *Geol J China Universities* 17(3):351–367 (in Chinese with English abstract)
33. Ni HW, Hui H, Steinle-Neumann G (2015) Transport properties of silicate melts. *Reviews Geophys* v 53(3):715–744. 10.1002/2015RG000485
34. Ni HW, Zhang L, Xiong X, Mao Z, Wang J (2017) Supercritical fluids at subduction zones: evidence, formation condition, and physicochemical properties. *Earth Sci Rev* 167:62–71. 10.1016/j.earscirev.2017.02.006

35. Qi J, Chi GX, Tang JX, Wang YM, Tang P, Wang MD (2025) In-situ trace element and sulfur isotope analyses of sulfides as indicators of ore-forming fluid evolution in the Lakang'e porphyry Mo-Cu deposit, Tibet, China. *Ore Geol Rev* 183:106690
36. Qu X, Hou ZQ, Zaw K et al (2007) Characteristics and genesis of Gangdese porphyry copper deposits in the southern Tibetan Plateau: Preliminary geochemical and geochronological results. *Ore Geol Rev* 31(1–4):205–223. 10.1016/j.oregeorev.2005.03.012
37. Rippe D, Unsworth MJ (2010) Quantifying crustal flow in Tibet with magnetotelluric data. *Phys Earth Planet Inter* 179(3–4):107–121. 10.1016/j.pepi.2010.01.009
38. Roberts JJ, Tyburczy JA (1999) Partial-melt electrical conductivity: Influence of melt composition. *J Geophys Res* 104:7055–7065
39. Somerton WH (1992) Thermal properties and temperature. Elsevier, -related behavior of rock/fluid systems
40. Sheng Y, Jin S, Comeau MJ, Becken M, Dong H, Zhang LT, Wei WB, Ye GF (2022) Controls on the metallogenesis of the Lhasa-Mozugongka district, Gangdese Belt, Tibetan Plateau: Constraints on melt distribution and viscosity from the 3-D electrical structure of lithosphere. *Ore Geol Reviews* Doi. 10.1016/j.oregeorev.2022.104881
41. Sheng Y, Jin S, Comeau MJ, Hou ZQ, Becken M, Dong H, Zhang LT, Wei WB, Ye GF (2023) Evidence for partial melting and alkali-rich fluids in the crust from a 3-D electrical resistivity model in the vicinity of the Coqen region, western Lhasa terrane, Tibetan Plateau. *Earth Planet Sci Lett* 118316. 10.1016/j.epsl.2023.118316
42. Sillitoe RH (2010) Porphyry Copper Systems. *Econo Geol* 105(1):3–41. 10.2113/gsecongeo.105.1.3
43. Sun YJ, Dong SW, Wang X, Liu M, Zhang H, Shi Y (2022) Three-dimensional thermal structure of East Asian continental lithosphere. *J Geophys Research: Solid Earth* 127:e2021JB023432. <https://doi.org/10.1029/2021JB023432>
44. Tang JX, Yang HH, Song Y, Wang LQ, Liu ZB, Li BL, Lin B, Peng B, Wang GH, Zeng QG, Wang Q, Chen W, Wang N, Li ZJ, Li YB, Li YB, Li HF, Lei CY (2021) The copper polymetallic deposits and resource potential in the Tibet Plateau. *China Geol* 4(1):1–16. 10.31035/cg2021016
45. Tang JX, Wang LQ, Zheng WB, Zhong KH (2014) Ore deposit Metallogenic regularity and prospecting in the eastern section of the Gangdese Metallogenic Belt. *ACTA GEOLOGICAL SINICA* (English abstract), 88. 122545–2555. 10.3969/j.issn.0001-5717.2014.12.027
46. Tang P, Tang JX, Lin B, Wang LQ, Zheng WB, Leng QF, Gao X, Zhang Z, Tang X (2019) Mineral chemistry of magmatic and hydrothermal biotites from the Bangpu porphyry Mo (Cu) deposit, Tibet. *Ore Geol Rev* 115:103122. 10.1016/j.oregeorev.2019.103122
47. Tang P, Tang JX, Wang LQ, Lin B, Li FQ, Qi J, Wang MD, Xiong Y, Xie JL, Tao G (2024) Apatite and zircon geochemistry deciphers difference in the nature of ore-forming magma in the Bangpu porphyry Mo-Cu deposit, Tibet. *J Asian Earth Sci* 264:106049
48. Tang P, Tang JX, Lin B, Zhou A, Li FQ, Fang X, Qi J, Wang MD, Xiong Y, Xie KK, Yang ZK, Yao XF (2025) Genesis of the South Pit Deposit in Jiama District, Tibet: Constraints from Geology, Geochronology

- and Amphibole Geochemistry[J]. *J Earth Sci* 36(4):1479–1492
49. Tapponnier P, Xu Z, Roger F, Meyer B, Arnaud N, Wittlinger G, Yang J (2001) Oblique stepwise rise and growth of the Tibet Plateau. *Science* 294:1671–1677
 50. Tang ZL, Qian ZZ, Jiang CY, Yan HQ, Jiao JG, Liu MW, Xu ZH, Xu G, Wang YL (2011) Trends of research in exploration of magmatic sulfide deposits and small intrusions metallogenic system. *J Earth Sci Environ* 33(1):1–9. 10.3969/j.issn.1672-6561.2011.01.001
 51. Unsworth MJ, Jones AG, Wei W, Marquis G, Gokarn SG, Spratt JE, Team (2005) Crustal rheology of the Himalaya and Southern Tibet inferred from magnetotelluric data. *Nature* 438(7064):78–81. 10.1038/nature04154
 52. Wang R, Richards JP, Zhou LM, Hou ZQ, Stern RA, Creaser RA, Zhu JJ (2015) The role of Indian and Tibetan lithosphere in spatial distribution of Cenozoic magmatism and porphyry Cu–Mo deposits in the Gangdese belt, southern Tibet. *Earth Sci Rev* 150:68–94. 10.1016/j.earscirev.2015.07.003
 53. Wang R, Richards JP, Zhou LM, Hou ZQ, Stern RA, Creaser RA, Zhu JJ (2015) The role of Indian and Tibetan lithosphere in spatial distribution of Cenozoic magmatism and porphyry Cu–Mo deposits in the Gangdese belt, southern Tibet. *Earth-Science Reviews*, 2015, Vol.150: 68–94. 10.1016/j.earscirev.2015.07.003
 54. Wang R, Weinberg RF, Collins WJ, Richards JP, Zhu DC (2018) Origin of postcollisional magmas and formation of porphyry Cu deposits in southern Tibet: *Earth-Science Reviews*, v. 181. 122–143. 10.1016/j.earscirev.2018.02.019
 55. Wang R, Weinberg RF, Zhu DC, Hou ZQ, Yang ZM (2021) The impact of a tear in the subducted Indian plate on the Miocene geology of the Himalayan-Tibetan orogen. *GSA Bull* Doi. 10.1130/B36023.1
 56. Wang R, Zhu DC, Wang Q, Hou ZQ, Yang ZM, Zhao ZD, Mo XX (2020) Porphyry mineralization in the Tethyan orogen. *Science China (Earth Sciences)*
 57. Wang Y (2012) The Research on Gravity and Magnetic Anomaly Characteristic and Prospecting Law of Porphyry Type Copper Mine in Tibet. (A dissertation submitted to Chengdu University of Technology for doctoral degree)
 58. Wei WB, Unsworth M, Jones A, Booker J, Tan HD, Nelson D, Chen LS, Li SH, Solo K, Bedrosian P, Jin S, Deng M, Ledo J, Kay D, Roberts B (2001) Detection of widespread fluids in the Tibetan crust by magnetotelluric studies. *Science* 292(5517):716–719. 10.1126/science.1010580
 59. Weidelt P (1985) Construction of conductance bounds from magnetotelluric impedances. *J Geophys - Z Fur Geophysik* 57(3):191–206
 60. Wu W, He RZ, Ji ZB, Niu X, Wang C, Li ZX (2023) Crustal structure and mineralization indications of the Jiama- Qulong deposits. *Dizhi Xuebao/Acta Geologica Sinica* 97(8):2534–2546
 61. Xu B, Griffin WL, Xiong Q, Hou ZQ, O'Reilly SY, Guo Z, Pearson NL, Gréau Y, Yang ZM, Zheng YZ (2017) Ultrapotassic rocks and xenoliths from South Tibet: Contrasting styles of interaction between lithospheric mantle and asthenosphere during continental collision. *Geology*, 2017, Vol.45(1): 51–54
 62. Xu B, Hou ZQ, Griffin WL, O'Reilly SY, Zheng YC, Wang T, Fu B, Xu JF (2022) In-situ mineralogical interpretation of the mantle geophysical signature of the Gangdese Cu-porphyry mineral system.

63. Xu ZQ, Yang JS, Hou Z, Zhang Q, Zeng ZM, Li LS, Zhang HB, Li JX, Z. H., Ma XX (2016) The progress in the study of continental dynamics of the Tibetan Plateau. *Geol China* 43(1):1–42 (in Chinese with English abstract)
64. Xue QW, Wang R, Liu SY, Shi WX, Tong XS, Li YY, Sun F (2021) Significance of chlorite hyperspectral and geochemical characteristics in exploration: a case study of the giant Qulong porphyry Cu-Mo deposit in collisional orogen, southern Tibet. *Ore Geology Reviews*, p 104156
65. Yang ZM, Lu YC, Hou ZQ, Chang ZS (2015) High-Mg Diorite from Qulong in Southern Tibet: Implications for the Genesis of Adakite-like Intrusions and Associated Porphyry Cu Deposits in Collisional Orogens. *J Petrol* 56(2):227–254. 10.1093/petrology/egu076
66. Yang ZM, Fu Y (2020) Distinct evolution history of magmatic oxygen fugacity and its control on associated porphyry Cu deposits under subduction and collisional settings. *Geological Journal*, (5)
67. Yang ZM, Hou ZQ (2009) Porphyry Cu deposits in collision orogen setting: a preliminary genetic model. *Mineral Deposits* 28(5):515–538
68. Yin A, Harrison TM (2000) Geologic evolution of the Himalayan–Tibetan orogen. *Annu Rev Earth Planet Sci* 28:211–280. 10.1146/annurev.earth.28.1.211
69. Yin A (2004) Gneiss domes and gneiss dome systems. *Special Paper of the Geological Society of America*, 380. 10.1130/0-8137-2380-9.1
70. Yu L, Evans RL, R. N., Edwards (1997) Transient electromagnetic responses in seafloor with triaxial anisotropy. *Geophys J Int* 129:292–304
71. Zhang HR, Hou ZQ (2015) Pattern and process of continent-continent collision orogeny: a case study of the Tethys Collisional Orogen. *ACTA GEOLOGICA SINICA*, pp 1539–1559. 9
72. Zhao Z, Mo X, Dilek Y, Niu Y, DePaolo DJ, Robinson P, Zhu D, Sun C, Dong G, Hou ZQ (2009) Geochemical and Sr-Nd-Pb-O isotopic compositions of the postcollisional ultrapotassic magmatism in SW Tibet: petrogenesis and implications for India intra-continental subduction beneath southern Tibet. *Lithos* 113:190–212
73. Zhao Y, Yu JX, Xu B, Zhang YF, Wang ZX, Hou ZQ, Kou GY, Zhao ZY (2023) Zircon Hf-O and apatite Sr-O isotopes jointly reveal the origin and mineralization of the Miocene adakitic porphyries in the Gangdese belt. *Ore Geol Rev*, 105536
74. Zheng YC, Liu SA, Wu CD, Griffin WL, Li ZQ, Xu B, Yang ZM, Hou ZQ, O'Reilly SY (2018) Cu isotopes reveal initial Cu enrichment in sources of giant porphyry deposits in a collisional setting. *Geol Doi*. 10.1130/G45362.1
75. Zheng YC, Wu CD, Tian SH, Hou ZQ, Fu Q, Zhu DC (2020) Magmatic and structural controls on the tonnage and metal associations of collision-related porphyry copper deposits in southern Tibet. *Ore Geol Rev* 122:103509. 10.1016/j.oregeorev.2020.103509
76. Zhu DC, Zhao ZD, Niu Y, Mo XX, Chung SL, Hou ZQ et al (2011) The Lhasa terrane: record of a microcontinent and its histories of drift and growth. *Earth Planet Sci Lett* 301(1–2):241–255. 10.1016/j.epsl.2010.11.005

77. Zhu DC, Zhao ZD, Niu Y, Dilek Y, Wang Q, Ji WH et al (2012) Cambrian bimodal volcanism in the Lhasa terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc in the Australian proto-Tethyan margin. *Chem Geol* 328(11):290–308. 10.1016/j.chemgeo.2011.12.024

Figures

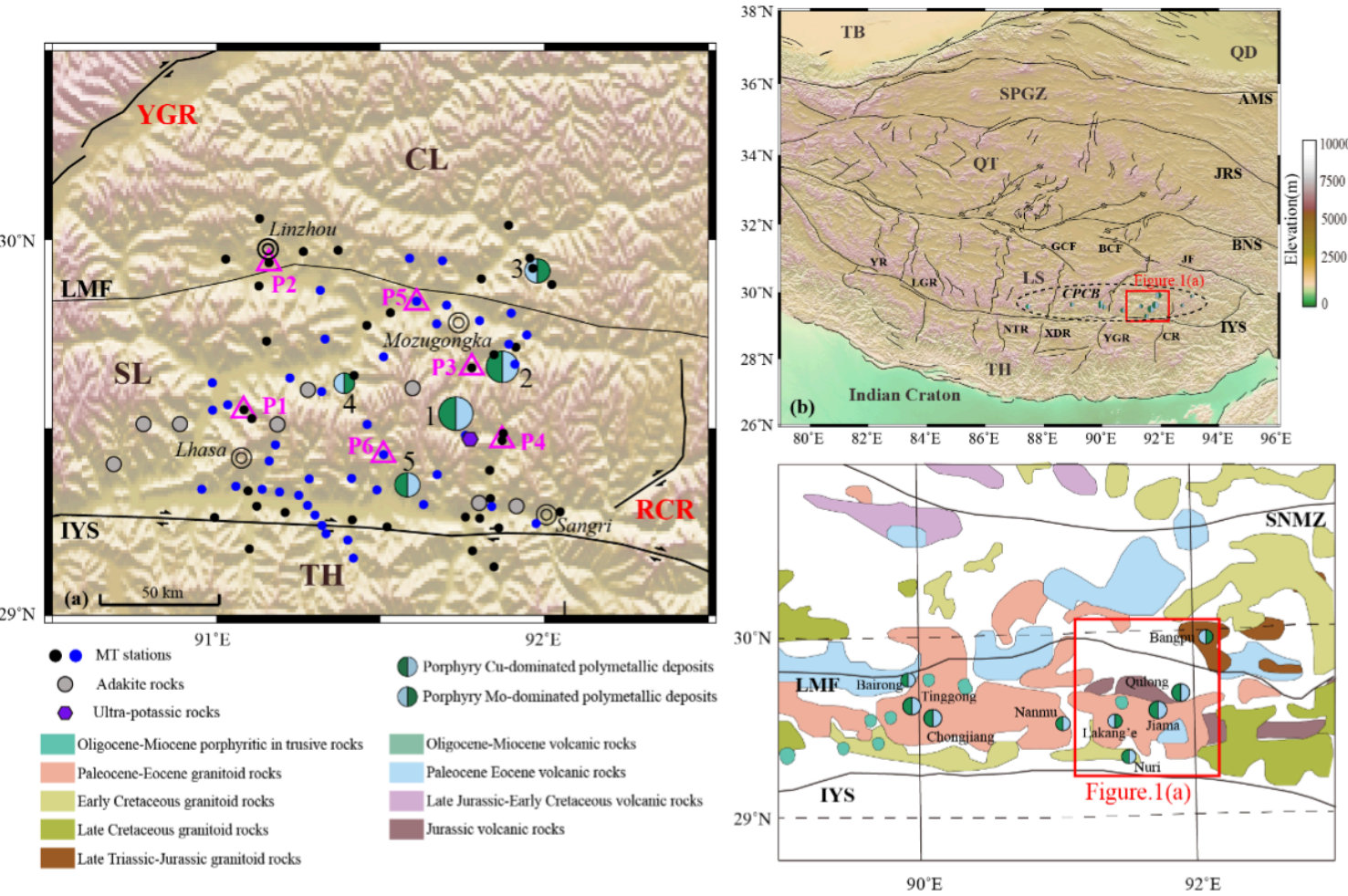


Figure 1

Map of the study area. (a) The locations of magnetotelluric measurements (black dots and black dots with red circles; the latter represent the new newly acquired measurements) and major tectonic structures (black lines with red labels=rifts, black lines with black labels=terranes). The six sites circled in pink are shown in Figure 3. (b) Topography of the Tibetan Plateau and its adjacent areas. The red rectangle outlines the study area. (c) Magmatic rocks. The main ore deposits and mineralization districts are indicated (derived from Hou et al., 2015), in addition to adakitic (red squares) and ultrapotassic magmatic rocks (black squares) (derived from Nie et al., 2025). TH=Tethys-Himalaya terrane, LS: Lhasa terrane, SL: Southern Lhasa terrane, CL: Central Lhasa terrane, QT: Qiangtang terrane, SPGZ: Songpan-Ganzi terrane, QD: Qaidam Basin, TB: Tarim Basin; IYS: Indus-YarlungZangbo suture; LMF: Luobadui- Milashan Fault; SNMZ: Shiquan River- Nam Tso Mélange Zone; BNS: Banggong- Nujiang suture; JRS: Jinsha River suture; AMS: Animaqing suture; CR: Riduo-Woka-Cuona; YGR: Yadong-Gulu Rift; XDR: Xainza-Dinggye Rift; NTR: Niyima-Tingri Rift; LGR:

Longgar Rift. YR: Yari Rift. CPCB: Collision-related porphyry copper- polymetallic metallogenic belt; Ore deposits: 1 Qulong, 2 Jiama, 3 Bangpu, 4 Lakang'e, 5 Nuri.

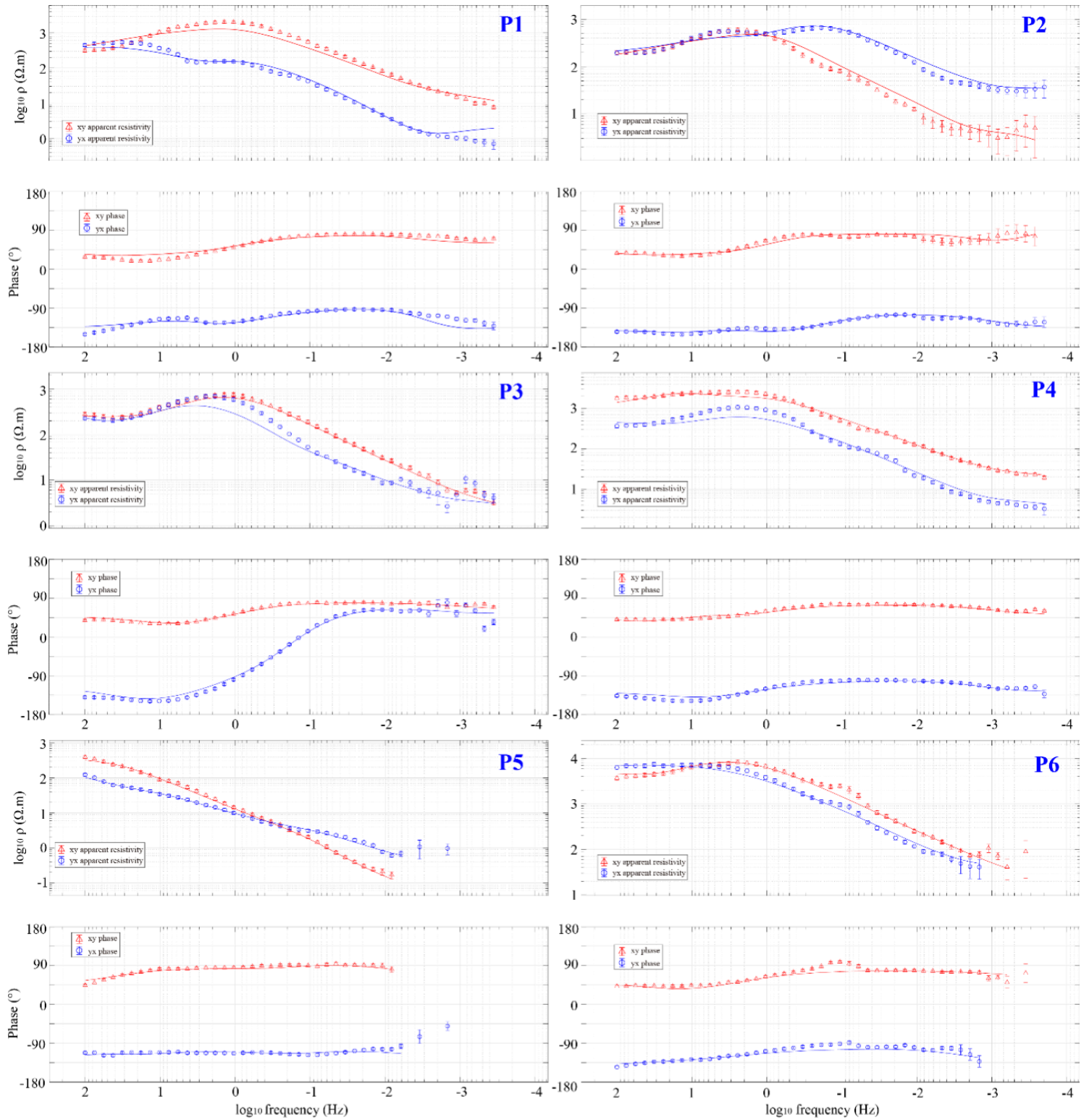


Figure 2

Typical apparent resistivity and impedance phase data (dots). The blue and red colors denote two different modes. The lines are from the 3-D model. A good fit between data and model is observed.

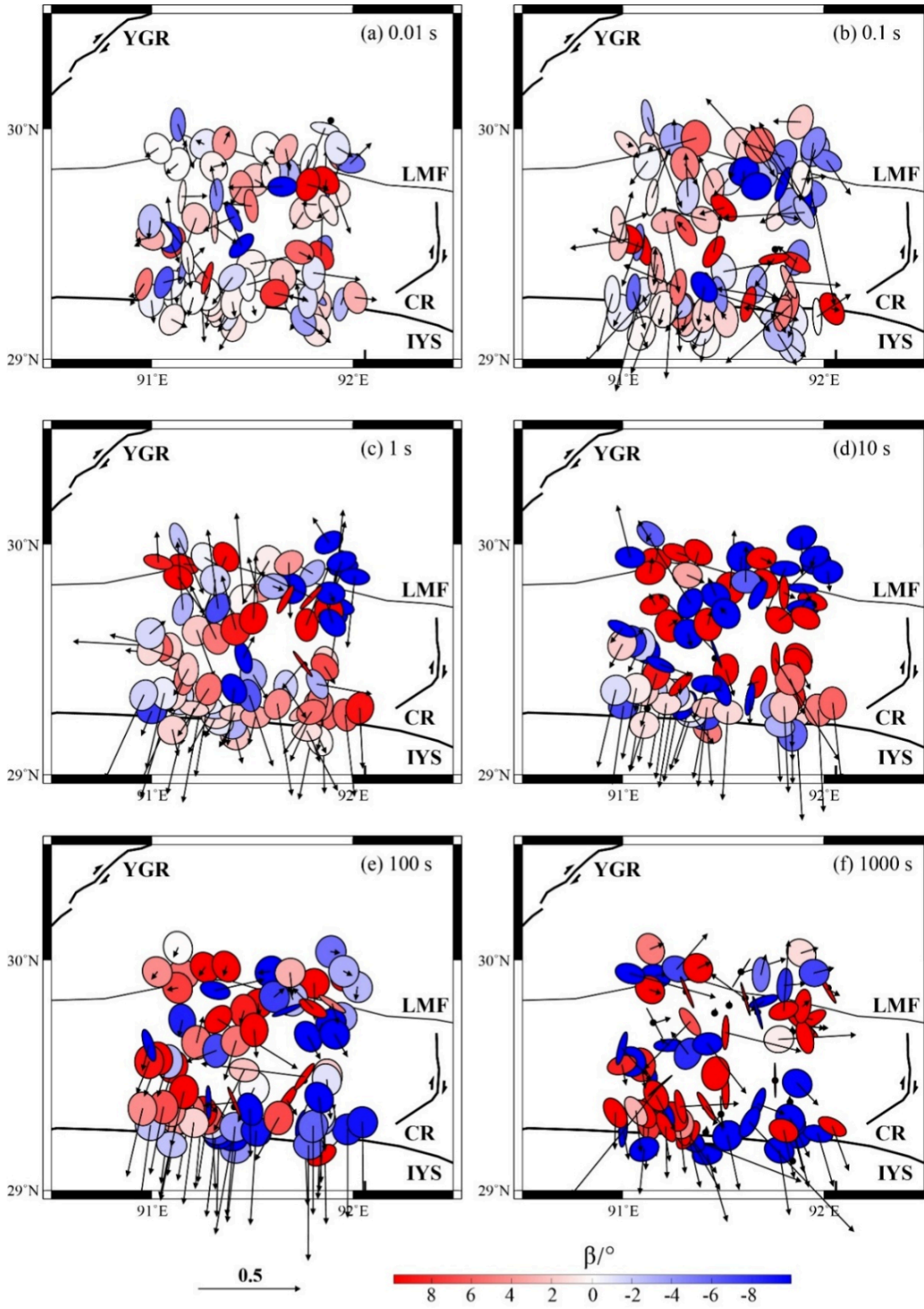


Figure 3

Phase tensor and induction vectors of the MT data

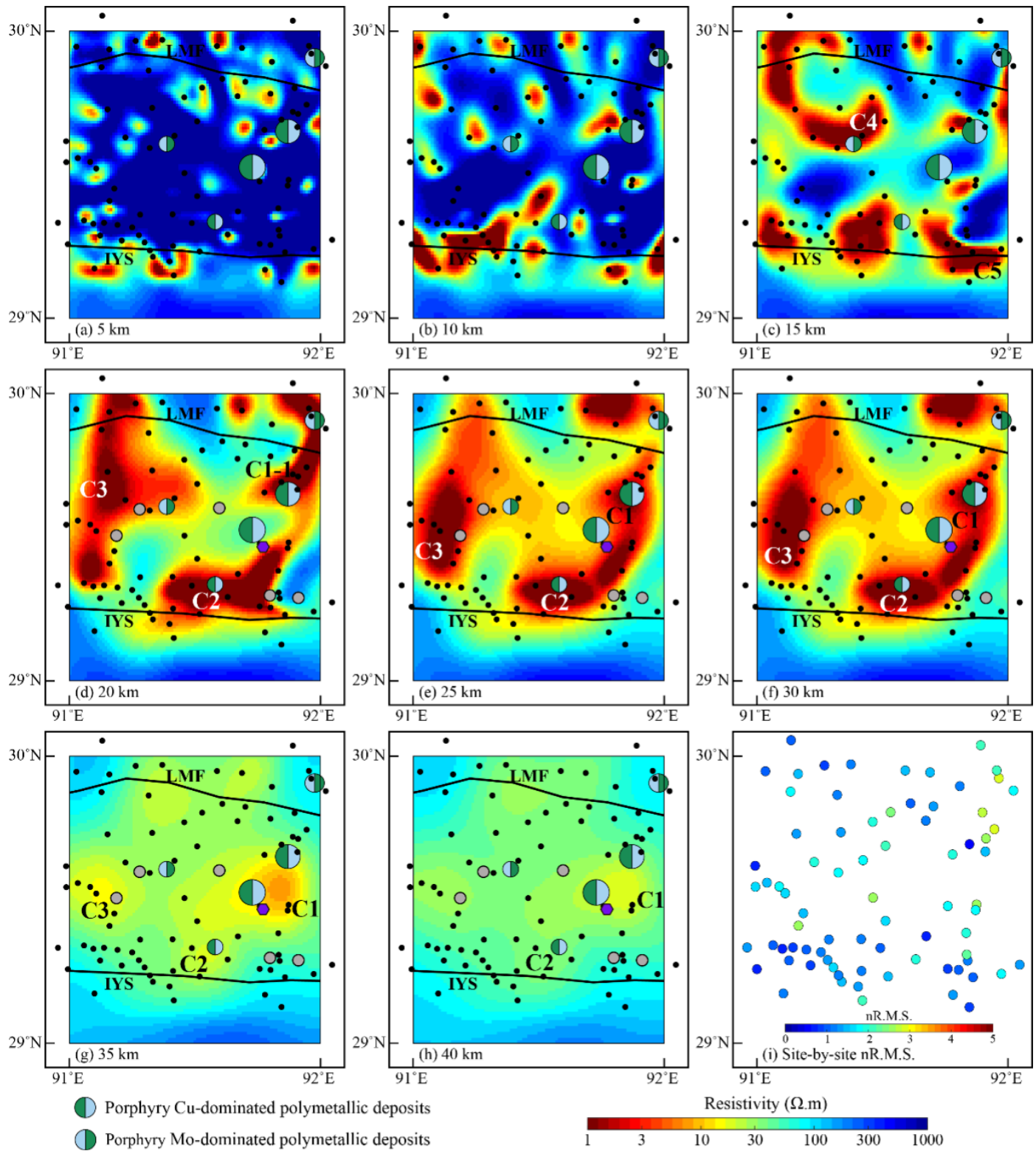


Figure 4

Horizontal slices of the electrical resistivity model at depths of (a) 5 km, (b) 10 km, (c) 15 km, (d) 20 km, (e) 25 km, (f) 30 km, (g) 35 km, and (h) 40 km. (h) Site-by-site nR.M.S. of the 3-D inversion. Conductive zones: C1, C2, C3, C4, C5 and C1-1.

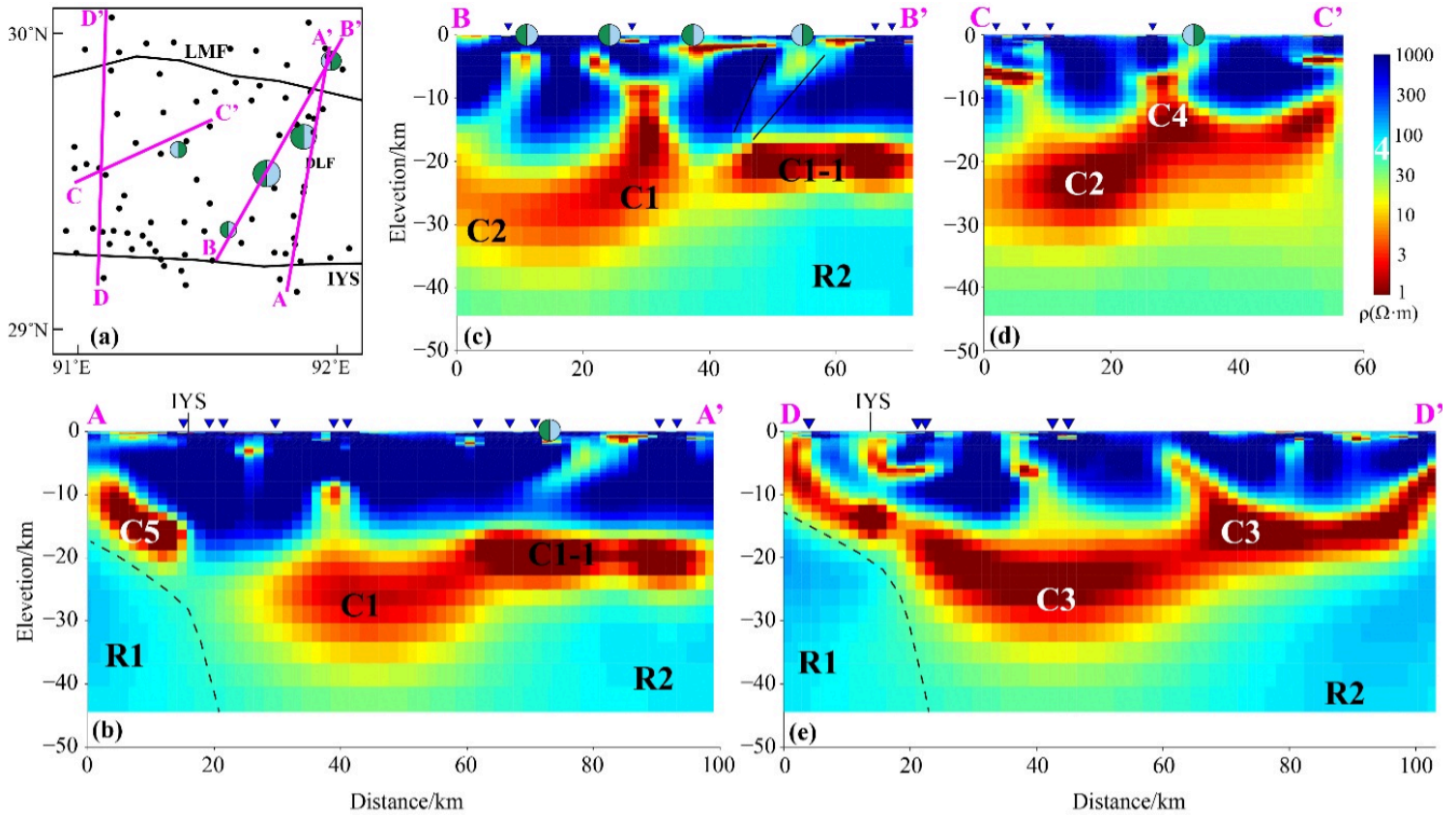


Figure 5

Vertical cross-section of the electrical resistivity model along different profiles. (a) Locations of the MT vertical cross-sections; (b)-(d) Vertical cross-section of the electrical resistivity model. Conductive zones: C1, C2, C3, C4, C5 and C1-1. Resistive zones: R1 and R2.

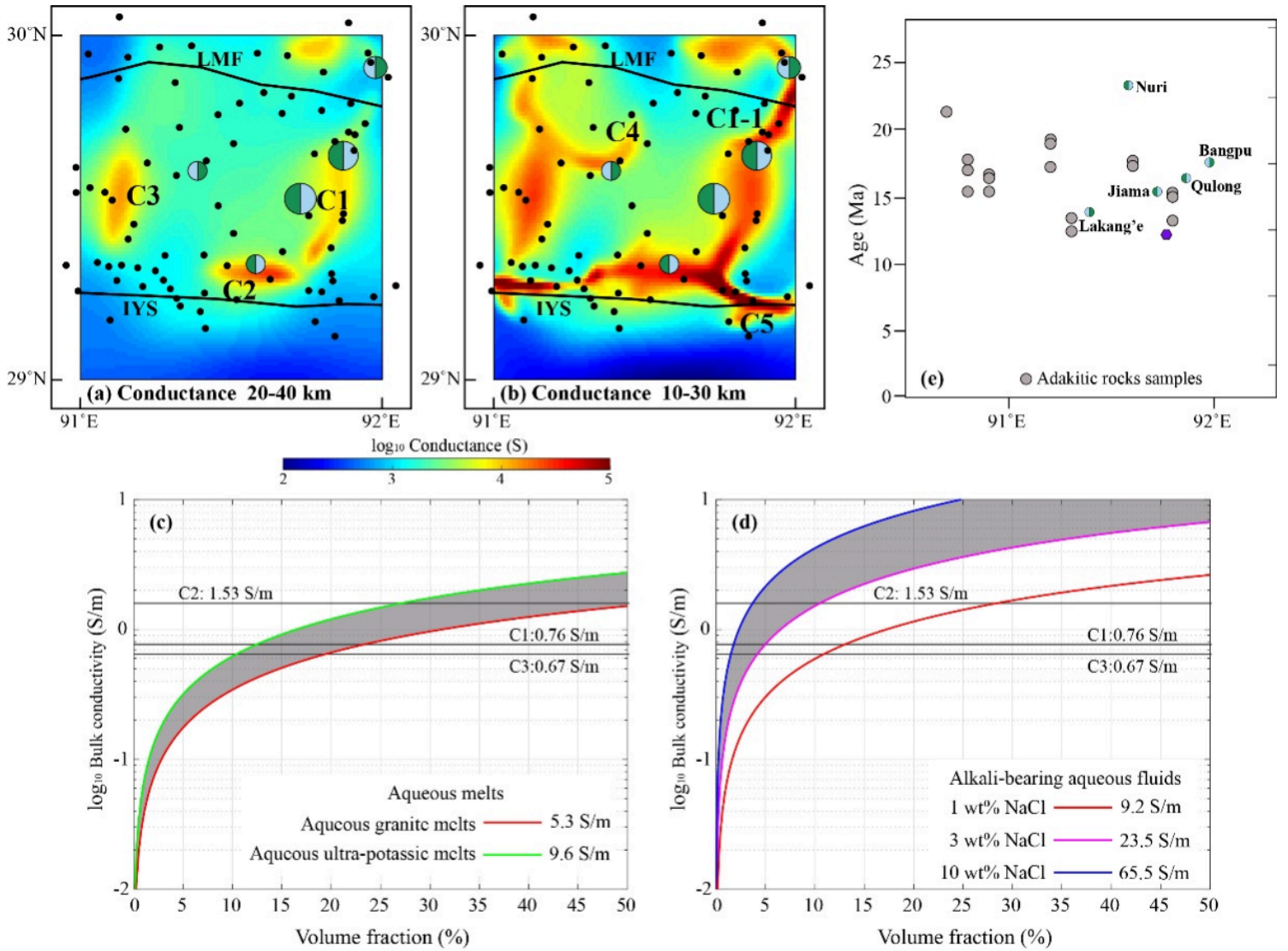


Figure 6

Volume fractions of melts and fluids in the conductive zones. (a) Conductance at depths of 20-40 km in the conductive zones C1, C2 and C3; (b) Conductance at depths of 10-30 km in the conductive zones C4, C5 and C1-1; (c) Curves of bulk conductivity and the volume fractions of melts; (d) Curves of bulk conductivity and the volume fractions of the Alkali-bearing aqueous fluids. (e) Comparative plot of magmatic rock ages and metallogenic ages. The ages of adakitic rocks are from the summary of Bian et al. (2022). The ages of the porphyry Cu polymetallic deposits are from the summary of Hou et al. (2015).

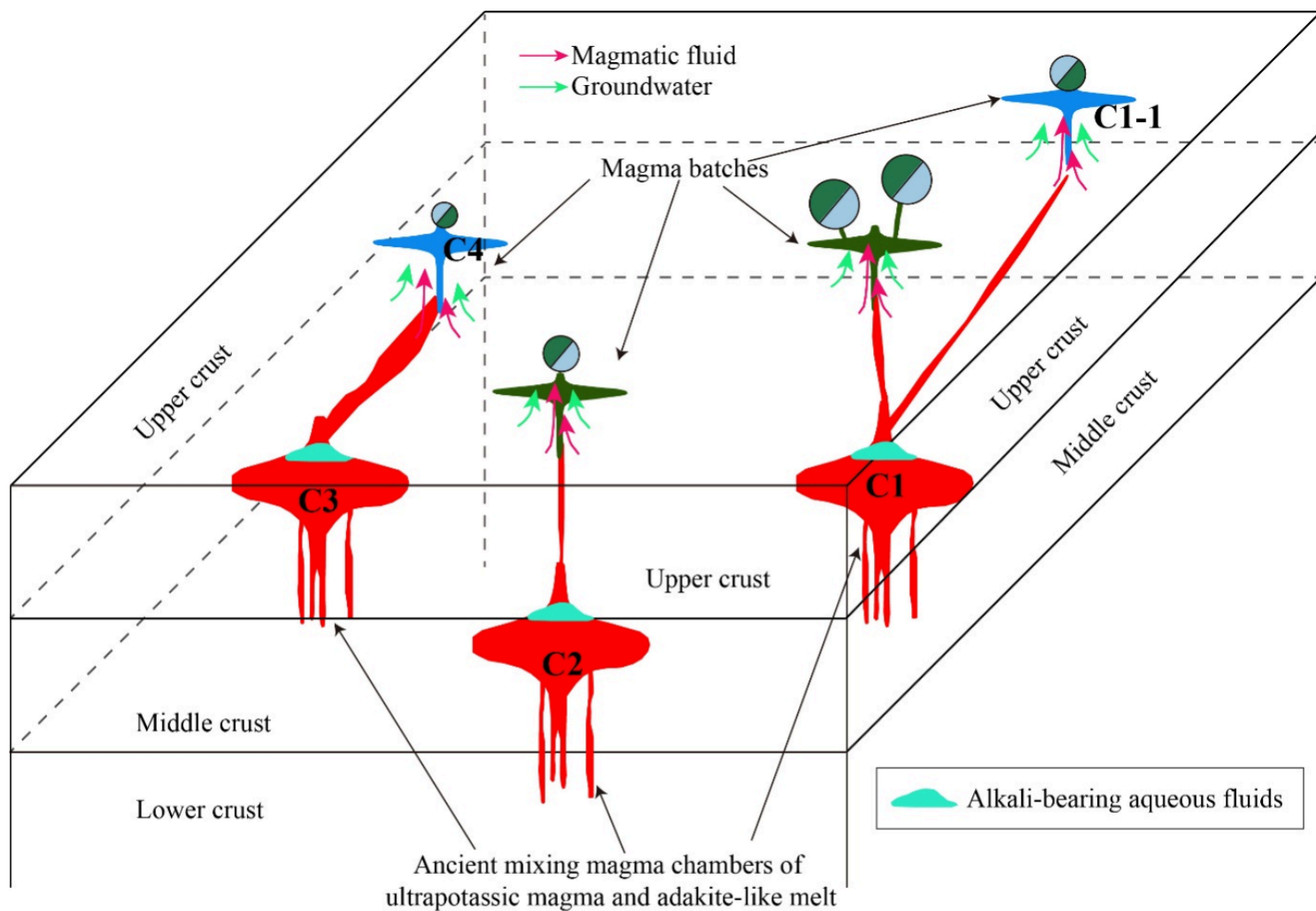


Figure 7

Metallogenic backgrounds of the eastern segment of the collision-related porphyry copper polymetallic metallogenic belt

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Graphicalabstract.doc](#)
- [SupportingInformation.docx](#)