Translithospheric magma plumbing system of intraplate volcanoes as revealed by electrical resistivity imaging

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ABSTRACT

The magma plumbing systems of volcanoes in subduction and divergent tectonic settings are relatively well known, whereas those of intraplate volcanoes remain elusive; robust geophysical information on the magma pathways and storage zones is lacking. We inverted magnetotelluric data to image the magma plumbing system of an intraplate monogenetic volcanic field located above the stagnant Pacific slab in northeast China. We identified a complex, vertically aligned, low-resistivity anomaly system extending from the asthenosphere to the surface consisting of reservoirs with finger- to lens-like geometries. We show that magma forms as CO_2-rich melts in a 150-km-deep asthenospheric plume crossing the whole lithosphere as hydrated melt, inducing underplating at 50 km depth, evolving in crustal reservoirs, and erupting along dikes. Intraplate volcanoes are characterized by low degrees of melting and low magma supply rates. Their plumbing systems have a geometry not so different from that of volcanoes in subduction settings.

INTRODUCTION

Volcanoes on Earth are concentrated along subduction zones, mid-ocean ridges, and continental rifts. Volcanism in intraplate settings is poorly understood and is interpreted as the result of mantle melting processes induced by the rising of hot plumes or by the release of fluids from stagnant slabs (Chen et al., 2017). The magma plumbing systems of intraplate monogenetic volcanoes above stagnant slabs are enigmatic and lack robust geophysical constraints. In particular, the full magma pathway from the asthenosphere to the surface as well as the size and geometry of the storage zones are poorly known (Smith and Németh, 2017). Northeast China has monogenetic volcanic fields such as the Jingpohu monogenetic volcanic field (JMVF) and a metasomatized mantle plume located above the ~500-km-deep stagnant Pacific slab (Figs. 1A–1D; Chen et al., 2017; Li et al., 2020b). We obtained well-resolved images of the JMVF magma plumbing system from a depth of ~150 km to the surface by inverting magnetotelluric (MT) data, which are useful in identifying magma storage zones below volcanoes (Hill et al., 2009; Comeau et al., 2015). Data were collected from an array of MT stations centered on the JMVF (Fig. 1E). We recognized a complex resistivity pattern below the JMVF. The observed anomalies, integrated with rock-physics models, provide a well-constrained picture of the structure of the plumbing system of a monogenetic volcanic field from the asthenosphere to the surface. Our results at the JMVF provide new insights into the geometry, size, and depth of magma reservoirs for volcanoes in intraplate settings (Smith and Németh, 2017).

GEOLOGIC SETTING

JMVF activity mainly developed in the Pleistocene and Holocene, with the last eruptions occurring in historical times (2470 and 3940 yr B.P.; Wei et al., 2003). The JMVF vents follow two main alignments: a large-scale northeast-southwest alignment and a local north-south alignment (Fig. 1F). The northeast-southwest alignment is controlled by the left-lateral, ENE-WSW– to northeast-southwest–striking Dunhua-Mishan fault (DMF) system, which affects the entire crust and the mantle to depths of 35–40 km (Xu et al., 2017). The Yilan-Yitong fault (YYF) system is located north of the JMVF and bounds the Songliao sedimentary basin. The JMVF eruptions produced ~2 km³ of basaltic, trachybasaltic and basanitic lava flows and scorias. The compositions of basalts record mixing between enriched mantle 1 (EM1) and depleted mantle (DM) sources and contamination by lower-crust material (Zhang et al., 2000; Yan and Zhao, 2008). The alkaline volcanism of northeast China, including the JMVF, involved carbonate melts (C melts) supplied from the mantle transition zone (MTZ) by the eclogites in the stagnant Pacific slab and peridotites associated with the overlying mantle wedge (Figs. 1B–1D; Xu et al., 2020; Zhang et al., 2020).

MAGNETOTELLURIC DATA AND MODELING

Magnetotelluric data were collected using nine long-period MT (LMT) and 31 broadband MT (BBMT) stations (Fig. 1E) arranged around the JMVF. We deployed 25 BBMT instruments in a grid with an average spacing of ~33 km. In the central area, six BBMT stations were added to the network to better constrain the crust structure beneath the JMVF. The BBMT data were collected using a minimum acquisition time of
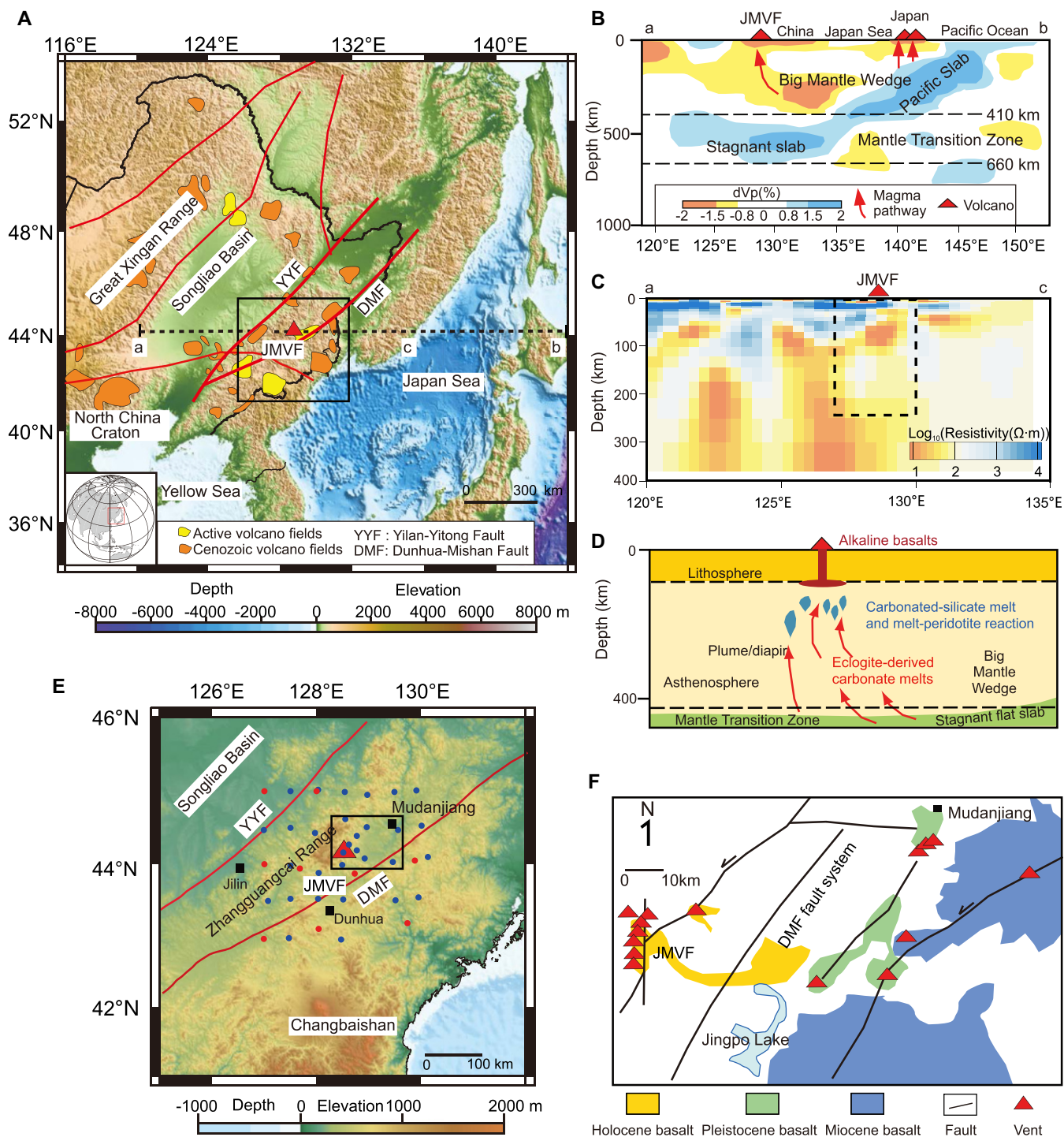
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Figure 1. Tectonic setting of northeast China and the structural scheme of the Jingpohu monogenetic volcanic field (JMVF) area. (A) Distribution of volcanism and major tectonic structures in northeast China. (B) Location of high- and low-Vp anomalies along profile a–b in A (modified from Ma et al., 2019). (C) Resistivity model along profile a–c in A (modified from Li et al., 2020b). (D) Schematic illustration of petrological model for northeast China magmatism modified from Xu et al. (2020) and Zhang et al. (2020). (E) Location of JMVF area and distribution of magnetotelluric (MT) stations (LMT—long-period MT; BBMT—broadband MT). Box around the JMVF outlines the area of JMVF geologic map in F. Volcanic fields are marked with red triangles. (F) Simplified geologic map of JMVF area (modified from Zhang et al., 2000).

20 h and processed to obtain full impedance with periods from ~0.003 s to 2000 s, while >20 d LMT data had responses with periods from 10 s to ~20,000 s. Representative apparent resistivity and phase curves of off-diagonal and full-impedance tensors around JMVF are reported in Figures S1 and S2, respectively, in the

Supplemental Material[1]. A three-dimensional,

nonlinear, conjugate-gradient inversion technique was applied to convert the MT responses to resistivity images from data sets including off-diagonal and full-impedance tensors. Compared to the off-diagonal impedance inversion model, the full-impedance inversion model showed a more complicated resistivity pattern

at crustal depth (Fig. S3), likely due to some distortion of diagonal impedances by noise (Fig. S2). As the two prominent anomalies in the mantle are key to understanding the deep structure below JMVF, we preferred the inversion model from off-diagonal impedances. Selection of this model also considered the facts that the fitting of the full-impedance tensor was not satisfactory, that of off-diagonal data was good (Fig. S1), and the diagonal component was often significantly smaller than the off-diagonal impedance (e.g.,

curve on site 47 in Fig. S2). Details on the data elaboration, inversion methods, evaluation of the quality of the inversion from off-diagonal impedance tensor data, and sensitivity analysis are provided in the Supplemental Material and Figures S4–S9.

RESULTS

Figure 2 shows the resistivity structure of the JMVF and surrounding area. The anomaly pattern is characterized by deep-rooted, vertically

aligned, low-resistivity zones in the mantle and shallower anomalies at the Moho and in the crust. From the surface to ~20 km depth, the crust beneath the JMVF is generally highly resistive, with resistivity values up to ~10^4 $\Omega \cdot m$ (anomaly R in Figs. 2D and 2E). These values are consistent with the occurrence of the Precambrian and Paleozoic plutonic rocks of the Zhangguangcai Range (Xu et al., 2017). Localized sheet-like low-resistivity anomalies also exist, which are mostly distributed along the
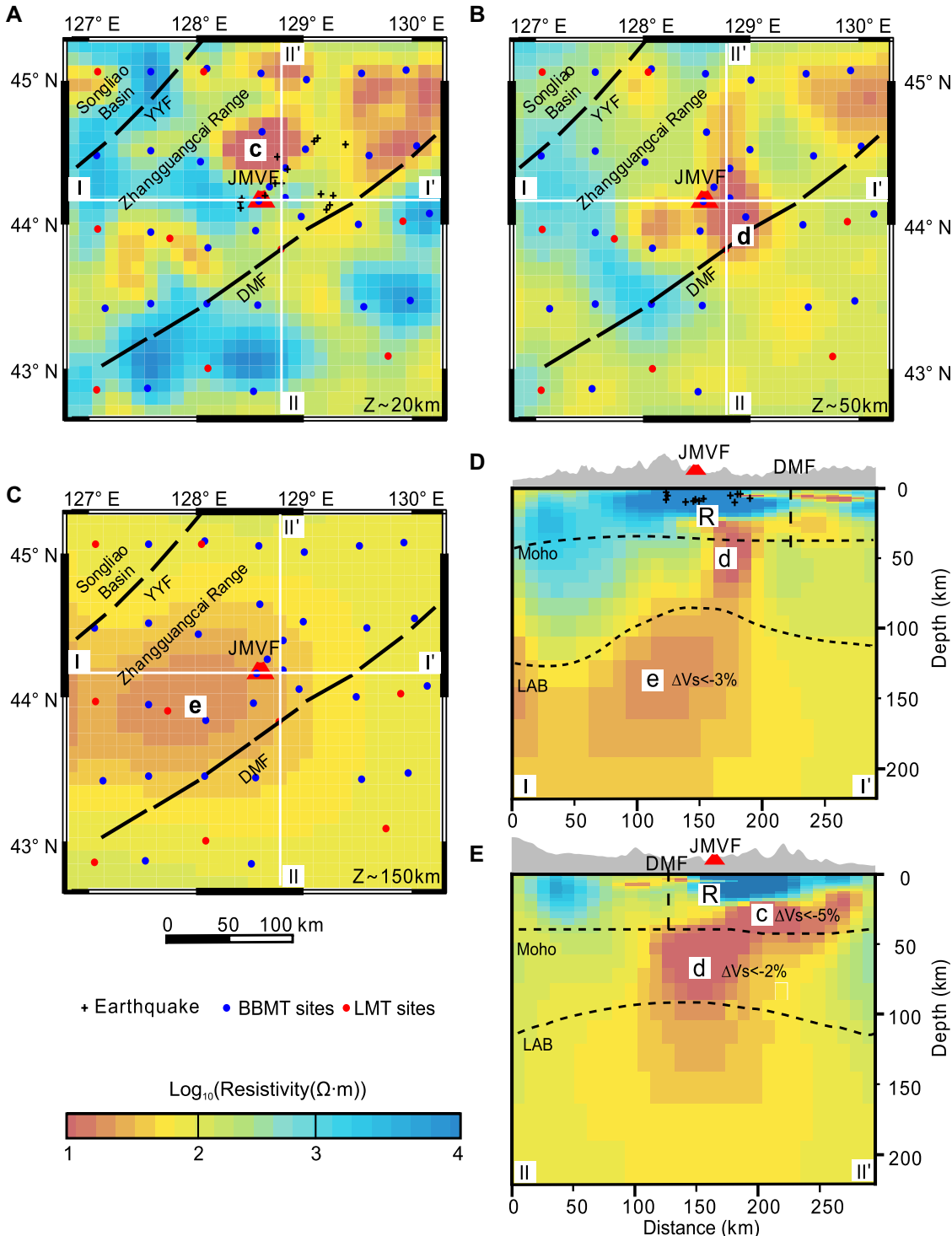

Figure 2. Magnetotelluric resistivity images beneath the Jingpohu monogenetic volcanic field (JMVF, northeast China). Slices are at depths of (A) 20 km, (B) 50 km, and (C) 150 km below sea level. (D,E) Cross sections along profiles I-I′ (D) and II-II′ (E). Anomalies are marked by bold letters R, c, d, and e. Earthquakes were recorded from January 2009 to December 2020. Magnitude (Ms) was between 0.1 and 1.8 (data from http://data.earthquake.cn). Depths of the Moho and lithosphere-asthenosphere boundary (LAB) in D and E were inferred from Xu et al. (2017) and Yan and Zhao (2008), respectively. Velocity perturbations in anomaly e in D are from Kang et al. (2016), while those in anomalies d and c in E refer to Fan and Chen (2019) and Pang et al. (2016), respectively. DMF—Dunhua-Mishan fault; YYF—Yilan-Yitong fault; LMT—long-period magnetotelluric data; BBMT—broadband magnetotelluric data.
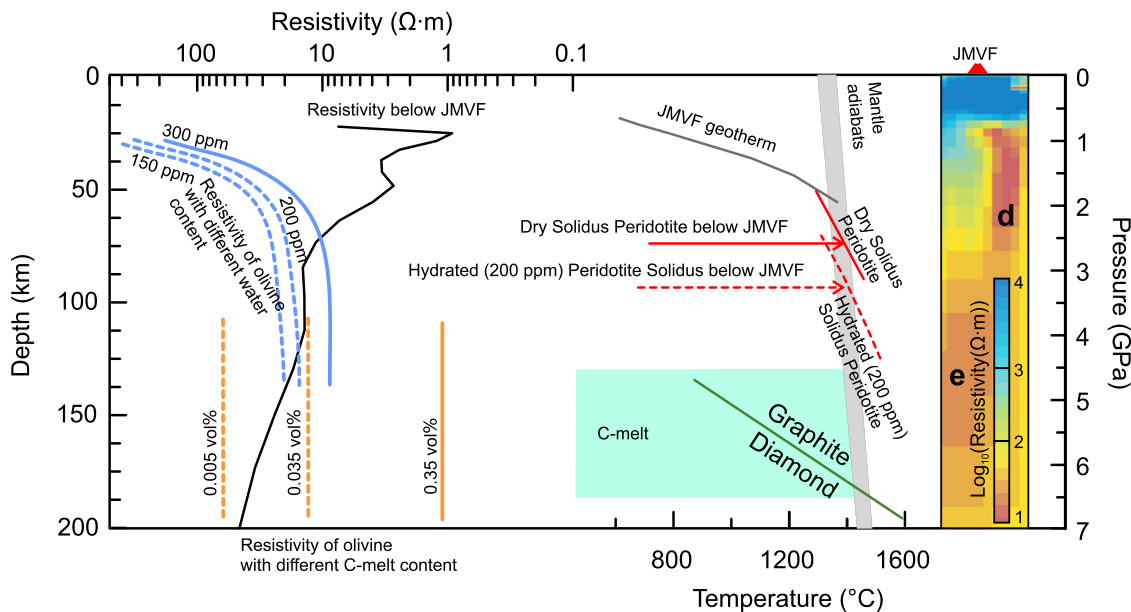
Figure 3. Rock physics interpretation of resistivity anomalies. Black line is resistivity depth profile beneath the Jingpohu monogenetic volcanic field (JMVF, northeast China) extracted from the right panel, where anomalies d and e are labeled by bold letters. Resistivities (blue lines) of olivine containing H_2O are from Gardés et al. (2014) along mantle adiabats (gray zone field; from Fischer et al., 2010). Resistivities of olivine with carbonate melt (brown lines) are from Gaillard et al. (2008). Geotherm beneath the JMVF was extrapolated from Fischer et al. (2010) with heat flow of ~90 mW/m² (An and Shi, 2007). Solidus (red lines) of dry and 200 ppm hydrated peridotite is from Hirschmann et al. (2009) according to geotherm beneath the JMVF. Azure area marks depths where conductivity is dominated by carbonate (C) melts, and the line represents stability fields of graphite and diamond from Fischer et al. (2010).

DMF at depths of 10–15 km (Figs. 2D and 2E), reflecting the presence of intracrustal fluid-rich zones, the depths of which are possibly controlled by crustal discontinuities (Wannamaker et al., 2009). A low-resistivity zone (anomaly c in Figs. 2A and 2E) is observed between depths of 20 and 40 km. This ~50-km-wide anomaly is located to the north of the JMVF in the middle-lower crust. The average resistivity is ~2–3 $\Omega \cdot m$, but in the central part, it is characterized by values <1 $\Omega \cdot m$ (Fig. S3). Below the JMVF, an up to 50–70-km-wide, low-resistivity anomaly, anomaly d (~20 $\Omega \cdot m$), extends down to the lithosphere-asthenosphere boundary at a depth of ~75 km (Figs. 2B, 2D, and 2E; Yan and Zhao, 2008). At depths of ~130 km, the mantle becomes less resistive than 25 $\Omega \cdot m$ in a spindle-like zone slightly tilted upward to anomaly d. We defined this low-resistivity zone as anomaly e (Figs. 2C and 2D). It probably represents the top of an up to 400-km-deep, low-resistivity anomaly detected in the asthenosphere (Fig. 1C; Li et al., 2020b). In its central area, the resistivity becomes as low as 15 $\Omega \cdot m$. In this moderately resistive situation, the 20,000 s period of our LMT data is sufficient to guarantee such a depth of investigation. The resistivity of the anomalies detected must be interpreted with some caution because MT data are primarily sensitive to the integrated conductance of conductive bodies. However, the inversions with identical data coverage to real observations demonstrate that the detected anomalies at depths from 20 km to 150 km are resolved rather well (Fig. S6). The robustness of the single anomaly described above is demonstrated by the results of model perturbation analysis (Figs. S8 and S9).

DISCUSSION

Anomaly e in the asthenosphere may be ascribed to high-temperature carbonate melts, peridotite, and/or hydrated melts in the asthenosphere (Fig. 3). Producing this low-resistivity anomaly with only high temperatures requires temperatures as high as ~1800 K (Gardés et al., 2014), which are incompatible with the pressure and temperature conditions for peridotite melts (~1500 K) and exceed the mantle adiabat (~1600 K). Alternatively, we can use olivine containing ~200 ppm H_2O to interpret the observed resistivity. However, such a high water content corresponds to ~700–1000 ppm H_2O in peridotite, i.e., well above the mantle water storage capacity (Hirschmann et al., 2009); in addition, this range of H_2O contents is not consistent with the relatively dry source(s) of the JMVF and northeast China basalts (Hsu and Chen, 1998). These difficulties lead us to associate anomaly e with C melts (Gaillard et al., 2008), where ~0.03 vol% of interconnected C melts may reproduce the observed resistivity values (Fig. 3). The reduction in S-wave velocity (Fig. 2D; Kang et al., 2016) in correspondence with anomaly e could reflect the occurrence of such melts. Results from the MAGLAB platform (Massuyeau et al., 2021) suggest a melt with ~300 ppm CO_2 and 240 ppm H_2O for anomaly e (Fig. S10). The widespread mantle-derived CO_2 around the JMVF area (Liu et al., 2018), the experimental petrological data on the stability of C melts (Zhang et al., 2020), the presence of alkali olivine basalts (Zhang et al., 2000), and the available isotopic data (δ^{26}Mg values of −0.6‰ to −0.30‰ in basalts) (Li et al., 2017) support our interpretation. Anomaly e

thus represents a volume where C melts occur beneath intraplate volcanoes, a feature mainly observed in divergent geodynamic contexts (Key et al., 2013; Sifré et al., 2014). C melts from the asthenosphere ascend across their stability field at a depth of ~120 km (Key et al., 2013; Sifré et al., 2014). Consequently, the low resistivity of anomaly d, originating from a depth of ~100 km, should be ascribed not only to C melts (Key et al., 2013) but also to peridotite partial melting (Yan and Zhao, 2008) triggered by ~200 ppm H_2O (Fig. 3; Hirschmann et al., 2009). The melting in anomaly d may be only ~1–2 vol% with a relatively low water content (1–2 wt%; Fig. S11; Hsu and Chen, 1998), and the low resistivity at the top of anomaly d suggests magma accumulation at the base of the crust, which could explain the ~2%–3% seismic velocity decrease (Fig. 2E; Fan and Chen, 2019). In the central sector, anomaly d shows a resistivity of 2–3 $\Omega \cdot m$, a value suggesting ~10 vol% of melt in its core (Fig. S11). The anomalies detected below the JMVF suggest, on average, low melting fractions (4–6 vol%) and water contents (<1.5 wt%). These values are significantly lower than the up to 12 vol% melting fraction and 2.5–9 wt% water content of the sources feeding the volcanoes in subduction settings (Comeau et al., 2015; Laumonier et al., 2017).

Therefore, anomaly d represents the mantle source of the JMVF basalts. In this scenario, the EM1 component of the JMVF basalts (Hsu and Chen, 1998) could be lithospheric, thermally eroded underplated material (Konter and Becker, 2012), implying active underplating processes. In the JMVF, ~2 km³ of basaltic lavas erupted
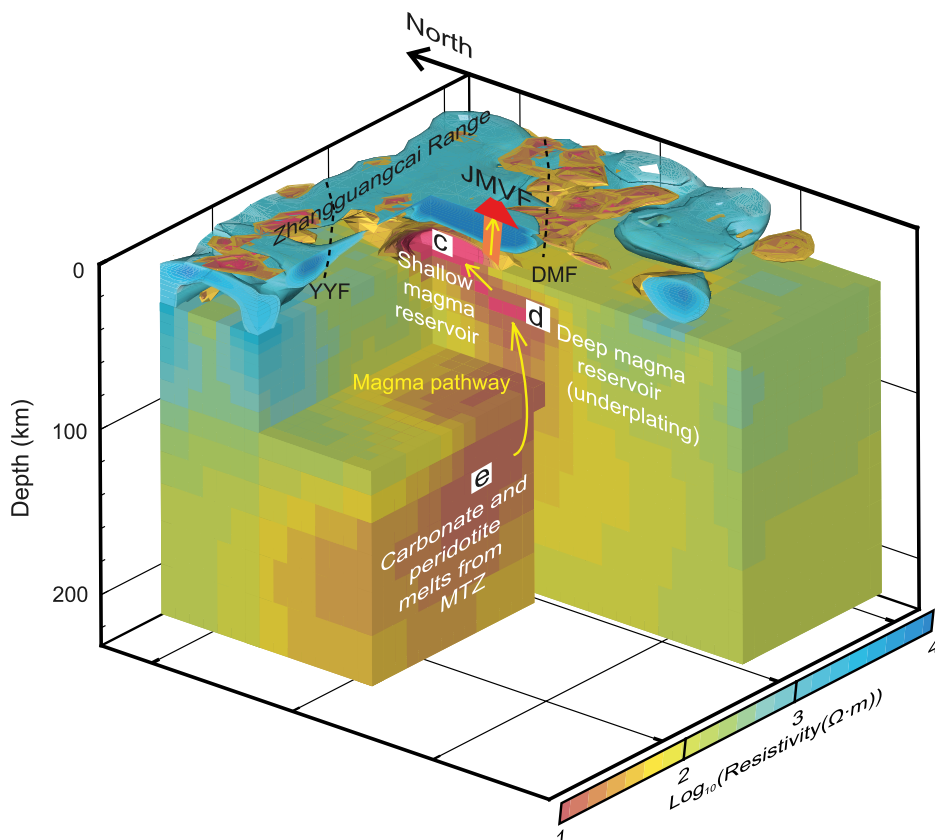
Figure 4. Conceptual model of the Jingpohu monogenetic volcanic field (JMVF, northeast China) intraplate plumbing system based on inversion of magnetotelluric data. Magma pathways are marked by yellow arrows. Bold c, d, and e indicate resistivity anomalies. Structural and volcanological significance of three main magma storage zones are discussed in text. DMF—Dunhua-Mishan fault; YYF—Yilan-Yitong fault; MTZ—mantle transition zone.

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from the source in ~8000 yr (Yan and Zhao, 2008), equal to an average magma production rate of 2.5×10^{-4} km^3/yr, a value within the 10^{-5}–10^{-3} km^3/yr range estimated for alkaline volcanoes in intraplate settings and significantly lower than that of subduction volcanoes (0.4–0.6 km^3/yr; Crisp, 1984). We suggest that the JMVF magmatic system is characterized by a high ratio between intrusions and erupted products. This observation and the low melt fraction and water content of the JMVF reservoirs may explain why the magma production rate of intraplate volcanoes is lower than that of volcanoes in subduction settings. The low-resistivity midcrust anomaly c is located just above anomaly d. We interpret anomaly c as the shallow magma reservoir of the JMVF. This reservoir could have been the source of the andesitic magma erupted in the Eocene (Qin et al., 2008). The 1–2 $\Omega \cdot$m bulk resistivity of anomaly c implies an ~10 vol% melt with 2.5 wt% water (Li et al., 2020a). The presence of this midcrustal hot melting zone is supported by (1) a low-velocity zone in the same region (Fig. 2E; Pang et al., 2016), (2) an ~100 kg/m^3 density decrease at 20–30 km below the JMVF (Suo et al., 2015), and (3) the occurrence of seismicity confined to the upper 12 km of the crust (Fig. 2D). The hypocentral

depths suggest a brittle-ductile transition shallower than the ~20 km depth expected for an intraplate setting with underlying Paleozoic basement (Xu et al., 2017). This could reflect the thermal anomaly associated with the low-resistivity anomaly c. Although the conduits for eruptions cannot be seen in our image due to the large instrument spacing, transcrustal magma transfer can occur, according to field data, along the dikes associated with major faults (Xu et al., 2017).

Our results reveal the multilevel structure of the JMVF plumbing system, which is characterized by (Fig. 4): (1) a deeper zone located in the asthenospheric mantle fed by a C-melt–rich plume, possibly ascending from the MTZ above the stagnant Pacific slab (Ma et al., 2019; Xu et al., 2020); (2) an intermediate storage zone extending from the upper mantle to the Moho, in which hydrated peridotite melts form and underplating processes develop; (3) a shallower, intracrustal reservoir; and (4) a surface, fault-guided dike system responsible for the alignment of monogenetic vents. With the exception of the asthenospheric mantle zone, this configuration is unexpectedly very similar to that of silicic stratovolcanoes typical of arc settings (Afanasyev et al., 2018).

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