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Research progress and prospect of Emeishan mantle plume metallogenic system

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The Emeishan Large Igneous Province (ELIP) in southwestern China, formed by the Emeishan mantle plume, hosts diverse mineralization systems. This study classifies deposits into two types: those directly and indirectly related to the plume. Directly related deposits (~260 Ma) include magmatic Fe-Ti-V oxide and Cu-Ni-PGE sulfide deposits, and hydrothermal Nb-Ta-Zr-REE deposits, concentrated in the ELIP's inner zone. Indirectly related deposits, such as weathering crust-type REE-Sc-Ti ores and Carlin-type gold deposits, formed post-ELIP through weathering, sedimentation, and hydrothermal processes, and are distributed in the middle-outer zones. Spatiotemporal analysis reveals that directly related deposits formed synchronously with ELIP magmatism, while indirectly related deposits exhibit dispersed ages from the Late Permian to Quaternary. The former originated from plume-driven magmatism, whereas the latter were influenced by thermal effects, ancient faults, and later geological processes. The study highlighted the plume's role in global mineralization, proposing a resource effect law where mantle plumes enhance mineral and hydrocarbon formation. Comparative research with other Large Igneous Provinces is essential to address critical mineral shortages and ensure sustainable resource development.

KEYWORDS

Emeishan mantle plume, Emei mountain large igneous province, mineralization system, mineralization process, geological science and technology

1 Introduction

Large igneous provinces (LIPs) are widely distributed worldwide (Zhang Q. et al., 2022). One example is the Emeishan Large Igneous Province (ELIP) in southwestern China (Zhang et al., 2024). Since Zhao Ya first named the basalt in the Emeishan area of the Sichuan Province Emeishan basalt in 1929 (Sichuan Bureau of Geology and Mineral Resources, 1991), numerous genetic studies have been conducted. By the early 21st century, mantle plume genesis had been widely accepted (He et al., 2003). The ELIP is a large mafic igneous province covering an area exceeding 2.5 × 10^5 km^2 in southwestern China (as shown in Figure 1), and it has long been a research hotspot for scholars at home and abroad. The eruption time (Mundil et al., 2004) and distribution space (He et al., 2003; Tian Y. et al., 2021), high and low titanium basalt (Jiang et al., 2009), the relationship between layered rock mass and basalt (Zhou et al., 2005), mineralization related to basalt (Hu et al., 2005),

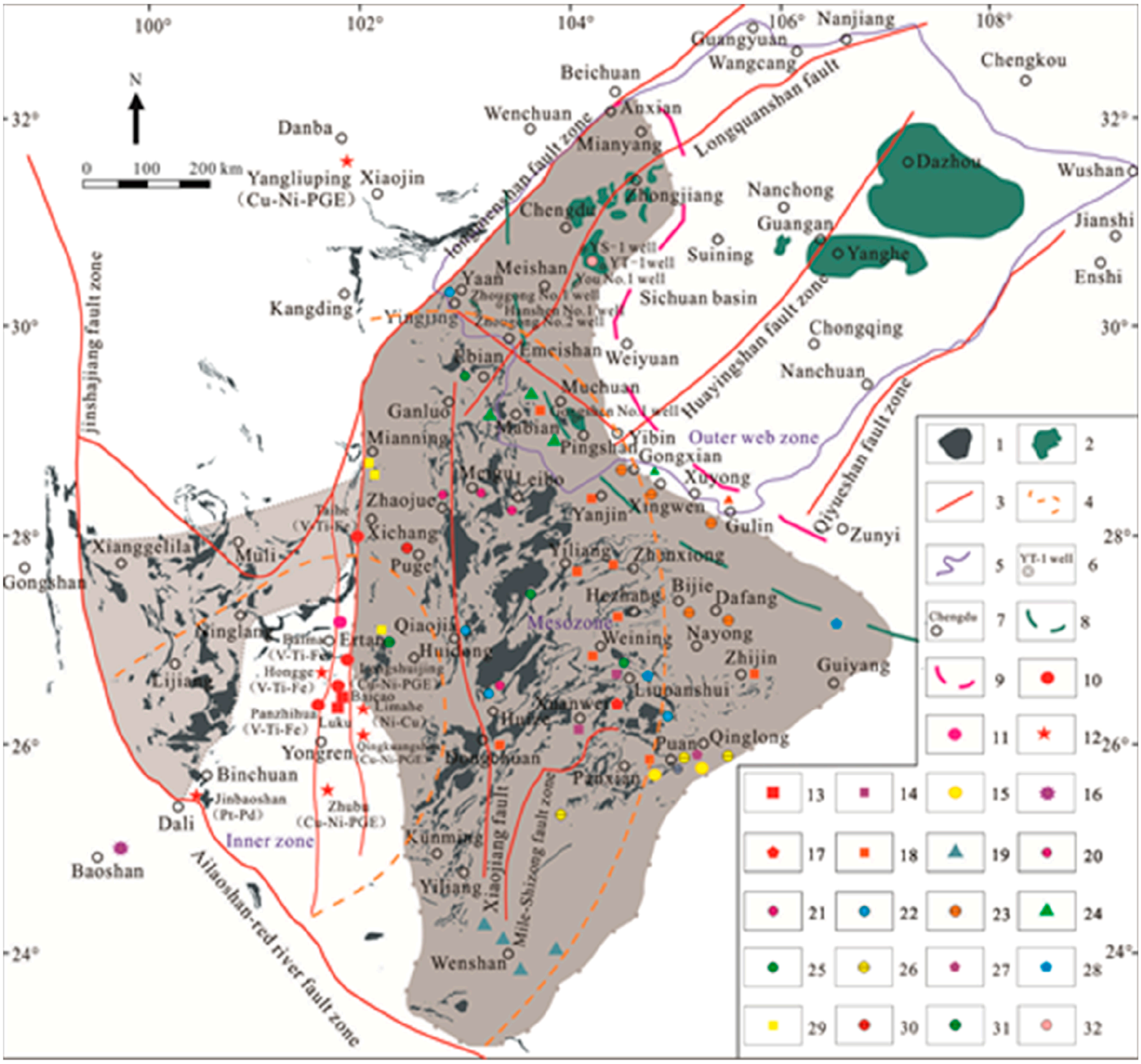

FIGURE 1
Map of the distribution of Emeishan basalts and deposits related to the Emeishan Mantle Plume (modified after He et al., 2003; Xu and Chung, 2001; He et al., 2008; Ma et al., 2019).

mass extinctions (Yin and Song, 2013), and genetic links to mantle plumes have received extensive attention from scholars, and many results have been reported.

The mantle plume acts as a channel for material and energy exchange among various core, mantle, and crust layers, providing a dynamic mechanism for intraplate tectonic magmatism and mineralization (van der Zwan et al., 2023). The formation of the Emeishan Large Igneous Province (ELIP) has significant implications for the generation of heat and the supply of minerals, creating optimal conditions for mineralization. While extensive research has been conducted globally on mantle plume genesis, eruption timelines, spatial distribution, magmatic evolution, the interplay between layered rock masses and basalt, and the mass extinctions associated with the ELIP, the characterization of various mineralization types within the Emeishan mantle plume's metallogenic system remains incomplete. The upwelling of the Emeishan mantle plume has led to both endogenous mineralization, including magmatic and hydrothermal processes, and exogenous mineralization resulting from weathering, leaching, and sedimentation in subsequent stages. Additionally, ancient deep faults, rift basins, thermal effects, and reservoir reconstructions associated with the plume exert direct and indirect influences on the concentration of metals, as well as oil and gas resources. Over the past century, considerable detail has been devoted to studying the mineralization processes linked to the Emeishan mantle plume. According to the previous study (Zhang Q. et al., 2022), and the correlation between mineralization and the ELIP, mineralization can be divided into that directly and indirectly related to the Emeishan

TABLE 1 Classification of ore deposit types related to the Emeishan Mantle Plume.

Class	Type classification		Genesis	Common points
Deposit types directly related to Emeishan mantle plume	Magmatic deposits	Fe-Ti-V oxide deposits associated with ferromafic-ultramafic intrusions	The formation of vanadium-titanomagnetite deposits may be related to the source area of iron-rich rocks (eclogite and pyroxenite). The source area partially melted to form iron- and titanium-rich picrite magma. During magma ascent in the channel, vanadium titanomagnetite deposits are precipitated and enriched by separation and crystallization (Song et al., 2013; Bai et al., 2019) (Figure 2)	The deposit types are classified as follows:With the upwelling of the Emeishan mantle plume, magmatic mineralization and hydrothermal mineralization will occur during the upwelling process, and finally magmatic deposits and hydrothermal deposits are formed respectively. These deposits are called deposit types directly related to the Emeishan mantle plume
		Cu-Ni-PGE sulfide deposits associated with ferromafic-ultramafic intrusions	According to Wang et al. (2005), the formation of three types of Cu-Ni-PGE deposits has undergone a similar magmatic process in the open system of magmatic channels. Magmatic conduits develop along cross-linked structures formed by many strike-slip faults, and each intrusion appears to be part of a grid of connected conduits that form complex channels from the mantle to the surface (Wang et al., 2005) (Figure 3). Cu-Ni enrichment type deposit: due to crustal contamination, the magmatic sulfur in the staged magma chamber reaches saturation, resulting in immiscibility of sulfide melt and segregation enrichment. Cu-Ni-PGE enrichment type deposit: The earlier magmatic pulse melted and separated in the stage magma chamber to form sulfide melt, forming Cu-Ni enrichment mineralization, and then experienced the interaction between the late sulfur-unsaturated magma continuous pulse and the early separated sulfide melt in the stage magma chamber, forming Cu-Ni-PGE enrichment type deposit in the stage magma chamber. PGE-rich deposits: Base on the formation of Cu-Ni-PGE-rich deposits, the late sulfur-unsaturated magma melts the pre-existing sulfide melt to form PGE-rich magma, which rises to an independent space formed by strike-slip faults and accumulates ore deposits	
		volcanic rock type Fe deposits associated with volcanic exhalation sedimentation of overflow basalts	The zircon U–Pb age of this type of iron deposit was determined to be 259.7 ± 1.2 Ma (Zeng et al., 2016), consistent with the time of activity in the ELIP (260 Ma), indicating that the formation of this type of iron deposit was directly related to the eruption and deposition of the Emeishan basalt. The mineralization is volcanic exhalation and this type of iron deposit is a volcanic rock-type iron deposit	
	Hydrothermal deposits	Nb-Ta-Zr-REE deposits related to syenite dykes	The formation of Nb–Ta–Zr–REE deposits can be roughly divided into the syenite vein formation and rare earth metal mineral enrichment stages. The formation process of the syenite veins is as follows: after the alkaline magma intruded into the dyke in the late Emeishan mantle plume, residual magma rose along the dyke and formed numerous syenite veins in the rock surrounding the hanging wall (gabbro) and fissures in the upper part of the dyke. At this time, rare earth metal minerals were not enriched (Wang et al., 2012). Rare earth metal minerals in Nb–Ta–Zr–REE were enriched to the greatest extent during the evolution of alkaline magma until the late magmatic hydrothermal stage, and the contents of alkali elements (mainly Na) and volatiles were high. At this time, the main ore-forming elements, such as Nb, Ta, Na, F, and other elements, formed complexes. The fluid underwent sodium metasomatism along the fissures and gaps of early rock-forming minerals, and the structure of the complexes was destroyed. Nb, Ta and other elements crystallized into well-crystallized Nb-Ta minerals at albitization sites (Wang et al., 2012). Zeng and Liu (2022) revealed the enrichment mechanism of niobium and tantalum in syenite based on an in-depth study of different types of zircons in the syenites of the Baicao, Luku, and Baima mining areas. The enrichment can be divided into four stages, as shown in Figure 4	
		modern weathering crust type	At present, modern weathering crust-type deposits include weathering crust-type REE, Sc, and Ti polymetallic and laterite-type gold deposits. 1. The modern weathering crust-type REE, Sc, and Ti polymetallic deposit occurs in the modern weathering crust of the Emeishan basalt (Liu, 2020; Zhang et al., 2021). It can be directly determined that the ore-forming material is derived from the Emeishan basalt. 2. The formation process of laterite-type gold deposits is as follows: gold-rich basaltic volcaniclastic rock was enriched in the Quaternary soil of the modern karst negative terrain under long-term weathering, denudation, and leaching (Yang et al., 2007). The ELIP provided the main mineral source for modern weathering crust-type deposits	

(Continued on the following page)

TABLE 1 (*Continued*) Classification of ore deposit types related to the Emeishan Mantle Plume.

Class	Type classification		Genesis	Common points
	The types of deposits providing mineral sources	modern sand-ore type deposits	Modern sand ore-type deposits are sand ore-type Nanhong agate deposits, which are distributed in the Baoshan area of Yunnan Province. The agate amygdaloid body formed in the basalt through low-temperature hydrothermal filling in the late stage of Emeishan basalt magma. After weathering, denudation, transportation, and sedimentation, the Nanhong agate deposit was deposited in Quaternary strata (Liu et al., 2018; Lu, 2018)	
		ancient weathering crust type	Paleo-weathering crust-type deposits are lateritic iron deposits distributed in the Liupanshui–Weining area of the Guizhou Province. They were produced in the purple-red iron clay paleo-weathering crust of the Emeishan basalt. The floor of the ore layer is basalt and the roof is aluminum mudstone from the Xuanwei Formation. The U–Pb isotopic age of detrital zircons proves that the provenance is the Emeishan basalt (Meng et al., 2015). Ore-controlling factors include the vertical uplift of ancient terrain caused by the upwelling of the Emeishan mantle plume (Xu et al., 2017) and the weathering and denudation of basalt under hot and humid climate conditions (Zhou et al., 1986)	
		ancient weathering crust-sedimentary type	Ancient weathering crust–sedimentary deposits are Nb–Sc–Ti–Ga–Zr–V–REE polymetallic deposits occurring at the bottom of the Xuanwei Formation.Many scholars believe that its source is mainly derived from Emeishan high-titanium basalt (Mclennan et al., 1993), and its mineralization is mainly weathering leaching and sedimentation (Du et al., 2019; Chen et al., 2020; Tian et al., 2021b; Dai et al., 2014)	
		sedimentary type	The sedimentary deposits include sedimentary bauxite, sedimentary conglomerate-type Nanhong agate, sedimentary “Madouzi type” copper, sedimentary pyrite, and sedimentary sand shale-type copper deposits. 1. Based on petrogeochemical and U–Pb zircon geochronological evidence, Zhang et al. (2022a) concluded that the Emeishan basalt and volcanic ash from the ELIP provided the main sources for the formation of the bauxite deposits. 2. The provenance of the sedimentary conglomerate-type Nanhong agate deposit is the primary agate. The formation process of the primary agate is: the siliceous hydrothermal fluid in the Emeishan basalt is filled in the pores or fissures of the basalt in the late magma, forming the almond-shaped cryptocrystalline quartz (primary agate) (Liu et al., 2018). 3. The sedimentary ‘Madouzi’ copper deposit is derived from the bottom of the Xuanwei Formation. Wang et al. (2011) confirmed that its provenance is the Emeishan basalt. Its formation process is the weathering and leaching of Emeishan basalt with a high copper background value, and copper migrates to water body. In a favorable lake or swamp environment, chalcocite and bornite are formed with sediment deposition. Later, through hydrothermal metasomatism and superposition, chalcopyrite was further enriched and formed, and finally, the ‘Madouzi’ copper deposit was formed (Wang et al., 2011). 4. The sedimentary pyrite deposit occurs at the bottom of the Upper Permian Longtan Formation and above the limestone denudation surface of the Middle Permian Maokou Formation. Iron in pyrite is mainly derived from the weathering of mafic minerals, such as pyroxene, in the Emeishan basalt. After the iron is resolved, Fe^{2+} is transported to the reducing environment, and Fe^{2+} and HS^{-} combine to form pyrite (Yang et al., 2007). 5. Sedimentary sand shale-type copper deposits are distributed in Muchuan, Mabian, Pingshan, and other places in Sichuan. Copper ore bodies mainly occur in gray-green clay rock and siltstone at the bottom of the Feixianguan Formation. Rock geochemistry and detrital zircon U–Pb geochronology revealed that the provenance is the high-titanium basalt with a high copper background value (Zhang et al., 2006; Zhang et al., 2019). The metallogenic model is as follows: in the Early Triassic, the Emeishan basalt in Kangdian ancient land was weathered and eroded, and the copper in the basalt was transported to the tidal flat subfacies and intertidal mixed flat microfacies, representing a relatively quiet low-energy environment conducive for sedimentary mineralization	

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TABLE 1 (*Continued*) Classification of ore deposit types related to the Emeishan Mantle Plume.

Class	Type classification		Genesis	Common points
Deposit types indirectly related to Emeishan mantle plume		hydrothermal type	Three types of hydrothermal deposits can be observed: basaltic copper deposits, Carlin-type gold deposits, and antimony–gold deposits in Dachang, Qinglong, and Guizhou. 1. Basalt copper deposits were mainly produced at the top of the Emeishan basalt. Natural copper minerals are sporadically distributed in basalts and can also be found in olivine phenocrysts of picrites (Zhang et al., 2006), indicating that copper was initially enriched during the formation of the Emeishan basalts. Zhu (2005) obtained a metallogenic age of 228–226 Ma, which shows that the metallogenic age is notably younger than the formation time of the ELIP. Notably, this type of deposit is further enriched and mineralized by the later hydrothermal superposition transformation. 2. Carlin-type gold deposits related to the ELIP are distributed in the Youjiang Basin at the western margin of the Yangtze Block.In recent years, Zhu et al. (2020) proposed that the Emeishan basaltic magma formed a thick gold-rich cumulate through fractional crystallization in the lower crust, and the gold in the gold-rich cumulate was activated and migrated to sedimentary rocks by the later hydrothermal activity. Zhang et al. (2006) and Tao et al. (Tao et al., 2007) found native gold in picrite olivine phenocrysts, and rocks of the ELIP, providing solid evidence for the existence of gold-rich rhyolite. The dating results show that Carlin-type gold deposits in the Youjiang Basin were formed between ~235 and 200 Ma and ~150–130 Ma (Hu et al., 2017), notably later than the time of activity of the Emeishan mantle plume (~260 Ma). The formation age of Carlin-type gold deposits in the Youjiang Basin is consistent with the subduction event of the Paleo-Pacific (~235–155 Ma) and Neo-Tethys (~140–115 Ma) oceanic crust. Notably, Carlin-type gold deposits were formed in the back-arc extension environment caused by oceanic crust subduction. After the formation of gold-rich cumulates at ~260 Ma, the late magmatic hydrothermal activity related to the oceanic subduction event activated the gold in gold-rich cumulates and migrated along the deep fault to the ore-bearing wall rock, precipitating mineralization.The Carlin-type gold mineralization model in the Youjiang basin is shown in Figure 5. 3. The Dachang antimony and gold ore bodies in Qinglong, Guizhou, occur in a set of siliceous altered rocks—“Dachang layer”—above the limestone of the Middle Permian Maokou Formation and underneath the Emeishan basalt (Chen et al., 2018). In the Middle–Late Permian, the Qinglong area was a shallow sea environment, which was covered by the Emeishan continental overflow basalt. Simultaneously, a large number of volcanic eruptions and hot water jet sedimentation occurred along tensile faults, resulting in the deposition of many “Dachang layer” pyroclastic rocks. Sb and Au elements were initially enriched in the “Dachang layer” (Du et al., 2020). Li (2020) obtained a mineralization age ranging from 125.2 to 148 Ma, younger than that of the ELIP, indicating that this type of deposit was formed by the preliminary enrichment of ore-forming elements in the ELIP and by the subsequent Yanshanian hydrothermal transformation (Figure 6)	After the end of the upwelling of the Emeishan mantle plume, after a certain period of time, the upwelling event of the Emeishan mantle plume provides the ore-forming material source, ore-transporting channel and ore-forming space for the deposit. These deposits are called deposit types indirectly related to the Emeishan mantle plume
	types of ore deposits providing ore transport channels	REE deposits of carbonatite-syenite complex in Panxi area	Carbonatite–syenite complex-type REE deposits are distributed in the Cenozoic Panxi rare earth metallogenic belt. Although the Cenozoic Panxi rare earth metallogenic belt was located in the Panxi ancient rift, its main ore-controlling structure was the strike-slip fault produced by the India–Asia continental collision. Although the Panxi ancient rift did not directly control the Cenozoic Panxi rare earth metallogenic belt, the ancient deep fault formed by the upwelling of the Emeishan mantle plume, close to the Panxi ancient rift, was activated by the strike-slip fault caused by the collision of the Indian–Asian continent, promoting the emplacement of the Cenozoic carbonate–alkaline complex.Therefore, the ancient deep fault developed in the Panxi ancient rift provided a congenitally advantageous ore transport channel for the intrusion of carbonate magma along the Cenozoic strike-slip fault. The upwelling of the Emeishan mantle plume provided an ore transport channel for rare earth deposits in the Cenozoic Panxi area, which indirectly restricted the mineralization	
		oil and gas deposits	The provision of ore transport channels for oil and gas deposits is mainly reflected in the fault system formed by the rise of the Emeishan mantle plume, which reflects the correlation between source rocks and reservoirs (Ma et al., 2019)	

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TABLE 1 (*Continued*) Classification of ore deposit types related to the Emeishan Mantle Plume.

Class	Type classification		Genesis	Common points
	deposit types providing ore-forming space	sedimentary coal-copper-rhenium-molybdenum deposits in the Panxi rift	Xu et al. (2001) confirmed that the Panxi paleo-rift at the southwestern margin of the Yangtze Block is the product of mantle plume activity in the Emeishan Block. The sedimentary rock layer in the Panxi ancient rift basin is thick and contains numerous minerals. Examples include the coal deposits in the Upper Triassic Daqiaodi Formation, copper, rhenium, and molybdenum polymetallic deposits in the middle and lower part of the Lower Cretaceous Feitianshan Formation (K_1f) (Hao et al., 2021), and sedimentary sandstone-type copper deposits in the bottom glutenite of the Upper Cretaceous Xiaoba Formation (K_2x). The Panxi ancient rift provided metallogenic space for these deposits	
		oil and gas deposits	The constraints of the Emeishan mantle plume on oil and gas reservoirs are reflected in the following aspects: 1. Volcanic rocks in the ELIP serve as good porous volcaniclastic reservoirs. During 2018–2019, explosive- and overflow-phase porous volcaniclastic rock reservoirs and the acquisition of industrial gas flow in the western Sichuan Basin were discovered (Ma et al., 2019; Yang et al., 2007). 2. The thermal effect of the Emeishan mantle plume promotes the maturity of organic matter and forms high-quality source rocks. The inversion results of ELIP formation temperature showed that the magma latent temperature of the ELIP reached 1,550°C (Xu et al., 2001). Zhu et al. (2010) reported that the Sichuan Basin exhibited a heat flow peak at ~259 Ma, and the Emeishan basalt eruption area or concealed basalt distribution area was confirmed to have a high heat flow. The significant heat baking of the Emeishan slow column promoted the hydrocarbon generation and expulsion of the source rocks of the Cambrian Qiongzhusi Formation (Zhu et al., 2010; Wang et al., 2021), which is consistent with the ELIP in terms of the spatiotemporal distribution. 3. The uplift of the Emeishan mantle plume controlled the distribution of Middle Permian beach facies reservoirs. The upwelling of the Emeishan mantle plume caused the large-scale and longitudinal kilometer-level uplift of the paleotopography, controlled the rise and fall of the sea level, governed the distribution of sedimentary facies belts, and formed a gentle slope carbonate platform sedimentary pattern (high southwest and low northeast). Beach facies deposits were widely developed in the Qixia and Maokou formations, which created good conditions for subsequent hydrocarbon accumulation (Zhang et al., 2011). 4. The limestone of the Middle Permian Maokou Formation that was transformed by the Emeishan mantle plume became a karst reservoir. Recent oil and gas exploration results showed that the Middle Permian Maokou Formation is a high-quality karst reservoir (He et al., 2004). He et al. (2005) reported that the upwelling of the Emeishan mantle plume caused the limestone of the Maokou Formation to be uplifted into land and subjected to denudation and supergene karst transformation (Zhang et al., 2020), making the limestone of the Maokou Formation a karst reservoir. 5. The upwelling of the Emeishan mantle plume indirectly controlled the formation of sedimentary caps and reservoirs in the Xuanwei, Longtan, Wujiaping, and Feixianguan formations overlying the Emeishan basalt. The influence model of the Emeishan mantle plume on oil and gas deposition is shown in Figure 7.	

mantle plume. In many studies, the focus was placed on the former (Zhang Z. et al., 2022; Gao et al., 2004; Luo, 2014), leading to a lack of research on the latter. The reason for this result is that the magmatic deposits and hydrothermal deposits formed during the upwelling of the Emeishan mantle plume are large in scale. These deposits play a key role in the development of the social economy, so scholars have studied them more. For deposits formed later than the ELIP, few scholars believe that they are genetically related to the Emeishan mantle plume. However, with the transformation of economy and society, deposits indirectly related to the Emeishan mantle plume have received more and more attention.

Previous literature has proved that the Emeishan mantle plume has a direct genetic relationship with magmatic deposits and hydrothermal deposits formed during the upwelling of the Emeishan mantle plume. This study on the Emeishan mantle plume metallogenic system introduces several innovations. Firstly, it proposes a novel classification of deposits into directly related (formed at ~260 Ma, synchronous with ELIP, e.g., Fe-Ti-V oxide deposits) and indirectly related (post-ELIP, e.g., weathering crust and oil-gas deposits), addressing a previous gap and emphasizing understudied indirect deposits, revealing their long-term metallogenic effects. Secondly, using zircon U-Pb and other geochronological methods, it systematically analyzes the spatiotemporal distribution, with direct deposits concentrated in the ELIP inner zone and indirect ones dispersed in the middle-outer zones, clarifying their evolution tied to plume activity and subsequent geological processes. Thirdly, it introduces a universal resource effect law applicable to global LIPs, highlighting how mantle plumes enhance mineral and hydrocarbon formation via heat and material release, offering a framework for comparative studies. Lastly, it links regional findings to global critical mineral shortages, advocating enhanced global research for resource security. These innovations deepen the understanding of the Emeishan system and hold broader global significance.

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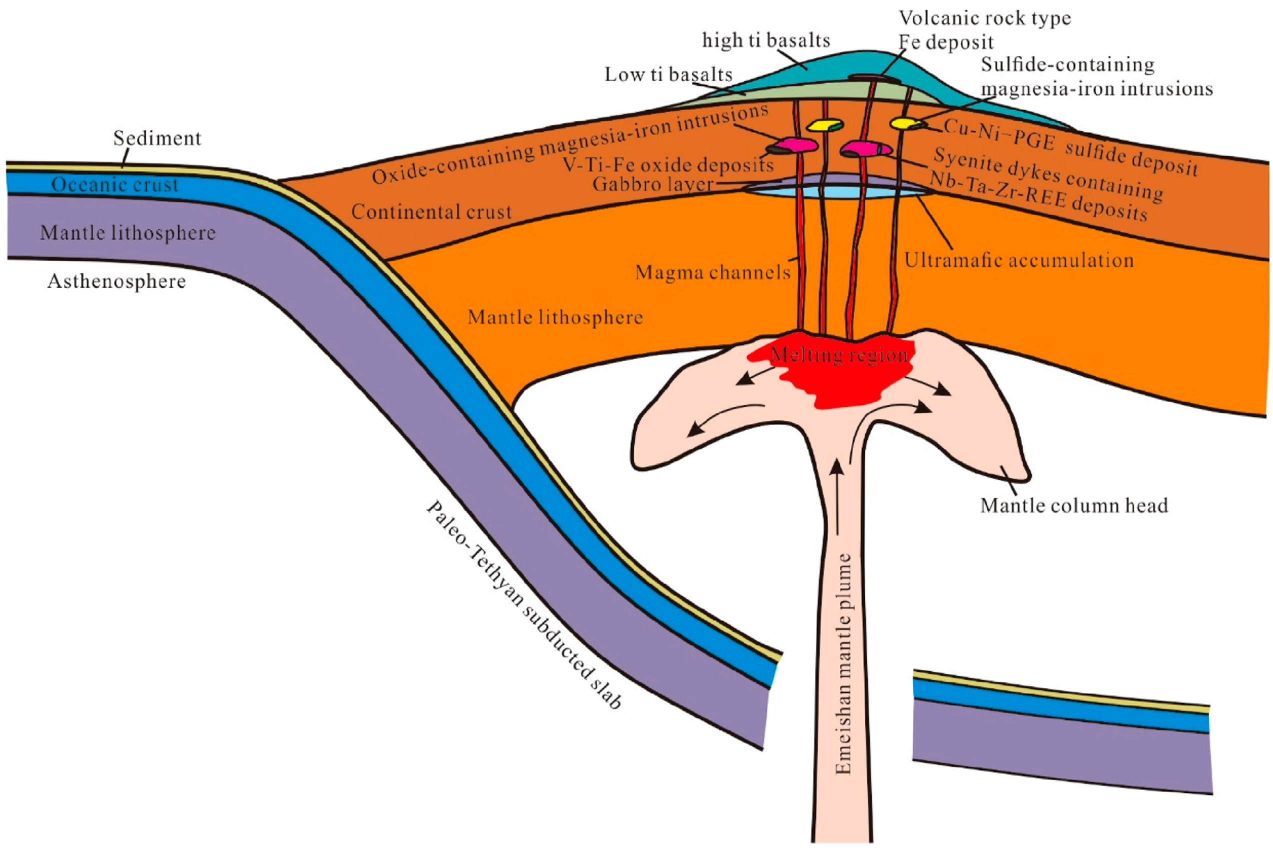

FIGURE 2
Evolution of an ore deposit directly related to the Emeishan mantle plume (modified after Zhang Z. et al., 2022; Bai et al., 2022).

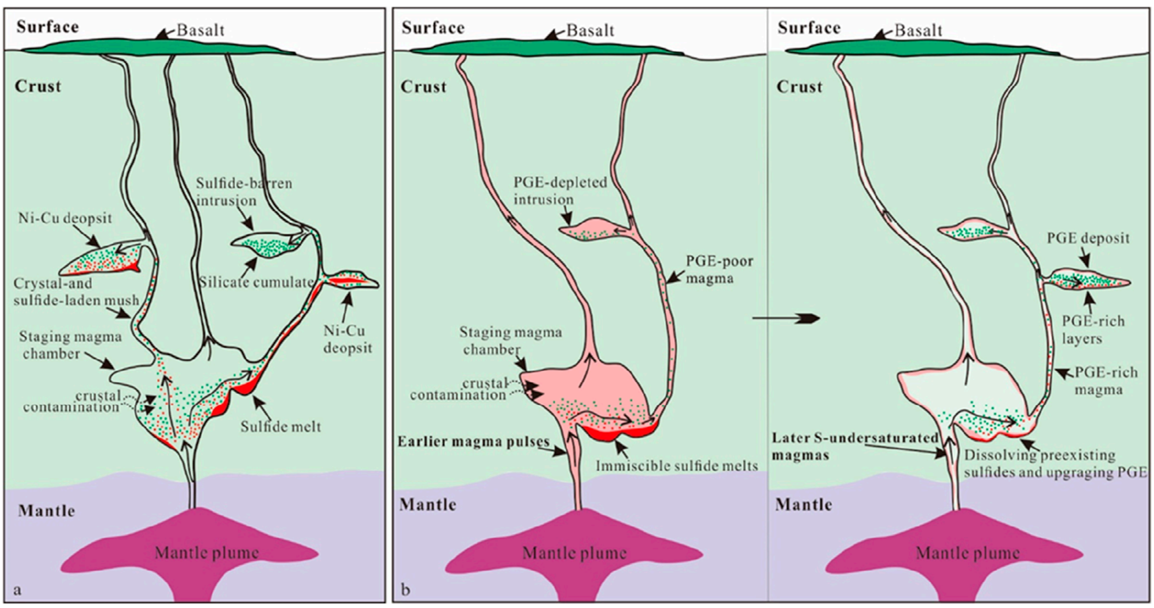

FIGURE 3
Evolution of Cu–Ni–PGE sulfide deposits in the Emeishan mantle plume metallogenic system (modified after Wang et al., 2018).

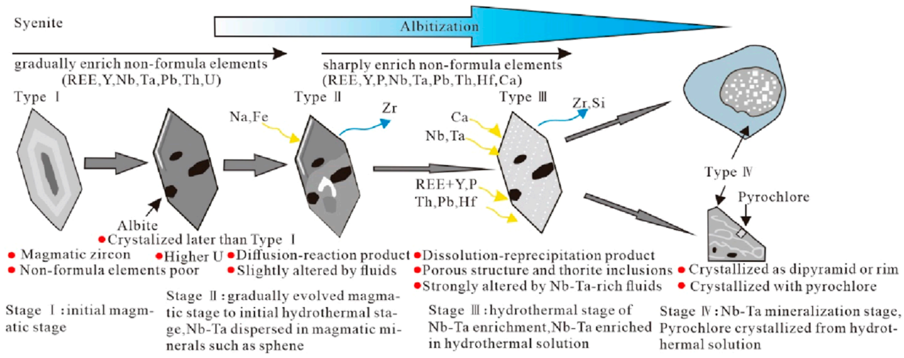

FIGURE 4
Formation patterns of I, II, III, and IV zircons in the four stages of Nb–Ta mineralization in the Baicao and Luku deposits (modified after Zeng and Liu, 2022).

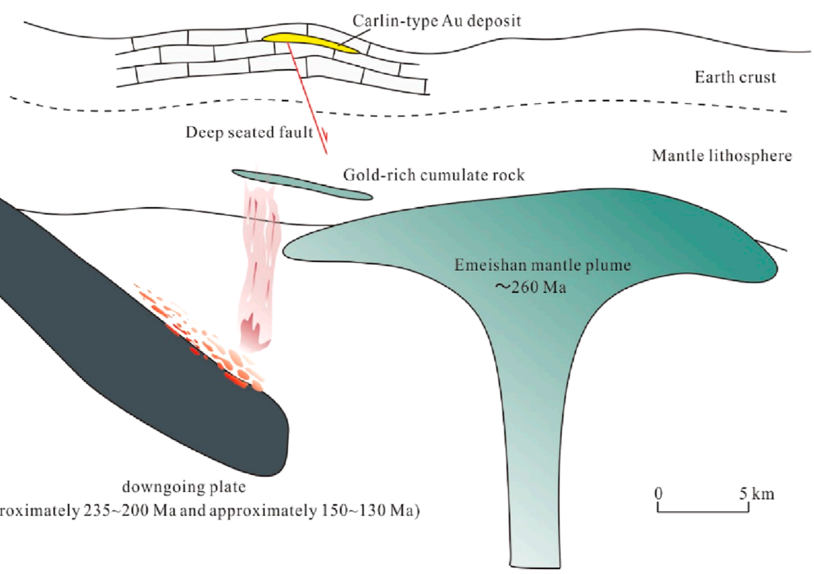

FIGURE 5
Model of the Carlin-type gold mineralization in the Youjiang Basin.

1: Emeishan basalt; 2: concealed basalt; 3: fault zone; 4: boundary of the Emeishan Large Igneous Province; 5: Sichuan Basin boundary; 6: drilling location and name; 7: locations of interest; 8: the old boundary in the northeast of the Emeishan igneous province; 9: new boundary northeast of the Emeishan pyrodiagenetic province; 10: Fe–Ti–V magmatic oxide deposit; 11: volcanic Fe deposit; 12: Cu–Ni–PGE magmatic sulfide deposit; 13: Nb–Ta–Zr–REE deposit related to syenite dikes; 14: modern weathering crust REE–Sc–Ti polymetallic ore; 15: lateritic Au deposit; 16: modern placer type South Red Agate deposit; 17: paleo-weathering crust type Fe deposit; 18: sedimentary Nb–Sc–Ti–Ga–Zr–V–REE polymetallic deposit; 19: sedimentary bauxite deposit; 20: sedimentary conglomerate-type South Red Agate deposit; 21: sedimentary conglomerate-type South Red Agate deposit; 22: sedimentary "Madouzi type" copper deposit; 23: sedimentary pyrite deposit; 24: sand shale-type copper deposit deposited at the bottom of the Feixianguan Formation; 25: basalt copper ore; 26: Carlin-type gold deposit; 27: Dachang antimony and gold deposits, Qinglong, Guizhou; 28: hydrothermal uranium deposit; 29: carbonate syenite complex-type REE deposit in the Panxi area; 30: sedimentary Cu–Re–Mo polymetallic deposit in the Panxi ancient rift; 31: sedimentary coal–copper–rheniumvmolybdenum deposit in the Panxi ancient rift; 32: oil and gas deposits.

2 Classification of deposit types

Scholars have different classifications of deposit types related to the Emeishan mantle plume (Hu et al., 2005; Gao et al., 2004). Zhang Q. et al. (2022) proposed a simple and clear division scheme, which is consistent with the actual situation. Based on the principle of "simultaneity" of direct correlation, this study followed the classification method of Zhang Z. et al. (2022). Based on the temporal correlation between mineralization and

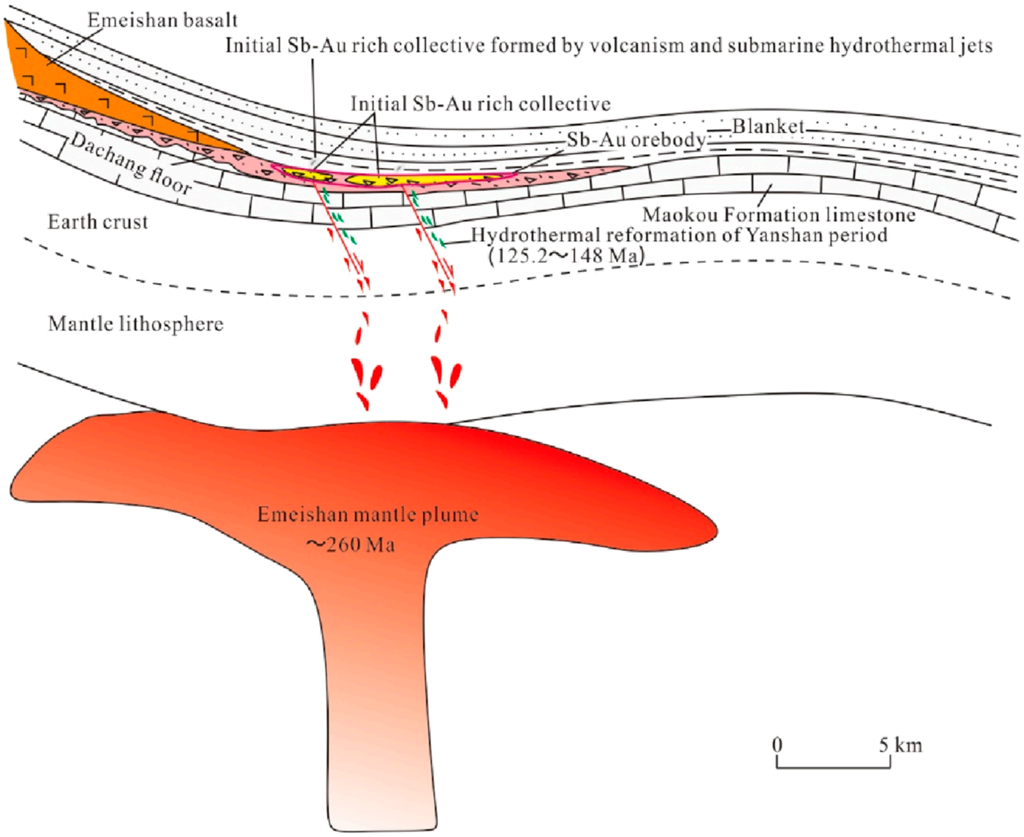

FIGURE 6
Metallogenic model of the Sb–Au deposit in Dachang, Qinglong, and Guizhou (modified after Du et al., 2020).

mantle plume event, deposits were divided into those directly and indirectly related to the Emeishan mantle plume (Table 1). The foci of this study included providing information regarding the deposit types related to the Emeishan mantle plume that has not been mentioned in the past and analyzing the genesis of these deposits.

3 Spatiotemporal distribution of deposits

3.1 Spatiotemporal distribution of deposits directly related to the Emeishan mantle plume

The investigation of the spatiotemporal distribution of deposits is essential for elucidating the metallogenic system associated with the Emeishan mantle plume. Various scholars have employed zircon U–Pb and 40Ar/39Ar geochronological methods to study Ni–Cu–PGE sulfide deposits. As illustrated in Figure 8, the metallogenic ages of Ni–Cu–PGE sulfides, Fe–Ti–V oxides, volcanic-type Fe, and Nb–Ta–Zr–REE deposits linked to syenite veins align with the formation age of the Emeishan Large Igneous Province (ELIP) at approximately 260 Ma. This temporal congruence indicates that the mineralization of these four deposit types is closely associated with mantle plume events, establishing a direct relationship with the mantle plume dynamics.

The deposits under discussion are primarily located within the inner zone of the ELIP, with a minor distribution in the middle zone along the north-south fault zone. Vertically, these deposits are situated in the middle and lower sections of the magma channel. Previous research indicates that the intrusion depth of the rock mass containing V–Ti–Fe oxide ore is greater than that of the rock mass associated with Ni–Cu–PGE sulfide ore. Notably, Nb–Ta–Zr–REE deposits linked to syenite veins typically intrude into the gabbro hosting Fe–Ti–V oxide deposits (Wang et al., 2018), suggesting similar vertical positions for these ore types. Additionally, volcanic-type Fe deposits in the Emeishan basalts are closely associated with ancient volcanic edifices and are predominantly found at the top of the magma channel, although weathering and erosion have led to their rarity in the Panxi area. Thus, ore deposits directly related to the Emeishan mantle plume arise from the diagenesis and mineralization of basaltic magma and its hydrothermal fluids across various spatial positions within the magma channel. The vertical zonation of these deposits, from the bottom to the top of the magma channel, is as follows: Fe–Ti–V oxides, Nb–Ta–Zr–REE, and Ni–Cu–PGE sulfide volcanic-type Fe deposits, as shown in Figure 9.

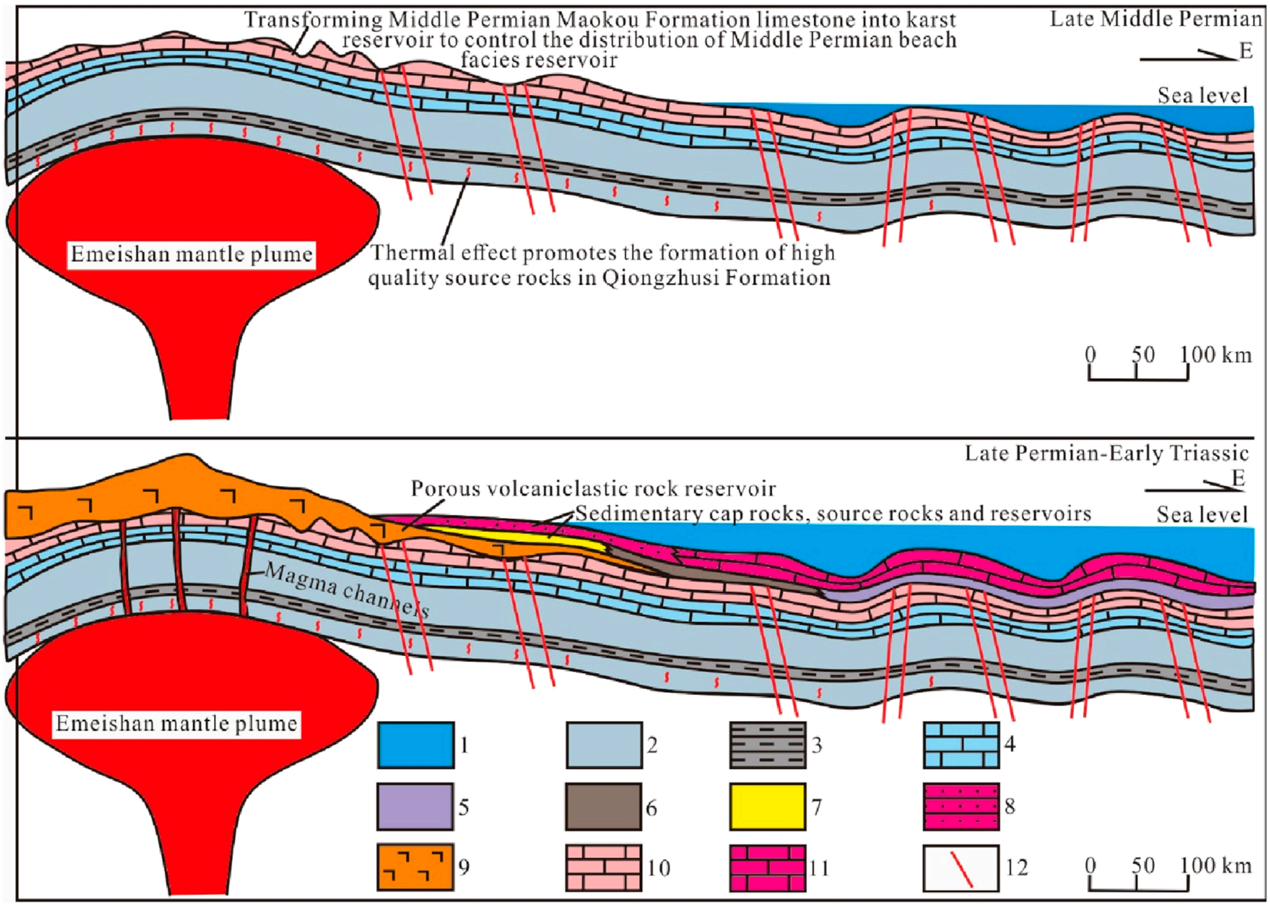

FIGURE 7
The influence model of the Emeishan mantle plume on oil and gas deposition (modified after Yang et al., 2007).

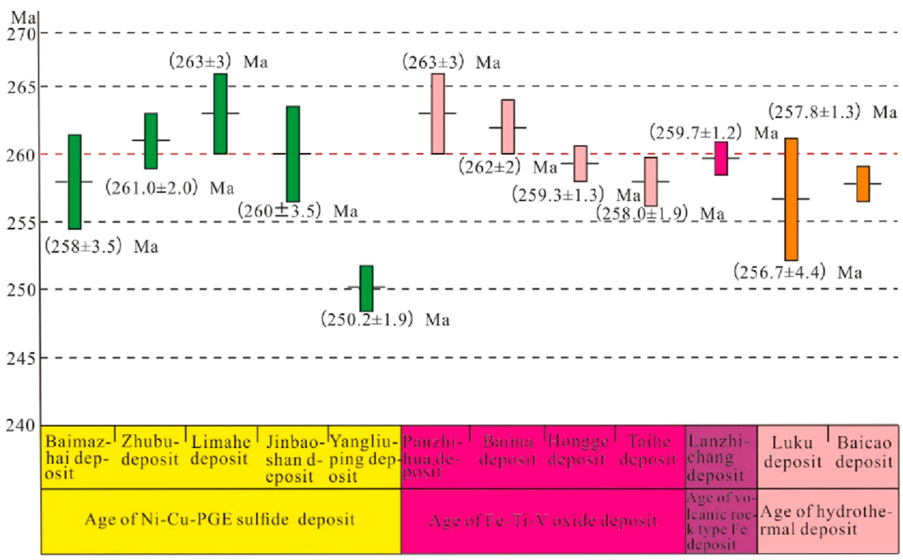

FIGURE 8
Metallogenic age distribution of ore deposits directly related to the Emeishan mantle plume. Note: The age of the Baimazhai deposit was obtained from Wang et al. (2005), that of Zhubu and Limahe deposits from Zhou et al. (2008), that of Jinbaoshan deposit from Tao et al. (2009), that of the Yangliuping deposit from Wang et al. (2007), that of the Panzhihua, Baima, Hongge, and Taihe deposits from Zhong et al. (2009), that of the Fe deposit in Lanzhichang from Zeng et al. (2016).

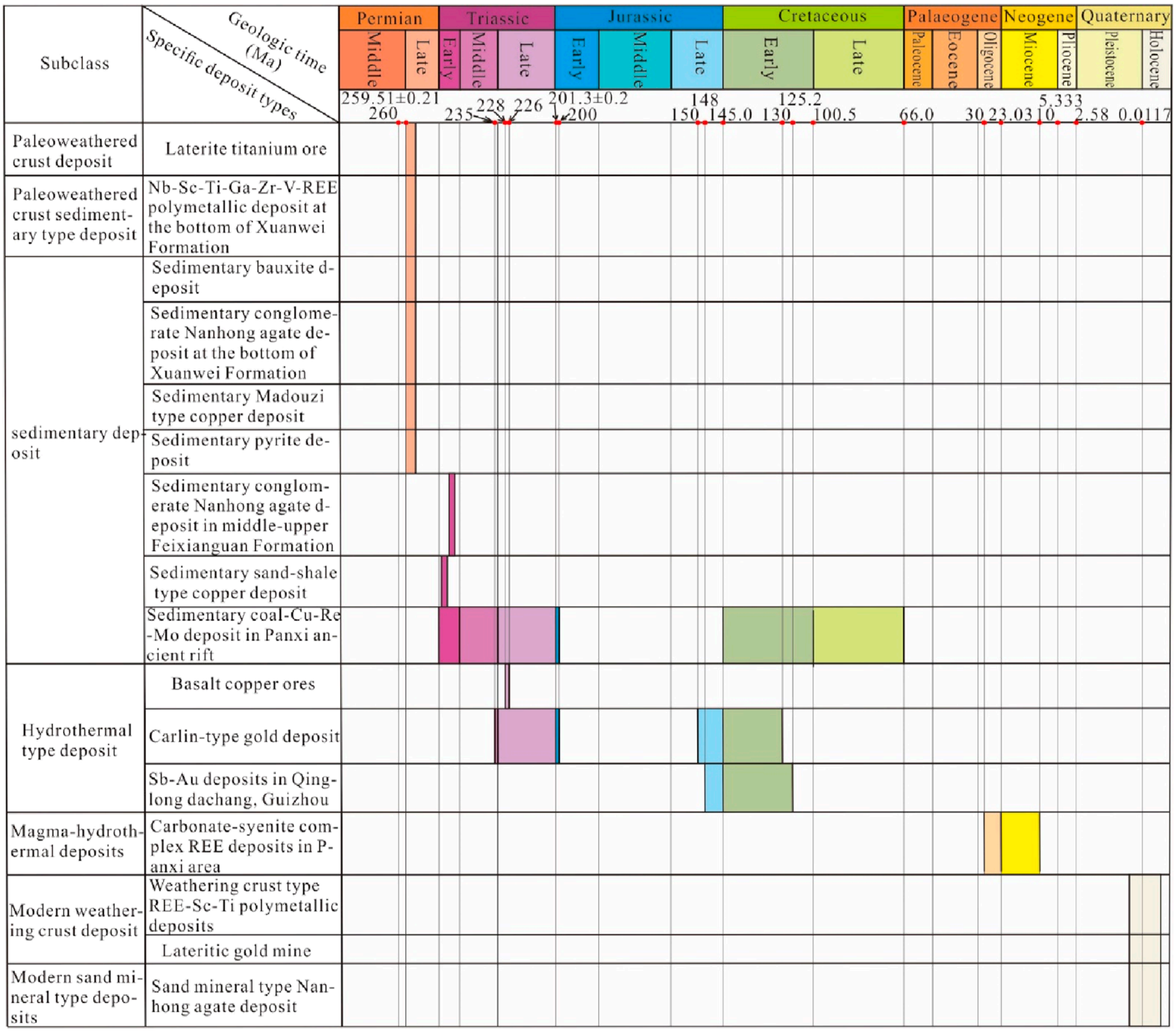

FIGURE 9
Mineralization age distribution of ore deposits indirectly associated with the Emeishan mantle plume.

3.2 Spatiotemporal distribution of deposits indirectly related to the Emeishan mantle plume

Deposits indirectly related to the Emeishan mantle plume are spatiotemporally dispersed. In terms of time, the ore-forming epochs of the deposits indirectly related to the Emeishan mantle plume occurred in the Late Permian, Triassic, Early Jurassic, Late Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary.

The Panxi ancient rift hosts sedimentary coal, copper, rhenium, and molybdenum deposits predominantly in the rift's inner zone, with other deposit types primarily in the middle and outer zones of the Emeishan Large Igneous Province. Modern weathering crust-type rare earth, scandium, titanium polymetallic deposits are localized within the Emeishan basalt's upper weathering crust, while laterite-type gold deposits originate from Quaternary soils overlying Middle Permian Maokou Formation limestones. Nanhong agate sand-type deposits are found in Quaternary sediments, and Dachang, Qinglong, and Guizhou antimony and gold deposits are associated with siliceous alteration zones above Maokou Formation limestones and below Emeishan basalt. Copper deposits are localized at basalt tops, and oil and gas deposits are concentrated in high-porosity basalt interiors, karstified Maokou limestones, and post-basaltic reservoirs. Paleo-weathering crust (laterite)-type iron ores, Nb–Sc–Ti–Ga–Zr–V–REE ores, sedimentary bauxite, conglomerate-type Nanhong agate, "Madouzi"-type copper ores, and pyrite are situated at the base of Upper Permian Xuanwei, Longtan, and Wujiaping formations. Sand shale-type copper deposits are at the base of the Lower Triassic Feixianguan Formation, with some conglomerate-type Nanhong agate in the middle–upper Feixianguan Formation's purple conglomerate layer. Carlin-type gold deposits span from Upper Permian Longtan to Lower Triassic Jialingjiang formations. Deposits linked to modern weathering and sedimentation are in Quaternary strata, those related to basalt paleo-weathering and sedimentation are in "sink area" strata sourced from Emeishan basalt, and those associated with hydrothermal processes are in Maokou Formation, Emeishan basalt, and subsequent sedimentary sequences.

3.3 Evolutionary history of the metallogenic system directly related to the Emeishan mantle plume

The evolutionary history of deposits directly related to the Emeishan mantle plume is closely related to the magmatism and hydrothermal action during its upwelling. The upwelling of the Emeishan mantle plume reached the super-thick lithosphere. Due to the upwelling of the mantle plume, a magmatic channel was formed in weak structural parts of the lithosphere. The basic–ultrabasic ore-bearing magma was positioned during the channel operation, forming Cu–Ni–PGE magmatic sulfide and V–Ti–Fe magmatic oxide deposits. In the late stage of the magmatic evolution, partial melting of the mantle plume and crust occurred when the mantle plume bottom invaded the crust, and assimilation and contamination–separation crystallization occurred in the crustal magma chamber, forming an alkaline magma, which was initially enriched in rare earth metal elements. In the late magmatic hydrothermal stage, rare earth metal elements were enriched to the greatest extent, and Nb–Ta–Zr–REE deposits related to syenite veins were formed. With further evolution of the magma, basalt magma overflowed the surface, and the volcanic rock-type Fe deposits formed near the crater.

3.4 Evolution history of the metallogenic system indirectly related to the Emeishan mantle plume

The Emeishan mantle plume's upwelling has significantly influenced the genesis and evolution of associated mineral deposits through its thermal, channeling, and enrichment effects on ore-forming elements. This process has yielded distinct evolutionary patterns among deposit types that serve as sources, conduits, and spaces for mineralization. Modern weathering crust-type and sand-type deposits primarily originated from the weathering of Emeishan basalts during the Quaternary period. In contrast, paleo-weathering crust-type, paleo-weathering crust-sedimentary, and sedimentary-type deposits are linked to the weathering and erosion of Emeishan basalts post the main eruption phase of the ELIP. These basalts, acting as a "source area," contributed to the formation of "sink areas" in strata such as the Xuanwei, Longtan, Wujiaping, and Feixianguan formations. The metallogenic system reflects these deposit types following the plume's upwelling. The Emeishan mantle plume provided the material basis for the initial enrichment of ore-forming elements in hydrothermal deposits; for instance, copper in basaltic copper deposits was enriched during the late stages of Emeishan basalt magma crystallization and further mineralized through subsequent hydrothermal processes. Carlin-type gold deposits contain gold-rich cumulates formed by the Emeishan mantle plume's magmatic event, with gold enrichment later activated by magmatic hydrothermal activity, migrating along deep faults to ore-bearing rocks. The Dachang antimony and gold deposit in Qinglong, Guizhou, resulted from volcanic activity associated with the Emeishan mantle plume, with initial enrichment of antimony and gold in the "Dachang layer," followed by Yanshan period hydrothermal fluid superimposition and final enrichment and mineralization. The carbonate-syenite complex rock-type REE deposit in the Panxi area is associated with ancient deep faults formed by the plume's upwelling, later activated by strike-slip faults from the India-Asia continental collision, with carbonate magma intrusion along these faults forming the deposit. Deposits providing metallogenic space include sedimentary coal-copper-rhenium-molybdenum deposits and oil and gas deposits in the Panxi paleo-rift, the former related to the paleo-rift's formation by the Emeishan mantle plume's upwelling, and the latter to oil and gas accumulation due to the plume's thermal effects, including hydrocarbon generation and the formation of high-porosity volcaniclastic rock reservoirs, beach facies reservoirs, karst reservoirs, and cap rock and reservoir overlying basalt. The evolutionary history of these deposits is intricately linked to the provenance layer or initial enrichment layer of ore-forming elements, ancient deep faults, and the ore storage space provided by the formation of the ELIP.

3.5 Implications for other mantle plume metallogenic systems worldwide

The significant amount of magma generated by the upwelling of the mantle plume often forms a LIP, which is a major geological event. Regardless of a magnesian LIP or a siliceous large igneous rock, the huge amount of heat and material related to it can form rich mineral resources.

Researchers have systematically studied deposits directly related to the Emeishan mantle plume. These deposits are often distributed in the center of the mantle plume; as the magma channel is distributed in the center of the mantle plume, magmatic deposits and magmatic–hydrothermal deposits are also often located there. Moreover, the distribution of such deposits is spatiotemporally concentrated, and their distribution is extremely dispersed. In contrast, deposits indirectly related to the mantle plume are widely distributed over the entire area of the LIP; furthermore, there is a lack of research on deposits indirectly related to the Emeishan mantle plume. Thus, collaborative research should be conducted in the future to achieve more prospecting breakthroughs and new discoveries.

In mafic LIPs, the partial melting of the mantle plume forms picrite magma. When the magma rises to the crust, a magma chamber is formed in the deep part of the crust and geological processes, such as fractional crystallization, crustal contamination, and immiscibility, occur. The primitive magma in the deep mantle can supplement and mix with the magma of the magma chamber. In these processes, oxides (including chromite and vanadium–titanium magnetite deposits) and Cu–Ni–PGE sulfide deposits are formed. The formation of the above-mentioned deposits is related to the magma source area and the nature and evolution of the original magma. The formation of vanadium–titanium magnetite deposits may be related to the source area of iron-rich rocks (eclogite and pyroxenite). The source area is partially melted to form iron–titanium-rich picrite magma and then separated and crystallized to form vanadium–titanium magnetite deposits. Cu–Ni–PGE sulfide deposits occur owing to the high degree of partial melting of the mantle peridotite, which leads to the formation of low-titanium picritic magma. During the ascent of the magma channel, it mixes with the crust, resulting in the liquation of the sulfide melt. Whether it is rich in PGEs mainly depends on the degree of crustal contamination and liquation. If the mantle source area contains carbonate, partial melting forms alkali-rich magma such as kimberlite and carbonatite. Kimberlite magma may capture diamonds in the lithosphere to form diamond deposits during the ascent and carbonatite magma can form REE and Nb deposits during the evolution and later hydrothermal action. In addition, mafic–ultramafic magma partially melts in the crust to form intermediate–acidic magma, which further evolves to form a series of hydrothermal deposits. Simultaneously, huge amounts of heat can also cause the metamorphic dehydration of surrounding rocks, resulting in the formation of metamorphic fluids and associated deposits. The siliceous LIP is dominated by felsic rocks, which can only form hydrothermal deposits.

After the formation of the LIP, the source layer or initial enrichment layer of ore-forming elements, ancient deep faults (ore transport channel), and ore storage space can be further enriched, migrated, and stored to form a series of deposits under the later geological action. Ore deposits providing ore-forming sources in LIPs include modern weathering crust-type, modern sand-type, ancient weathering crust-type, sedimentary-type, and hydrothermal-type deposits. Ancient deep faults generated in the mantle plume upwelling provide ore transport channels for later mineralization. In addition, the mantle plume thermal effect improves the maturity of organic matter and promotes the formation of high-quality source rocks. The rifting effect and porous volcaniclastic rocks caused by the upwelling of the mantle plume provide ore-forming space for the formation of sedimentary and hydrocarbon deposits.

In summary, the resource effect caused by the mantle plume upwelling event is significant. Under the background of the shortage and unbalanced distribution of several key mineral resources in the world, research on the mantle plume metallogenic system should be strengthened globally. Furthermore, it is necessary to compare the metallogenic effects with other LIPs worldwide to improve the guaranteed degree of global key minerals and promote the sustainable and healthy development of the global economy.

4 Conclusion

This study systematically reviews the distribution, characteristics, and genetic research progress of deposits related to the Emeishan mantle plume, providing new insights into its metallogenic system. The key findings are as follows.

(1) The ore-forming system of the Emeishan mantle plume includes deposits directly and indirectly associated with plume activity. Directly related deposits primarily consist of magmatic and hydrothermal types, including Fe–Ti–V oxide ores, Cu–Ni–PGE sulfide ores, volcanic iron deposits, and hydrothermal Nb–Ta–Zr–REE deposits linked to syenite dykes. Indirectly related deposits encompass various mineral sources, ore-transporting channels, and metallogenic spaces, such as weathering crusts, sedimentary deposits, carbonatite–syenite complex-type REE deposits, and oil and gas reservoirs in the Panxi region.
(2) The formation ages of deposits directly linked to the Emeishan mantle plume coincide with the emplacement of the Emeishan Large Igneous Province (ELIP) and are concentrated along the north–south fault zone near magmatic conduits. In contrast, indirectly related deposits formed later, with more dispersed ages, primarily occurring in the middle and outer zones of the ELIP.
(3) The evolutionary history of directly related deposits is closely tied to magmatism and hydrothermal processes along magma conduits. Indirectly related deposits, however, are influenced by pre-existing ore-rich layers, deep-seated faults, and ore-hosting structures shaped by the ELIP, each exhibiting distinct evolutionary pathways.
(4) Mantle plume upwelling, a major geological event, generates significant magmatic activity, forming Large Igneous Provinces (LIPs) and releasing substantial heat and material. This process not only enriches mineral resources but also enhances the maturation of organic matter, contributing to the formation of high-quality source rocks and abundant oil and gas reserves. Given the global scarcity and uneven distribution of critical mineral resources, further research on mantle plume-related metallogenic systems is imperative. Comparative studies with other LIPs worldwide will enhance our understanding of their metallogenic effects, strengthening global mineral security and supporting sustainable economic development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

ZL: Conceptualization, Investigation, Writing – original draft. JW: Investigation, Software, Writing – original draft. WZ: Project administration, Software, Writing – original draft. MC: Investigation, Methodology, Writing – original draft. HL: Investigation, Software, Writing – original draft. MZ: Formal Analysis, Methodology, Writing – original draft. YT: Conceptualization, Investigation, Writing – original draft. YG: Resources, Visualization, Writing – original draft.

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Conflict of interest

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