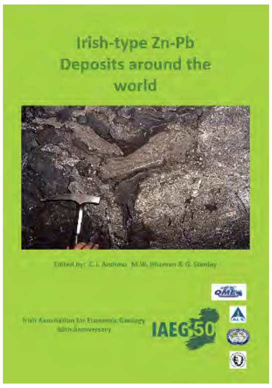

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Abstract China is endowed with mineral resources due to its prolonged and dynamic geological evolutionary history. Marine carbonate-hosted Pb-Zn deposits are mostly concentrated in the southern part of China, represented by the world-class metallogenic belt in the Sichuan-Yunnan-Guizhou ("SYG") triangle in the Yangtze Block, and those Pb-Zn deposits hosted in the Himalayan-Tibetan Orogenic Belt and in the Cathaysia Block. This paper presents a preliminary review of the geological characteristics of the major Pb-Zn mineral deposits in these regions, including the Huize, Maozu and Daliangzi deposits in the SYG triangle, the Jinding, Huoshaoyun and Chapupacha deposits in the Himalayan-Tibetan Orogenic Belt, and the Fankou and Panlong deposits in the Cathaysia Block. The aim is to gain an improved understanding of the geological controls on the carbonate-hosted Pb-Zn deposits in China. In general, the carbonate-hosted Zn-Pb deposits in the Yangtze and Cathaysia Blocks display many similarities, including the mineralization being mainly controlled by stratigraphy (i.e., coarse dolomite layers in certain stratigraphic units) and structure (i.e. well-developed fault systems). The deposits are distinctively high in Pb+Zn grades and enriched in dispersive elements including Ga, Ge, Ag, Cd, and Tl, and are spatially associated with the Permian Emeishan flood basalts. The most distinct geological features of the Zn-Pb deposits in the Himalayan-Tibetan Orogenic Belt is the occurrence of pervasive evaporites and the development of breccias and oxide ores. Overall, deep regional structures, including crustal faults and suture zones and the combined existence of organic matter and evaporites are among those crucial factors to form the large carbonate-hosted Pb-Zn deposits in China.

Keywords: China, Yangtze Block, Cathaysia Block, Sichuan-Yunnan-Guizhou Triangle,

Introduction

China is endowed with mineral resources owing to its unique history of geological evolution. Five mega stages of tectonic events have been recorded stretching from the Archaean to the Cenozoic, during which the Palaeo-Asian Ocean, Tethyan and Western Pacific domains reacted and formed a continental crust composed of cratonic blocks and orogenic belts (Fig. 1) (Wang & Mo, 1995). From the Archaean to Neoproterozoic (named as "Sinian" in Chinese literature) the tectonic evolution of China is characterized by the formation of continental crust nuclei and by the increasing size and stabilization of the continental crust. Continental crust nuclei were distributed mainly in North China in the Archaean and were assembled during the cratonization of North China through the amalgamation of micro-blocks. During the Mesoproterozoic China was in an extensional tectonic setting, when mature platforms formed

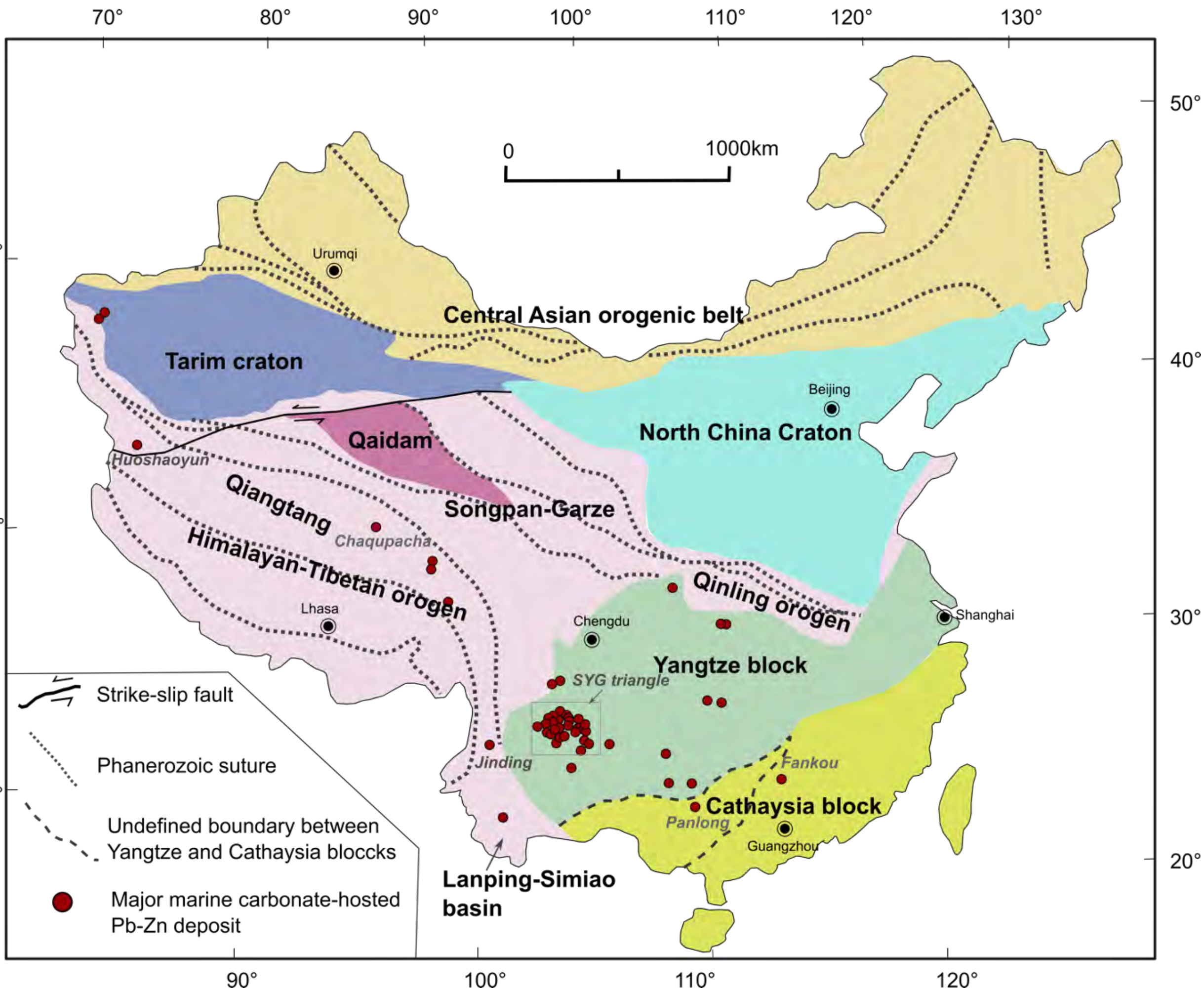

Figure 1: *Distribution of major marine carbonate-hosted Pb-Zn deposits in China (modified from Leach et al., 2019)*

mainly in a convergent regime in the Jinningian Stage. From the late Neoproterozoic to the Triassic China experienced a complicated development of continental margins through rifting, splitting and re-accretion of marginal massifs, eventually forming the Eurasian Supercontinent. Overall, extension prevailed in the Caledonian and compression in the late Hercynian and Indosinian Stages in China.

The end of the Indosinian Stage is marked with profound changes in the tectonic regime of China. The Palaeozoic tectonic framework was replaced by a Tethyan system in west China and a Pacific system in east China. The closure of Palaeo-Tethys in the Late Triassic resulted in several convergent and accretional crustal consumption zones as evidenced by the occurrence of ophiolite and ophiolitic mélange zones of Indosinian age in the Himalayan-Tibetan area. Almost every zone is accompanied with a magmatic belt, consisting of subduction- and collision-type volcanic and granitic rocks of Late Permian to Late Triassic age. The Indosinian convergence in the east Palaeo-Tethys region also formed foreland type sediments in the western border parts of the Ordos and Sichuan basins in Late Triassic. The post-Indosinian of China was mainly intracontinental. Continental collision, subduction and indentation of the massifs prevailed as the three surrounding plates, India, Siberia and Pacific, interacted. East and west China, however, were marked with different tectonic evolution history during the post-Indosinian time (Wang & Mo, 1995).

The main post-Indosinian tectonic events in East China include the formation of the giant Circum-Pacific tectono-magmatic belt and of the extensive rift basin system. Intracontinental subduction is predominant, followed by intracontinental collision during the Yanshanian Stage in east China. Extensive Yanshanian age volcanic rocks and granitic intrusive rocks were formed from intracontinental convergence and subduction. Since the Late Cretaceous, rifting and extension have prevailed in the eastern part of East China, forming rift basins and causing extensive eruptions of rift-related basalts. The Cenozoic magmatic events are also characterized by rift-related basaltic eruptions, whereas granites scarcely occur in East China. In West China, the generation and evolution of Neo-Tethys was the most significant tectonic event in the post-Indosinian period. This period was marked with the full development of the Yarlung Zangbo oceanic basin - the main branch of Neo-Tethys, and by the Triassic the opening of the Banggong-Nujiang oceanic basin, another branch of Neo-Tethys, probably in the Early Jurassic (Deng *et al.*, 2017). The general dispersion of lithosphere and the generation of new oceanic crust

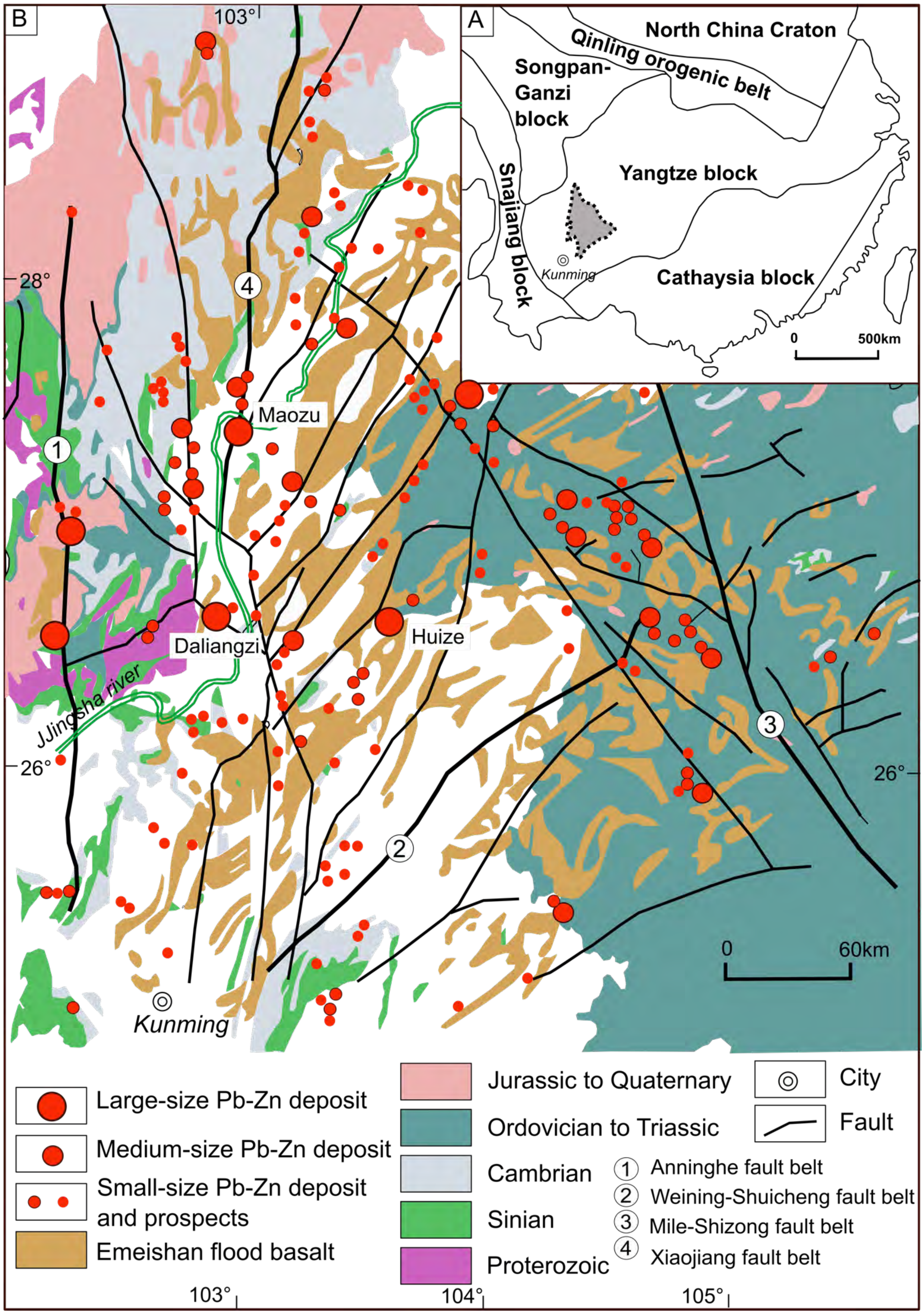

***Figure 2:** Simplified geological map **(A)** of the Sichuan-Yunnan-Guizhou triangle in grey and Simplified tectonic map of South China **(B)**, after Xu et al. (2019)*

was significant in West China from the Late Triassic to the early Cretaceous. In both the Yarlung Zangbo and the Banggong-Nujiang oceanic basins subduction started in the Late Jurassic, ending in the Late Eocene and Late Cretaceous, respectively. The destruction of Neo-Tethys, the northward movement of the Indian Platform and its collision with the Eurasian Supercontinent in the Early Cenozoic completed with a dramatic change from a divergent to a convergent tectonic condition in this region. Since the Cenozoic, the tectonic setting of West China was dominated by intracontinental convergence and subduction, which may be subdivided into two stages (Wang & Mo, 1995). The first stage is from Oligocene to Miocene, which is characterized by strong horizontal compression and intracontinental subduction leading to the formation of the Himalayas and Gangdise mountain ranges. The second stage is from Pliocene to Quaternary, and the main event was the quick differential uplift of the Qinghai-Tibet plateau.

The prolonged and dynamic geological evolution of China has resulted in major tectonic units comprising cratons such as the North China, Tarim and Yangtze, and several orogenic belts consisting of small blocks and arcs flanking these cratons, including the Central Asian, Qinling-Qilian-Kunlun, Tibet, and Sanjiang Orogenic Belts (Fig. 1) (Zheng *et al*., 2013), all of which host remarkable mineral resources (Zhang *et al*., 2014; Deng *et al.*, 2017). Marine carbonate-hosted Pb-Zn deposits in China are most abundant in the Yangtze Block, subordinately in the central and eastern Himalaya-Tibet orogen and the Cathaysia block (Fig. 1, Zhou *et al*., 2018; Leach *et al*., 2019; Song *et al*., 2019). This review paper presents primary geological characteristics of major carbonate-hosted Zn-Pb deposits hosted in the three districts, with a focus of understanding the key geological factors that control the formation of major carbonate-hosted Pb-Zn deposits in China.

Carbonate-hosted Pb-Zn deposits in the Yangtze block

The Yangtze block hosts a world-class Pb-Zn metallogenic district, confined in a region named as the Sichuan-Yunnan-Guizhou ("SYG") triangle at its southwestern margin. The SYG triangle covers an area of ~170,000km^2 across the northeastern Yunnan Province, northwestern Guizhou Province, and southwestern Sichuan Province (Fig. 2A), (Hu & Zhou, 2012). To date, more than 450 Zn-Pb deposits and occurrences have been identified in the SYG triangle, containing >2000Mt reserves of sulphide ore at grades of 10–35% Pb + Zn (Fig. 2B) (Han *et al*., 2023). Sulphide ores in the Pb-Zn deposits are in general characterized by high Zn+Pb grade with average >10 % and enrichment in Ag, Cu, Cd, Ge and Ga (Ye *et al*., 2011, Zhou *et al*., 2018). Among these deposits, the Huize Pb-Zn-(Ag-Ge) deposit, Daliangzi Pb-Zn-(Cd-Ge) deposit, Maozu Pb-Zn-(Ag-Ga) deposit, Maoping Pb-Zn deposit and Tianbaoshan Pb-Zn deposit are classified as being large Pb-Zn deposits with contained metal reserves of over 2Mt (Han *et al*., 2023). The geological characteristics of the Huize, Daliangzi and Maozu deposits are described in detail in the section below.

The basement of the SYG triangle is composed of the Late Palaeoproterozoic to early Mesoproterozoic Dongchuan and Mesoproterozoic Kunyang Groups (also named as Huili in literature), which dominantly comprise siltstones, slates, sandstones, and dolostones interbedded with tuffaceous units, and are tightly folded and weakly metamorphosed (Zhou *et al*., 2013; Hu *et al*., 2017). During the Sinian to Middle Triassic, the southwestern Yangtze Block was a passive continental margin, where thick submarine sedimentary sequences were deposited on top of the basement and are dominated by carbonates and clastic sediments in the SYG triangle. The lower Sinian units are mainly coarse volcaniclastic sediments, while the uppermost unit is a thick dolostone layer. Cambrian rocks are primarily clastic sediments and include black shales, sandstones interlayered with dolostones and limestones. Ordovician sediments are primarily limestones, dolostones, marls and shales. Silurian sediments are dominated by fine-grained sandstones, shales, dolostones, and limestones. Devonian sediments are dominated by quartz sandstones, calcareous sandstones, shales, limestones, dolomitic limestones, and dolostones, which are overlain by Carboniferous limestones, oolitic limestones, dolomitic limestones and dolostones. From the Late Permian to Early Triassic, the Yangtze Block was an intracontinental rift, where lower Permian sediments including microcrystalline limestones, brecciated limestones, dolomitic limestones, dolostones, brecciated limestones, dolomitic limestones, dolostones, and argillaceous siltstones, were deposited. The Late Permian strata are overlain by voluminous Permian Emeishan continental flood basalts. The Emeishan flood basalts were erupted and emplaced at ~260 Ma (Zhong & Zhu 2006) and are up to ~5km in thickness in Yunnan Province but only a few hundred meters to the maximum thickness in Guizhou Province (Xu *et al*., 2001). During Middle-Late Triassic, the SYG triangle was impacted by the closure of the Palaeo-Tethys Ocean, and subsequently the Indosinian orogeny and suturing (Cai & Zhang 2009). This led to the development of a series of thrust belts and foreland basins on the periphery of the region post the Late Triassic. Later on, the SYG triangle was subject to continuous intracontinental deformation and deposited terrigenous sandstones, conglomerates and freshwater marls of Jurassic to Cenozoic age. The carbonate-hosted Zn-Pb deposits are stratigraphically hosted in the Proterozoic Kunyang Group to middle Permian strata and are spatially associated with the Permian Emeishan flood basalts (Fig. 2B).

The SYG triangle is confined by three regional fault belts extending deep into basement rocks, including the N–S-trending Anninghe, NE–SW-trending Mile–Shizong, and NW–SE-trending Weining–Shuicheng fault belts. It also contains the deeply seated N–S trending Xiaojiang fault belt. These faults were activated and reactivated during major tectonic events, together with the development of numerous secondary NE- and NW-trending faults and fold-and-thrust belts in this area (Xu *et al.*, 2020; Han *et al.*, 2023, and references therein). In general, the NWW-trending extensional faults and NE- and NW-trending thrust faults and folds control most of the known lead-zinc deposits in the SYG triangle (Han *et al*., 2023).

Huize Pb-Zn-(Ag-Ge) deposit

The Huize Zn-Pb-(Ag-Ge) deposit is the thirst largest Zn-Pb deposit in China and the largest in the SYG triangle. The deposit has metal reserves in excess of 5 Mt at high Pb+Zn grades (> 25%). In addition, the deposit also produces Cd at a grade

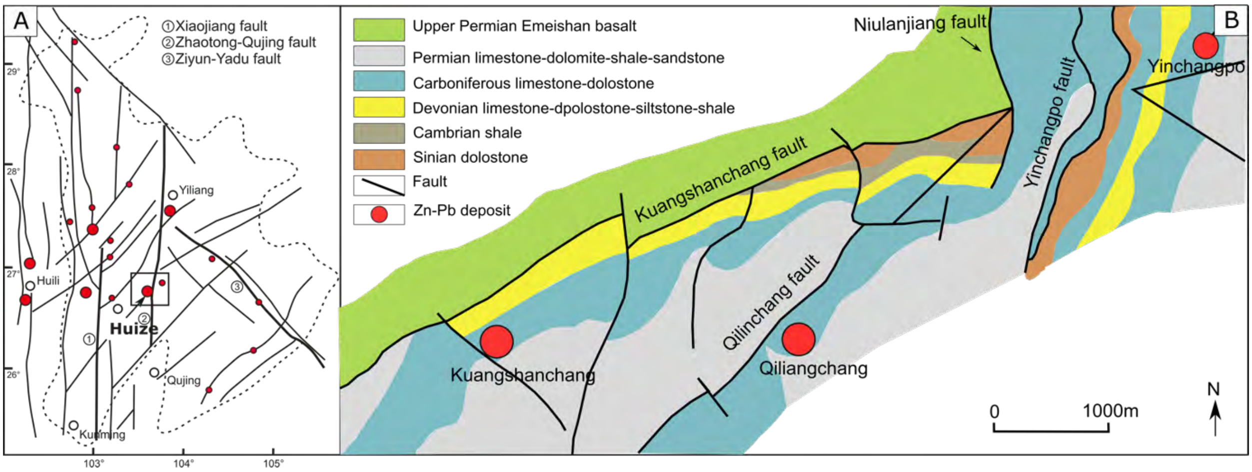

***Figure 3:** Sketch map of the regional structure **(A)** and deposit geology **(B)** of the Huize Zn-Pb-(Ag-Ge) deposit (modified from Han et al., 2015)*

of 233–488 g/t, Ag at a grade of 46–100 g/t and Ge at a grade of 30–81 g/t (Han *et al.*, 2007).

Huize is situated in the central of the SYG triangle. The mine area is structurally controlled by the NE-trending Dongchuan-Zhenxiong thrust-fold zone resulted from the sinistral shearing of the Xiaojing fault and Zhaotong-Qujing concealed fault (Fig. 3A). The Kuanghanchang and Qinlinchang faults, which are the two major faults in the deposit trending NE and NNE, respectively, are spatially associated with the mineralization (Fig. 3B). The basement is comprised of the Sinian and Palaeozoic strata and unexposed Mesoproterozoic Kunyang Group, which is covered by Middle-Upper Devonian, Carboniferous and Permian strata (Fig. 4). The Kunyang Group in the mine area consists of low-grade greenschist facies of shallow-marine carbonate-dominated and fluvial siliciclastic-dominated rocks. The Upper Proterozoic rocks mainly include volcanic rocks in the Lower Sinian and the marine dolomite of the Upper Sinian Dengying Formation. The Lower Carboniferous Baizuo Formation is the most important host rock for mineralization in Huize, which comprises of coarse crystalline dolomite intercalated with argillaceous dolomitic limestone and thin-layer barite-bearing evaporites. Magmatism is represented by the Late Permian Emeishan flood basalts, which outcrop along the Xiaojiang fault zone in the mine area (Fig. 3B), (Yuan *et al.*, 1985, Song *et al.*, 2001).

The deposit comprises the Kuangshanchang, Qilingchang and Dashujing, together with the smaller Yinchangpo Ore Zones (Han *et al.*, 2007), (Fig. 3). More than 50 orebodies of various sizes are distributed in the mine area, including 42 orebodies in the Kuangshanchang Ore Zone and 8 orebodies in the Qilingchang and Dashujing areas (Han *et al*. 2007). Among these, the No.1 orebody in the Kuangshanchang area and the Nos. 6 and 8 orebodies in the Qilingchang area are the most economically important. Mineralization is mainly hosted in the Lower Carboniferous Baizuo Formation (Fig. 4). The upper part of the Baizuo Formation mainly consists of greyish-white, yellowish-red, cream-coloured and coarse-crystalline dolomite, whereas the middle-lower parts are largely composed of light-grey compact-massive limestone and argillaceous dolomitic limestone. Mineralization is mostly distributed along interstratified fault zones of the dolomite between the middle and upper parts of Baizuo Formation (Fig. 5). The contrast of shear

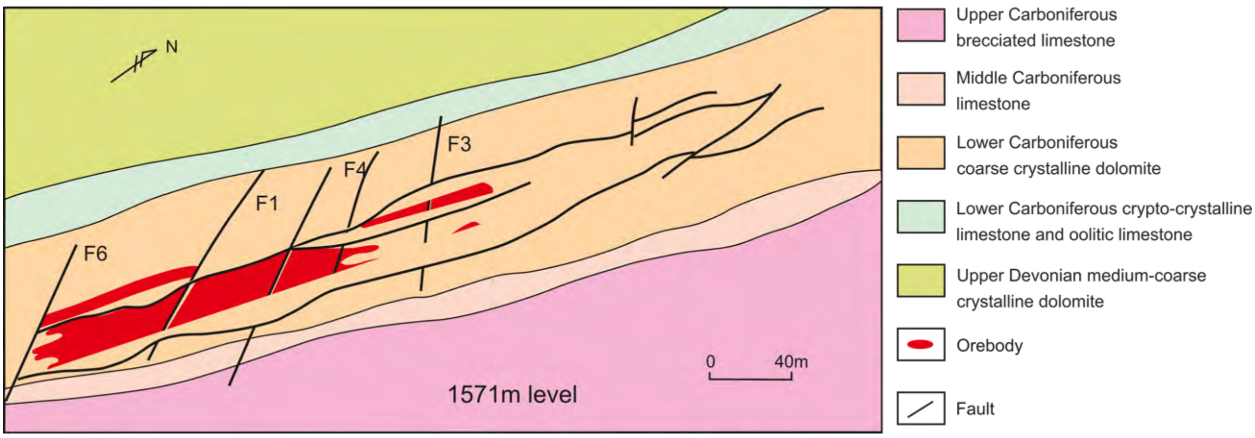

***Figure 4:** Planar map of No.6 orebody at 1571 m level in the Qilingchang ore zone of the Huize Zn-Pb-(Ag-Ge) deposit (modified from Han et al., 2015)*

Era	System	Formation	Thickness (m)	Lithology
Upper Palaeozoic	Permian	Basalt	600-800	Greyish-green,compact-massive, amygdaloidal basalts, the middle and upper parts are purple altered basalts with leaf-like native Cu between them, in pseudo-conformable contact with the underlying strata.
		Qixia-Maokou	450-600	Dark light grey limestone,dolomitic limestone intercalated with dolomite,dolomitic materials unevenly distributed.
		Liangshan	20-60	Upper: greyish black carbonaceous shale/ fine sandst-one intercalated with coal. Lower: yellowish white san-dstone intercalated with yellowish brown argillaceous shale.
	Carbon-iferious	Maping	27-85	Upper: pisolitic limestone and limestone. Middle: Intercalations of purplish red and yellowish greenshale. Lower: Purple, greyish purple brecciated limestone, the breccia cemented by purple, yellowish green argillaceous materials.
		Weining	10-20	Light grey limestone intercalated with oolitic limestone.
		Baizuo	50-80	Middle-Upper: white-white, cream-yellow coarse cryst-alline dolomite intercalated with light grey dolomitic limestone (the main ore-host bed).
		Datang	5-25	Grey limestone, and oolitic limestone, 0-5m thick greyish brown siltstone and purple mudstone at the bottom.
Lower Palaeozoic	Devonian	Zaige	200-310	Upper: Grey limestone,yellowish white and yellowish redmedium-coarse crystalline dolomite (subordinate ore- bearing bed). Pb-Zn orebodies hosted in light coloured coarse crystalline dolomite near Xiaoheiqing. Middle: light grey, medium to thick layered, siliceous dolomite intercalated with greyish yellow thin layered calcareousshales, light yellow, light yellowish red, fine crystallinedolomite observed locally at the top. Lower: Light grey,medium to thick layered, fine-medium coarse crystalline dolomite intercalated with light grey argillaceous dolomite.
		Haikou	0-11	Light grey, light yellow sandy siltstone/ green, greyish black argillaceous shale alterations; in pseudo-conformable contact with the underlying strata.
	Cambrian	Qiongzhushi	0-70	Black argillaceous shale intercalated with yellow sandymudstone and gypsum salt beds, in pseudo-conformable contact with the underlying strata.
Proterozoic	Sinian	Dengying	>70	Light grey, greyish white siliceous dolomite, in pseudo-conformable contact with the underlying strata.

Figure 5: *Stratigraphic column of the Huize Pb-Zn-(Ag-Ge) deposit, Yunnan Province, China (after Han et al., 2007)*

and compression strength between the upper and middle-lower parts generates interstratified fault zones for hosting mineralization. A detailed characterization of the lithological composition and fossil types was presented for the Baizuo Formation (Han *et al.*, 2007), based on which nine layers are divided from the lower to upper, including 1) gray bioclastic micritic limestone which contains Chaetetes *sp* coral fossils; 2) hoar bedded fine limestone and sparite in the lower part, hoar dolomitized fine-grained limestone and sparry clastic limestone in the middle part, which contains *Palaeosmilia sp* coral and *Striatifera sp* fossils; hoar bedded dolomitized fine-grained bioclastic limestone in the upper part, containing *Gigantoproductus sp* fossils, 3) gray bedded medium-grained and fine grained dolomite with 10cm algal-laminated micritic limestone in-between; 4) thick gray sparry sand calcirudite with algal-laminated structure, which contains pyrite and *Productus sp* fossils; 5) red coarse-grained dolomite with algal-laminated structure, which contains pyrite; 6) thick gray medium-grained and fine-grain dolomite with solution structure, which contains shell fossils; 7) thick hoarse dolomitized micritic limestone and sparry bioclastic calcarenite, which contains *Gigantoproductus sp* and *Heterocaninia sp* fossils; 8) thick light gray, bedded dolomitized bioclastic calcarenite, which contains *Gigantoproductus sp* fossils and 9) light gray fine grained limestone, which is intensively dolomitized and contains *Striatifera sp* and *Productus sp* fossils. In addition, thin-layer barite-bearing evaporite was identified to occur in the middle part of the Baizuo Formation. Nearly all the mineralization is hosted in Layer 5 of red coarse-grain dolomite with hydrothermal origin, as reflected in their close association with alteration of ferro-

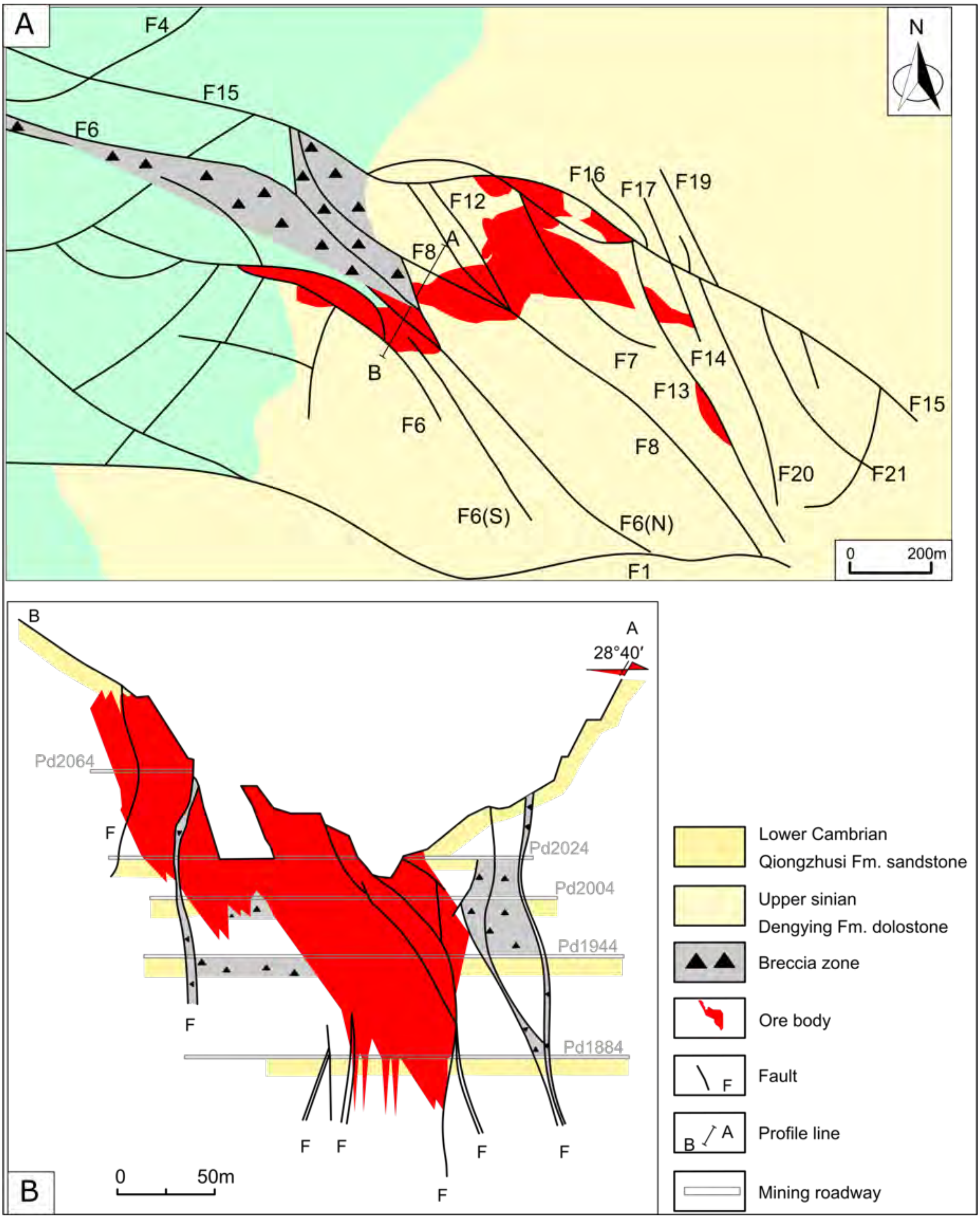

***Figure 6: (A)** Geological map of the Daliangzi Zn-Pb-(Cd-Ge) deposit and **(B)** A cross section A-B through the deposit (modified from Yuan et al, 2018)*

dolomitization and silicification. Dolomitization is extensively developed in the Huize area.

A highly oxidized Fe-cap was distinguished to occur in the upper part, which transitions to a mixed layer of oxide and sulphide ore zone in the middle part and then a massive sulphide ore zone in the lower part of the mineralized Baizuo Formation. The metallic sulphide minerals mainly include sphalerite, galena, pyrite, marmatite (Fe-rich sphalerite), chalcopyrite, acanthite, freibergite, and matildite. The gangue minerals include dolomite, calcite, quartz, and gypsum. Mineralization occurs as massive, veined, brecciated, fracture-filling, and replacement textures. Two periods of mineralization comprising supergene and hypogene processes are identified

(Oyebamiji *et al*, 2023). The hydrothermal mineralization period is further divided into three stages based on mineral assemblages, namely the pyrite-sphalerite, sphalerite-galena-pyrite, and pyrite-chalcopyrite stages. The supergene process is represented by the oxide ore zone, which is primarily composed of chlorargyrite, barite, gypsum Fe-hydroxides and hopeite, as well as pure Pb oxide ores (Oyebamiji *et al,* 2023).

Daliangzi Zn-Pb-(Cd-Ge) deposit

The Daliangzi Zn-Pb deposit has reserves containing 4.5Mt of Zn+Pb metal at average Zn + Pb grades of 10–12 %. In addition to Zn and Pb, the ores are rich in Ge and Cd with estimated reserves of 100 tonnes and 4,000 tonnes, respectively. The basement in the mine area is mainly composed of Archean-Palaeoproterozoic metamorphic complexes, Mesoproterozoic metamorphic fine clastic rocks intercalated with metamorphic volcanic sedimentary rocks, and Sinian metamorphic fine clastic rocks and carbonate rocks. The basement has a sedimentary cover comprised of the Upper Sinian, Cambrian, Ordovician, and Lower Permian marine carbonate rocks and fine clastic rocks, Upper Permian Emeishan basalts, and Mesozoic continental red beds. Mineralization is mostly hosted in the dolomite of Upper Sinian Dengying Formation. An unconformity is observed between the Dengying and overlying Qiongzhusi formations. The Dengying Formation in the mine area is 928m thick and dominated by dolostone, containing algae fossils in the lower section, fine grained clastic layers in the middle section and phosphorous and chert banding in the upper section. No igneous rocks crop out in the mine area except for the Late Permian Emeishan flood basalts on the northwest outer margin of the district.

Fault structures are extremely well developed in the mine area, forming an NWW-trending graben (Fig. 6A). Among those faults, faults F1 and F15 are the largest and represent branches of a regional fault. The regional fault extends into the basement in 15–20km length and is now filled with metamorphosed rocks of the Mesoproterozoic Kunyang Group. The area to the south of F1 and to the north of F15 is featured with a fault block structure, where more than 40 faults form two fracture block zones. Fault structures in the area can be divided into four orders (Kong *et al.*, 2022), include the first-order structures of F1, F2, F13, F15, and F64 in NWW- nearly E-W direction, which controls the distribution of deposits, the second-order structures of a series of N-W direction faults F3, F8, F6, F100, and F5 derived from the first-grade structures, the third-order structures of secondary and interlayer fault zones, which control individual ore bodies, and the fourth-order structures of sub-secondary faults and joint fissures, which control the shape and the occurrence of the vein-type mineralization.

The lead-zinc orebodies are mainly controlled by the NWW-trending faults. The NWW-trending faults also control the distribution of a distinct zone named as 'black fracture zone' for the deposit (Fig. 6A), which is spatially associated with the orebodies. The black fracture zone is characterized by its dark color and mixed breccias of dolostone and sand shale from the Dengying Formation and Qiongzhusi Formation, respectively. The breccias are angular in shape and variable in size, indicating that they were generated by faulting. The breccias are locally mineralized, which suggests that this fracture zone was formed before ore formation and that the mineralization postdates the deposition of the Cambrian Qiongzhusi Formation.

The orebodies are in pipe- or vein- shape and controlled by the high-angle faults, which constitutes >90% of the total reserves. The fault-controlled orebody extends 630 m in length, 0.8–204 m in thickness (average of 46m) and >400m in depth (Fig. 6B). The contact between the orebody and the host rock dolostone is sharp, and the boundary is either fault-controlled or dissolution controlled. Mineralization mainly occurs as open-space filling and subordinate replacement. The most abundant metallic minerals are sphalerite, followed by galena, pyrite, and chalcopyrite, arsenopyrite, marcasite, freibergite, and pyrargyrite. The ore has a distinctively high zinc content. The gangue minerals are dolomite, calcite, quartz, and chalcedony. The main ore textures include brecciated, colloform, vein, stockwork, and massive textures. Breccia-type ores are characterized by dolostone clasts cemented by sulphide, which transition to stockwork ores locally. In the breccia-type ores, the dolostone clasts are cemented by either sphalerite or pyrite or both. In other cases, sphalerite clasts were shattered by later shearing and subsequently cemented by calcite. In the deeper part of the deposit, the clasts of the breccia consist of dolostone in a variety of color and texture, and some of the clasts are subrounded, which may indicate a short distance of migration or dissolution from collapsed breccias. Most of the clasts in the breccia are angular and poorly sorted, and show single lithology, indicating that they are most likely formed from brecciation from the movement of faults during mineralization. Within the host rock dolostone, mineralization generally occurs as cavity or fracture fillings. Coarse-grain sphalerite and calcite formed at a late stage and usually fill in the vugs. Alteration mainly includes dolomitization and silicification, which are distributed in restricted areas within the orebodies and host rocks (Zheng & Wang, 1991).

Mineralization is divided into three periods: sedimentary, hydrothermal and supergene (Yuan *et al*., 2018). Minerals formed during the sedimentary process mainly include dolomite, and to a lesser extent pyrite in framboids, and occasionally sphalerite. The hydrothermal stage is responsible for all the hypogene mineralization and may be divided into three stages: pyrite-arsenopyrite, sphalerite-galena, and sphalerite-quartz. In the pyrite-arsenopyrite stage, a mineral assemblage of pyrite + arsenopyrite + chalcopyrite + marcasite + quartz was formed. The sphalerite-galena stage is characterized by the mineral assemblage of sphalerite + galena + chalcopyrite + calcite + quartz. Sphalerite formed in this stage is dark in color and colloform and contains chalcopyrite inclusions. Galena in this stage contains inclusions of freibergite. The minerals formed in the last hydrothermal stage mainly include coarse grained sphalerite without chalcopyrite inclusions. Supergene mineralization is formed from weathering of sulphide ores and mainly consists of smithsonite and cerussite.

Maozu Zn-Pb-(Ag-Ga) deposit

The Maozu deposit has ~ 2 Mt Zn+Pb metal reserves, grading at 4.15% Pb, 7.25% Zn, 33.6 g/t Ag and 180 ppm Ga (Liu, 2009). The orebodies are hosted in the dolostone of the Upper Sinian Dengying Formation (Fig. 7) and structurally controlled by the Maozu thrust fold (Fig. 8). Several folds including the

Era	System	Formation	Lithology
Cenozoic	Quaternary Tertiary	?	Sediments rocks that are exposed in valley or river areas
Mesozoic	Triassic	?	Sandstone,shale,and claystone,hosting coal
Palaeozoic	Permian	Emeishan basalt	Flood basalt, hosting native Cu ore body
		Yangxin	Limestone and dolostone
	Carboniferous	?	Limestone, dolostone, and sandy shale
	Devonian	Zaige	Dolostone
		Haikou	Sandstone and carbonates
	Silurian	?	Siltstone and carbonates
	Ordovician	?	Sandy shale and argillaceous limestone
	Cambrian	Qiongzusi/ Meishucun	Phosphorite, sandstone and carbonates
Proterozoic	Sinian	Dengying	Phosphorus-bearing and silicified dolomite Hosting Pb-Zn ore body of the Maozu
	Basement		Volcaniclastic and Metamorphic rocks

Figure 7: *Generalized stratigrapic column of the Maozu deposit (modified from Zhou et al., 2013)*

Ganshulin and Baika synclines and the Hongfadong and Changpo anticlines are identified in the mine area. Four orebodies are delineated in the upper part of the Dengying Formation, of which single orebody is 440–850m long, 221–725m wide and 2.63–5.09m, with 0.77–6.11% Pb and 3.85–11.48% Zn. The Zn/Pb ratios range from 5 to 9. The orebodies are strata-bound and mostly located at the stratigraphy boundary between the Dengying Formation containing phosphorite, sandstone and carbonates and the overlying Qiongzusi Formation comprising phosphorous-bearing and silicified dolomite (Fig. 8B). In addition, another 5 orebodies are recognized in the lower part of the Dengying Formation (Fig. 8B), of which single orebody is 240–930m long, 45–346m wide and 1.73–8.29m thick, with 1.13–7.20% Pb and 3.61–12.27% Zn. The Zn/Pb ratios are 3–5. Several vein-type ore bodies cross-cutting the stratigraphy layers were also recognized, which is 240–930m long, 45–346 m wide and 1.73–8.29m thick, with 1.13–7.20% Pb and 3.61–12.27% Zn. The vein-type orebodies link the upper and lower parts of mineralization in the Dengying Formation, and trend primarily 20–43^{o}NW (Fig. 8B).

Both sulphide and oxide ores are observed at Maozu, as well as a transitional type of mixed sulphide and oxide ores (Zhou *et al.*, 2013). Mineralization occurs in styles of brecciation, massive open space filling and banded layers. Replacement, and disseminated and veined textures are commonly observed. Sulphide ores are primarily massive in texture and composed of sphalerite, galena, pyrite, calcite, dolomite, quartz, and fluorite. Three periods of mineralization including sedimentary, hydrothermal and supergene processes were divided for the Maozu. The hydrothermal period is further divided into two stages, i.e., the sulphide-carbonate-quartz-fluorite and carbonate stages. Mineralization mostly occurs during the sulphide-carbonate-quartz-fluorite stage, which contains mineral assemblages of pyrite-sphalerite-calcite, quartz-sphalerite-pyrite-galena-calcite, and sphalerite-galena-calcite-quartz-

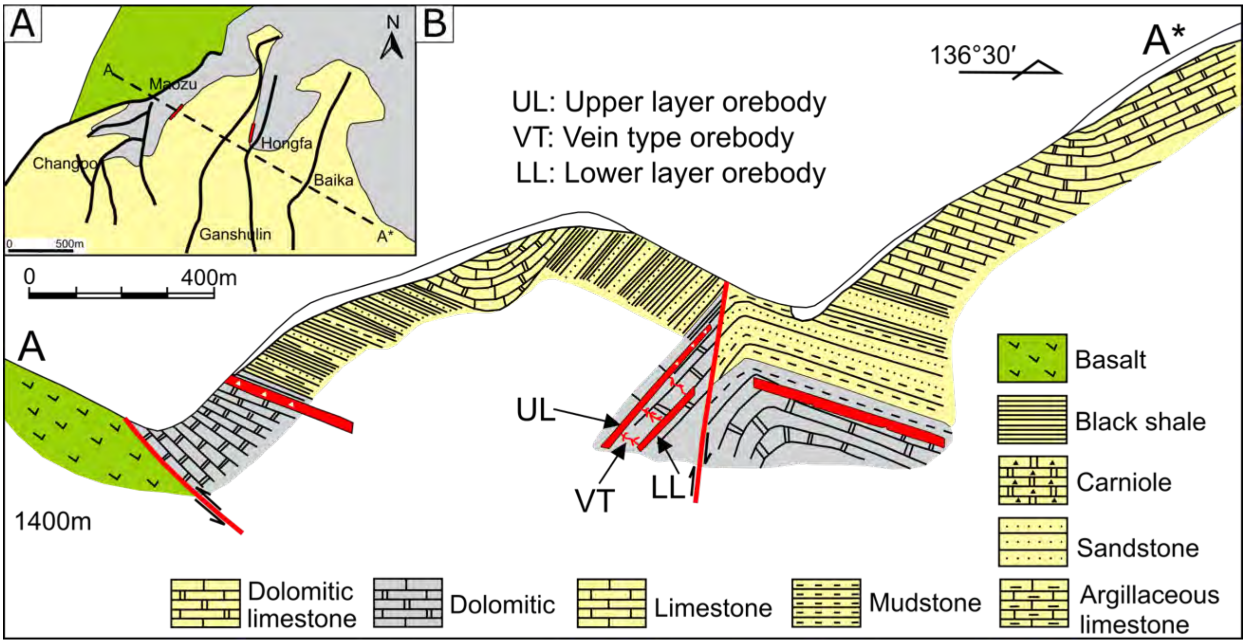

Figure 8: ***(A)*** *Geological map of the Maozu Zn-Pb-(Ag-Ga) deposit and* ***(B)*** *Representative cross-section A-A'-A" through the deposit (after Zhou et al., 2013)*

fluorite. Alterations mainly include Ca-Fe-Mn carbonatization and ferritization, which form hydrothermal calcite that is closely associated with Pb-Zn mineralization, as well as Fe-Mn carbonate and iron oxides on the surface which are important indicators for exploration. The supergene ores mainly include smithsonite and cerussite.

The orebodies of the Maozu deposit are strictly restricted to the dolostone layers in the Dengying Formation (Fig. 8B). Three layers of orebodies can be divided from shallow to deep (Li *et al*., 2020). The upper layer orebody is hosted in the fine to coarse-crystalline stratiform dolomite that is below the phosphorous-bearing layer, with a thickness of 15–30m. The main minerals are sphalerite, fluorite, and dolomite, together with minor amounts of tetrahedrite. The vein-type orebody is characterized by veinlet fillings in the tectonic fractured zones developed along the fault. The Pb-Zn mineralization occurs in the matrix of breccias, and the volume of galena in the sulphide ores is relatively higher than that of the other two types of orebodies. Different from the upper layer orebody, fluorite, quartz, and calcite are the main gangue minerals. The lower layer orebody is hosted in the siliceous dolostone and appear in stratiform shape with thickness varying between 50–120m. The minerals are predominantly sphalerite and quartz, and minor bitumen enclosing the sulphide minerals. Overall, the primary metallic minerals for Maozu are sphalerite and galena, together with minor pyrite and tetrahedrite. Non-metallic minerals consist of dolomite, calcite, fluorite, quartz, and bitumen.

Carbonate-hosted Zn-Pb deposits in the Himalayan-Tibetan orogen

The young and extensive Himalayan-Tibetan orogen is part of the Tethyan orogen that formed through collision between the India and Eurasia continents since the Late Cretaceous and early Cenozoic. It represents the youngest and most extensive continental-collision orogens on Earth. A significant amount of carbonate-hosted Pb-Zn deposits were distinguished during the past decade, distributing in the central and eastern Himalayan-Tibetan orogen (Fig. 9, Song *et al*., 2015, 2019). The major deposits include the Huoshaoyun and Jinding Pb-Zn deposits, the largest and second largest Pb-Zn deposits in China, respectively. Although both deposits show geological features that differentiate them from the classical MVT-type carbonate-hosted Pb-Zn deposits, they still share many common features including being hosted in carbonate-dominant basins and genetically related to limestone, as well as being characterized by strata-bound orebodies, replacement and breccia-type mineralization, simple primary sulphide assemblages of sphalerite, galena, pyrite and/or marcasite. The geological characteristics of the Huoshaoyun and Jinding are therefore reviewed in the section below to present a diverse view of a prominent marine carbonate-related Zn-Pb district in China, where oxidized ore zones are extremely well developed due to high relief, mild temperature all year around, and a large amount of annual precipitation.

The carbonate-hosted Zn-Pb deposits in the Himalayan-Tibetan orogen are mostly located north to the final closure of the Neo-Tethyan Ocean on the side of the Eurasian continent (Fig. 9). The majority of the Zn-Pb deposits in this belt are hosted by the Carboniferous-Cretaceous carbonates, mainly limestone (Fig. 10). An exception is the Jinding deposit, in which mineralization is hosted in brecciated limestone and sandstone (Fig. 10). Within the orogen, the Pb-Zn deposits are mainly distributed in the North Qiangtang block, Lanping-Simao basin and in the Cenozoic fold-and-thrust belts at the interior of the Himalayan-Tibetan orogen. This defines

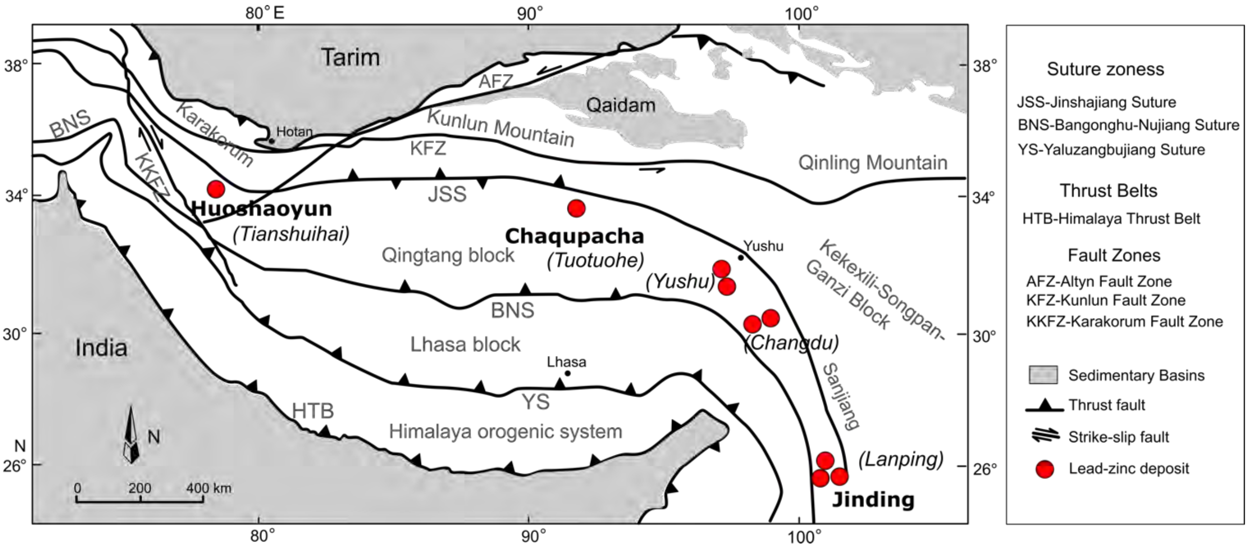

Figure 9: *Regional geology map of the major Pb-Zn deposits in distributed in the Himalayan-Tibetan orogenic belt, which are mainly concentrated in the Lanping, Changdu, Tuotuohe and Tianshuihai ore districts (after Li et al., 2019)*

a >2000-km-long Pb-Zn metallogenic belt (Fig. 9), (Hou *et al*., 2008; Song *et al*., 2011) that including several ore districts from SE to NW, namely the Lanping, and the Changdu, Yushu, Tuotuohe and Tianshuihai (Fig. 9).

The North Qiangtang block and Lanping-Simao basin contain Carboniferous carbonate and clastic rocks that were deposited in passive continental margin settings, and Permian to Triassic carbonate, clastic and volcanic rocks that were deposited in active continental margin settings. Foreland (or sag) basins were formed during the Jurassic to Cretaceous and were filed with red marine and terrestrial clastic rocks and marine carbonates (Fig. 10) (Song *et al*., 2019 and references therein). The India-Eurasia continental collision generated fold-and thrust belts and small foreland basins in central Himalayan-Tibetan orogen during 55–23 Ma, followed by N-S trending extensional structures since ~23Ma. In eastern Himalayan-Tibetan orogen, transpressional deformation during the Palaeocene and Middle Miocene generated fold and thrust belts and large-scale strike-slip faults, together with the formations of small foreland and transpressional faults; after the Middle Eocene, this region was characterized by a transtensional deformation regime. Different from the eastern section, the westernmost section of the Himalayan-Tibetan orogen, where the Tianshuihai ore district is situated, experienced Cenozoic thrusting in the interior and strike-slip faulting on its southeast and southwest margins.

Jinding Pb-Zn deposit

The Jinding deposit is the largest Zn-Pb deposit in China with a reserve of ~200 Mt ores grading 1.29% Pb and 6.08% Zn and covers a surface area of about 8 km^2. In association with Pb and Zn, the deposit is rich in Tl (8,167 t contained at grades of 6 to 20 ppm), Cd (170,000 t contained at grades of 0.01–0.2%), Ag (1,722 t contained at grades of 1–20 g/t, locally reaching 156 g/t) and Sr (1.47 Mt contained at grades of 13–18%).

Mineralization occurs as tabular orebodies hosted within the Early Cretaceous and Tertiary terrestrial clastic rocks in the Lanping-Simao Basin at the eastern Himalayan-Tibetan orogen. Nearly all the sulphide orebodies in Jinding are found in the brecciated limestones and sandstones below the Mesozoic nappe. The Meso-Cenozoic Lanping-Simao basin is an intracontinental basin bounded by the north-northwest trending Lancangjiang Fault to the west and the Jinshajiang-Ailaoshan Fault to the east, and the Lanping-Simao Fault in the central part of the basin (Fig. 11A) (Xue *et al.,* 2007). Geophysical and remote sensing data suggest that the faults cut deeply into the lower crust and upper mantle (Yin *et al*., 1990, Xue *et al*., 2002a). No igneous rocks outcrop in the mine area (Fig. 11B).

The basement of the Lanping-Simao basin consists of Proterozoic and Palaeozoic strata. The oldest Middle Proterozoic strata distribute along the margins of the Lanping-Simao basin. They were originally marine clastic rocks, carbonate and mafic and volcanic rocks and later metamorphosed into sericite schist, marble, gneiss, amphibolite, and biotite-plagioclase amphibolite. The metamorphic basement is similar to the sequence that underlies the Yangtze block. The Palaeozoic strata are exposed in the uplifted area and the basin margin, which are composed of thick weakly metamorphosed marine flysch sequences of mainly clastic rocks and locally carbonate in composition. A characteristic feature of the Lanping-Simao Basin is the development of six horizons of evaporites, dominantly of gypsum and halite in composition, and occasionally, sylvite (Jin *et al.,* 2003). The total thickness of the evaporite layers may well exceed 2000 m locally. The basin is filled with siliciclastic rocks, except for the lowest part of the sequence and the Upper Triassic Sanhedong Formation, which consists mainly of marine limestone and bears fossils. Mineralization is mainly hosted in the sandstones of the Lower Cretaceous Jingxing Formation and the breccia-bearing sandstones and limestone breccias in the upper part of the Palaeocene Yunlong Formation (Figs. 11B, C).

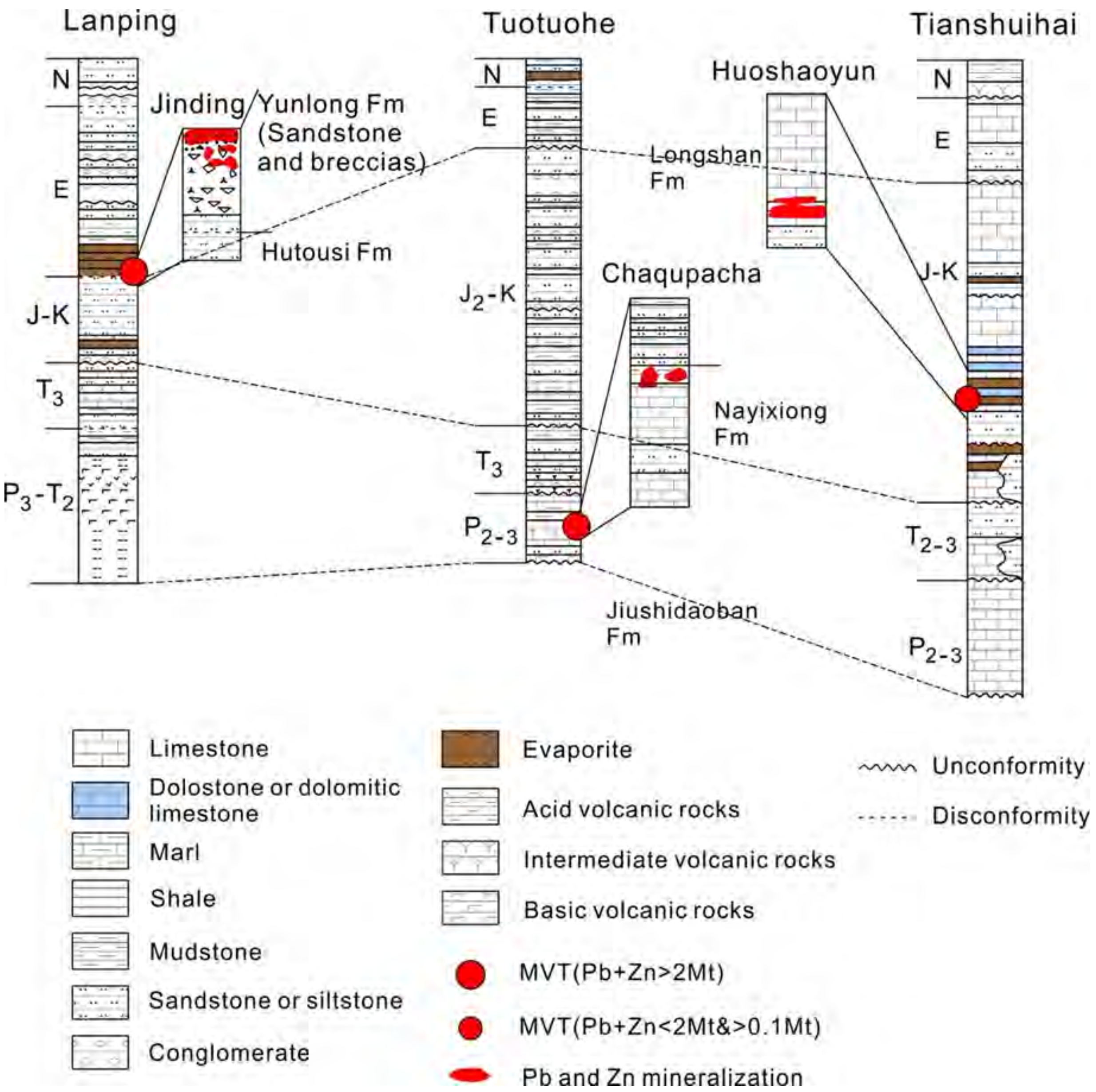

Figure 10: *Stratigraphic columns of the major Pb-Zn ore districts in the Himalayan-Tibetan orogenic belt, China (after Song et al., 2019)*

The most prominent structure in Jinding is the nappes formed from regional westward over-thrusting and a dome caused by uplifting (Fig. 11B). The autochthon beneath the nappes displays a normal stratigraphic sequence consisting of Tertiary rocks, which are dominantly the Palaeocene Yunlong Formation and the underlying Middle Cretaceous Hutousi Formation with an unconformity in-between, whereas the allochthon exhibits a reverse sequence consisting of the Upper Triassic Sanhedong Formation in the upper part and the Lower Cretaceous Jingxing Formation in the lower part. The allochthonous and autochthonous successions are separated by a major thrust fault F2. A series of thrusts parallel to F2 are developed within the nappes. Thrusting may have been initiated during, and continued after, sedimentation of the Yunlong Formation (Xue *et al*., 2003). Both the allochthon and autochthon and the thrust faults are domed after the over-thrusting, which formed the Jinding dome (Wu & Wu, 1989). The Jinding dome is roughly oval, about 3 km long and 2.5 km wide with an NNE-trending axis. The dome structure is presently eroded, with the Cretaceous sandstones and siltstones in the centre and surrounded by the Palaeocene Yunlong Formation (Fig. 11B). Due to the development of dome structure, the strata and the major thrust F2 currently dip west in the western part of the Jinding ore district, north in the northern part and east in the eastern part, respectively.

The deposit is located at the eastern margin of the Lanping-Simao Basin (Fig. 11A). Within the deposit, overturned Mesozoic strata overlie evaporite-bearing brecciated limestones and sandstones. The lower part of the Mesozoic unit comprises impermeable red mudstone and siltstone. More than 100 orebodies have been discovered in the Jinding area, which are

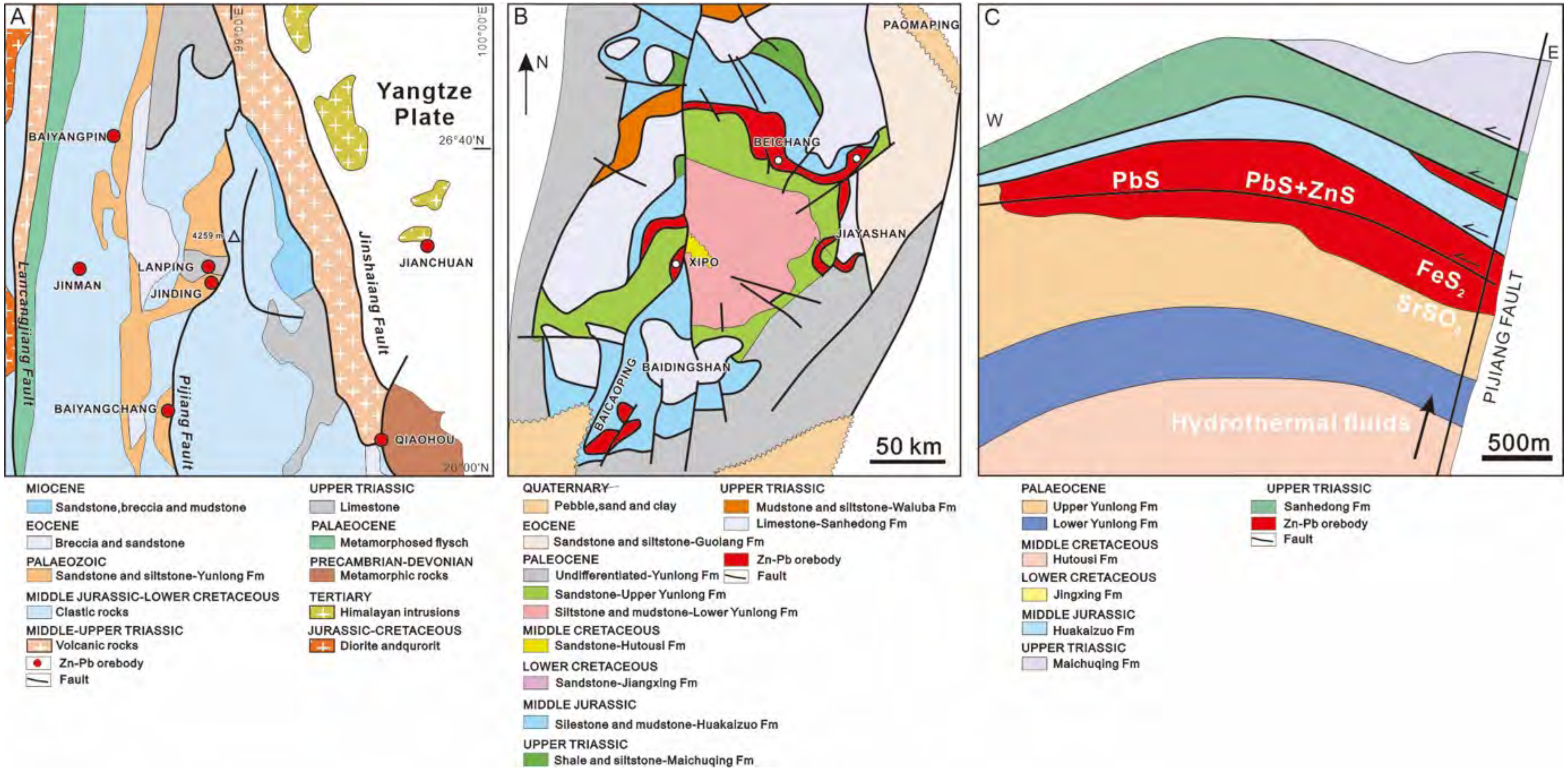

Figure 11: ***(A)*** *Sketch geological map of the Lanping-Simao basin in western Yunnan, China, showing the major structural features and the location of the Jinding deposit,* ***(B)*** *Geological map of the Jinding Pb-Zn deposit,* ***(C)*** *A sketch cross-section showing mineral zoning in the Jinding Pb-Zn deposit (after Xue et al., 2007, and references therein)*

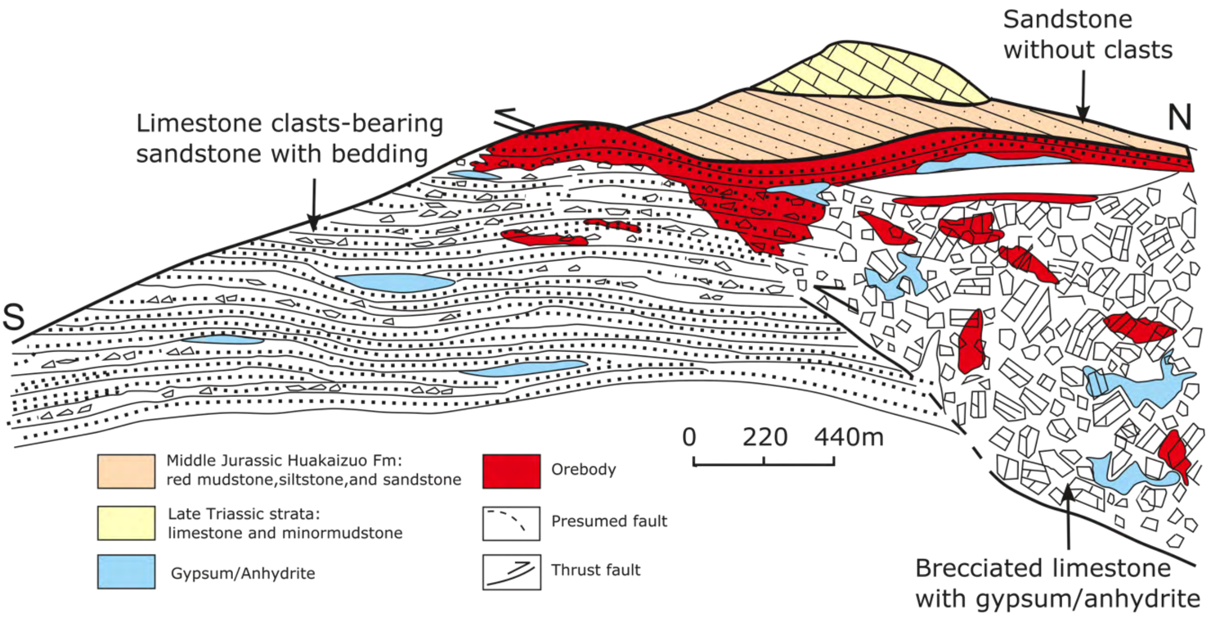

Figure 12: *North-South cross-section through the Jinding deposit in the eastern Himalayan-Tibetan orogen, which shows an allochthonous Mesozoic nappe in the upper part that separates with a complex rock system in the lower part by a thrust fault. The complex rock system consists of mainly sandstone without clasts, limestone clastsbearing sandstone, and brecciated limestone. Sulphide ores are hosted mainly by the sandstone without clasts and the limestone clasts-bearing sandstone, subordinately by the brecciated limestone (after Song et al., 2019)*

divided into six ore zones distributing around the core of the Jinding dome (Fig. 11B). The six ore zones possibly represent a primary orebody that was dislocated by a series of radial faults, and now include the Beichang, Paomaping, Jiayashan, Xipo, Fengzishan and Baicaoping. Among those, the Beichang is the most economically important ore zone, accounting for 75% of the total reserve (TGT, 1984; Luo & Yang, 1994). The No.1 orebody in Beichang is the largest one in the Upper Ore Zone, accounting for 60% of the total reserve of the Jinding deposit (Luo & Yang, 1994). The cap rock of the No.1 orebody consists of terrestrial sequences of the Middle Jurassic Huakaizuo Formation, which is rich in argillaceous materials and has a low permeability. The orebodies are mainly controlled by the thrust fault F2, and mineralization occur in both hanging wall and footwall of F2 (Fig. 11C). An Upper Ore Zone is defined for the orebodies hosted in the Lower Cretaceous Jingxing Formation in the hanging wall. Those hosted in the upper part of the Palaeocene Yunlong Formation in the footwall of F2 is named as the Lower Ore Zone (TGT, 1984). The orebodies in the Upper Ore Zone are usually tabular or strata bound in shape, restricted to sandstone layers rich in disseminated sulphides. The sandstones of Jingxing Formation mainly consist of quartz and siliceous lithic fragments, and a lesser amount of feldspar. The cements are mostly carbonates, mainly calcite, together with some argillaceous materials. Sulphide minerals (i.e., pyrite, sphalerite, galena, and marcasite), celestine and minor barite partially replace the cement in the low-grade ores, whereas in the high-grade ore zones sulphide minerals almost entirely replaced the cement. This style of mineralization is referred to as sandstone-type and usually has a gradual contact with the host rocks. A thin (0.5–1 m) alteration halo is developed in the contact zone of the No.1 orebody and host rock in the hanging wall, where red beds are bleached and silicified (TGT, 1984).

In comparison, the orebodies in the Lower Ore Zone are more variable in shape and size, and occur as breccias, lenses, veins, and irregular bodies (Fig. 12). The host rocks of the Lower Ore Zone are breccia-bearing sandstones in the Yunlong Formation and breccias of the upper part of the Yunlong Formation. The brecciated limestones are laterally transitional with the limestone-clast-bearing sandstone (Fig. 12). This style of mineralization is referred to as breccia-type ore due to its occurrence in breccias of the Yunlong Formation (TGT, 1984; Qin & Zhu, 1991; Luo & Yang, 1994). The breccia clasts mainly consist of bitumen-bearing limestones, which are similar to the limestone of the Upper Triassic Sanhedong Formation in composition. The clasts are subrounded to angular and poorly sorted, with diameters of several centimetres up to several meters. The breccia matrix includes fine-grained limestone, gypsum/anhydrite, calcite pseudomorphs after gypsum, and fine-grained sandstone. In the limestone-clast-bearing sandstone, the calcite cement is replaced by sphalerite, galena, and pyrite, similar to the mineralization in the Jingxing Formation sandstone without clasts. Mudstone and siltstone in the Yunlong Formation are generally not mineralized. In the upper part of the Yunlong Formation where brecciated limestones are mineralized, the matrix is composed of fine-grained sandstone that display similar mineralising features to the breccia-bearing sandstones, in which the carbonate cements are replaced by sphalerite, galena and pyrite. Large amounts of gypsum/anhydrite are present within the brecciated limestones (Jin *et al*., 2003). In addition,

Stratigraphy	Formation	Thickness (m)	Lithology description
Quaternary		>123	Recent soils & glacial tills
Upper Cretaceous	Tielongtan Formation	140->520	Sandstone and conglomerate & Limestone
Upper Jurassic	Hongqilafu Formation	>2101	Bioclastic limestone and mud limestone
Lower Jurassic	Bagongbulansha Formation	369-2313	Sandstone and conglomerate, limestone,with gypsum layer on the top
Upper Triassic	Keleqinghe Formation	1370	Lithic sandstone. mudstone,lithic quartz sandstone
Middle Triassic	Heweitan Formation	>3425	Sandy limestone, crystalline limestone, and micrite limestone
Lower Permian	Kongka-shankou Formation	>555	Limestone, feldspar quartz sandstone interbedded with mudstone
Upper Carboniferous	Qiaerti Formation	>3790	Argillaceous slate,limestone, quartz sandstone

Figure 13: *Stratigraphic column of the Linjitang basin, of which the Lower Jurassic Bagongbulansha Formation is the host rock of Huoshaoyun Pb-Zn deposit in the Himalayan-Tibetan orogen (after Li et al., 2019)*

sulphide minerals were also observed to occur as fillings in fractures and fissures of carbonates. Within the shallow brecciated limestones, supergene ore zones are well developed and composed mainly of hydrozincite, cerussite and strontianite, and minor cerussite, Fe oxides, barite, and calcite. The oxidized ore zones extend to a depth of more than 100 m and account for 40% or more of the total ore reserve. In general, the oxidized ore zones have higher Zn + Pb grade than the sulphide ore zones (TGT, 1984).

More than 30 minerals have been identified in the Jinding deposit, including sulphides, oxides, carbonates, sulphates, bitumen as well as native metals (Xue *et al.*, 2002b). Sphalerite and galena are the major sulphide ore minerals, together with the occurrence of pyrite and marcasite. Minor chalcopyrite, wurtzite, argentite and argentian tetrahedrite are also identified. Silver is identified as either fine-grain native silver or aphtonite inclusions in galena. Cadmium mainly occurs as solid solution within sphalerite; traces of greenockite were identified. Thallium mainly occurs as a trace element in the Fe-sulphides and no individual Tl-mineral phases have been recognised (Xue *et al.*, 2002b).

The sulphide ore is associated with quartz, celestine, calcite, bitumen, gypsum, anhydrite, hematite, and barite (Xue *et al.*, 2002b). Quartz is mostly detrital in origin and partly newly formed during early silicification; dissolution and secondary growth is commonly observed. Sulphate minerals, especially gypsum and celestine, have at least two origins: one precipitated during hydrothermal mineralization stage and the other formed during sedimentation as part of the evaporite-bearing sequence of the Yunlong Formation. Bitumen (i.e., asphalts

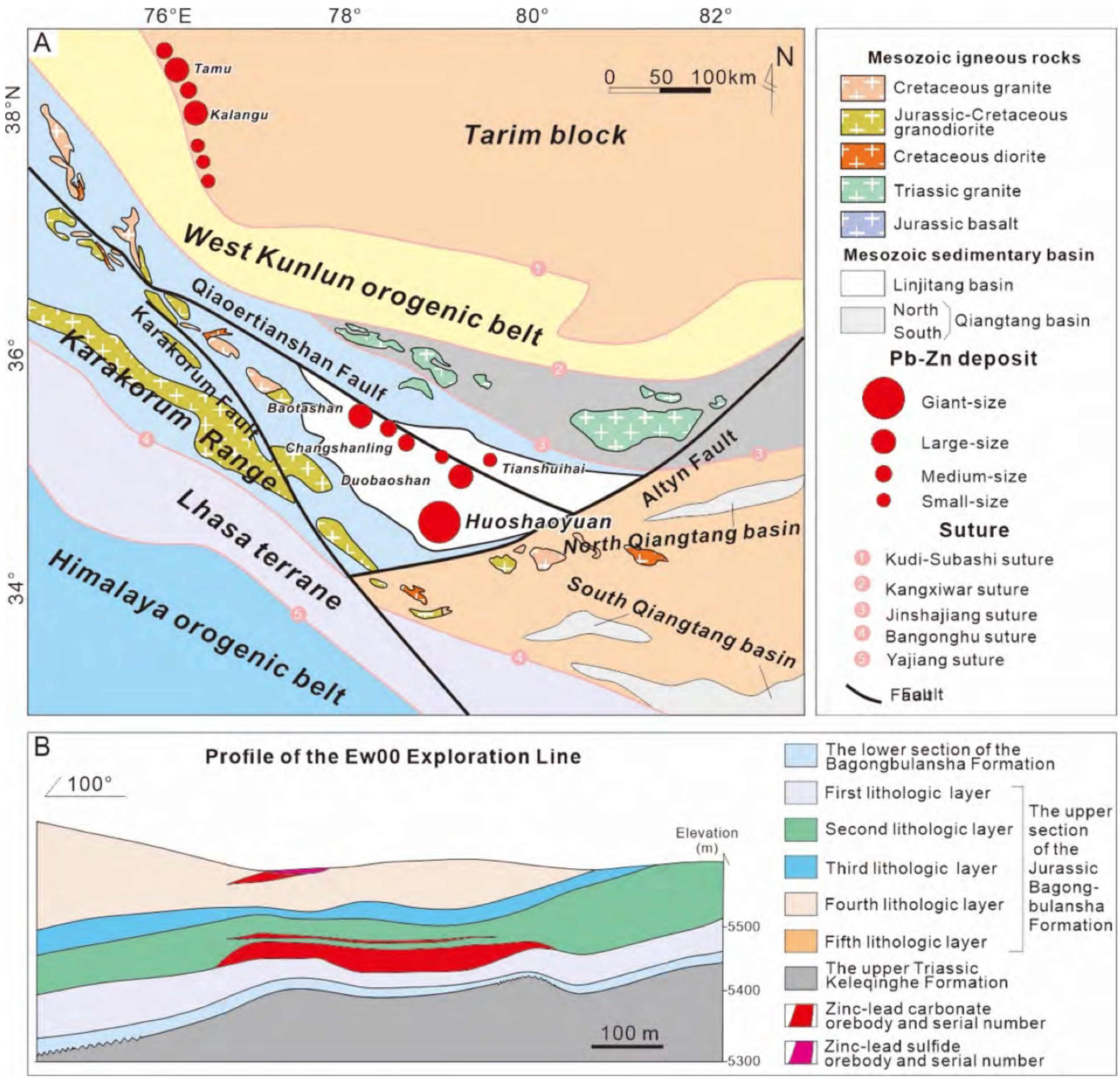

Figure 14: ***(A)*** *Tectonic units and distribution of carbonate-hosted Pb-Zn mineralization in the Tinshuihai district and along the margin of Tarim block,* ***(B)*** *A cross-section through the Huoshaoyun Pb-Zn deposit, showing the strata-bound ore-bodies I, II, III, and V (after Li. et al., 2019 and references therein)*

and heavy oils) either occurs in veins in the ore minerals and host rocks and associated with late-stage mineral assemblages of celestine, calcite and gypsum, or disseminates in the sandstone-type and breccia-type ores in both the Upper and Lower ore zones, which commonly have an oily smell.

Three stages of hydrothermal mineralization were proposed for Jinding based on paragenetic studies and intergrowth relationships of minerals, including stage 1 of quartz + sphalerite + galena, stage 2 of sphalerite + galena + celestine, and stage 3 of galena + calcite + celestine + gypsum. Galena of the third stage is coarse-grained and associated with calcite in veins and vugs, whereas galena of the earlier stages is fine-grained and disseminated. Celestine of the third stage occurs in veins and is associated with the remobilised bitumen, which is different from the sedimentary celestine in strata and the disseminated hydrothermal celestine in the second stage. Pyrite occurs in all stages but is most common in the second and the third stages. Abundant inclusion of hydrocarbons and bitumen were recognised at Jinding, and Xue *et al*. (2007, 2009) suspected that an oil-gas reservoir may have existed. The disseminated bitumen, which was formed before the Zn-Pb mineralization, was hydrothermally matured during mineralization, and remobilised during the third stage (Xue *et al*. 2009).

A distinct zoning of mineral assemblages, both vertically and laterally, was reported for the Jinding deposit (Fig. 11C). A general sequence of mineral assemblages from the east to the west and upward is proposed as follows: celestine-gypsum-barite → pyrite-marcasite → sphalerite → sphalerite-galena →

galena (TGT, 1984; Luo & Yang, 1994; Xue *et al.*, 2002b). This trend is associated with a change in element association: Sr-Ca-Ba → Fe-Tl → Zn-Cd → Zn-Pb-Cd-Ag → Pb-Ag. Laterally, the Zn/Pb ratios change from 7.8 at Jiayashan (east), through 4.9 at Beichang (central north), to 0.3 at Fengzishan (west) (Luo & Yang, 1994, Xue *et al.*, 2002).

Huoshaoyun Pb-Zn deposit

The Huoshaoyun Pb-Zn deposit is the second largest in China, with reserves of 56.53 Mt ores at grades of 24.35% Zn and 4.75% Pb (Fan *et al*., 2017), among which 95% are carbonate ores and 5% are sulphide ores. The deposit is located in the Tianshuihai ore district in the northwest Himalayan-Tibetan orogen (Fig. 9), at an elevation of 5500 to 5700m above sea level. The basement of the Tianshuihai area is composed of Paleoproterozoic shallow marine carbonate rocks that are metamorphized. The basement rocks are covered by Palaeozoic strata including Carboniferous and Permian clastic limestones and other carbonate rocks. The deposit is hosted by the Jurassic Bagongbulansha Formation, which comprises a gypsum-bearing carbonate unit and an underlying red sandstone and conglomerate (Fig. 13). A prominent carbonate-hosted Pb-Zn metallogenic belt in western China is recognised, including the Huoshaoyun Zn-Pb deposit and several other Pb-Zn occurrences being hosted in the Mesozoic clastic and carbonate rocks in the Tianshuihai ore district, as well as recently discovered Pb-Zn deposits hosted in late Palaeozoic carbonate in the Tarim foreland thrust belt (Fig. 14A).

The Huoshaoyun Zn-Pb deposit is located at the southern margin of the Linjitang basin, which is bounded by the Altyn Fault to the east and cut across by the SW-trending Qiaoertianshan Fault in the central (Fig. 14A). The Qiaoertianshan Fault has a major control on the location of mineralization in the district, reflecting from the dominant occurrence of Pb-Zn, Cd, Sb mineralization along this fault (Zhou & Ren, 2014; Dong *et al.*, 2015). The stratigraphy of the Linjitang basin is mainly from the Carboniferous to Cretaceous, among which the limestone unit of the Lower Jurassic Bagongbulansha Formation is the main host rock of Pb-Zn mineralization. The Bagongbulansha Formation consists, from bottom to top, mainly a grey- to purple-coloured sandstone and conglomerate unit, a grey limestone unit, and gypsum layers. The limestone unit consists of grey, medium- to thickly bedded bioclastic, oolitic, and micritic limestone and is locally dolomitised, partly fragmented and intercalated with organic-rich mudstone and sandstone. The limestone consists mainly of euhedral to anhedral calcite, partly in the form of calcite ooids, and contains a small amount of anhedral to euhedral quartz grains with calcite inclusions being observed occasionally. An unconformity was observed between the Bagongbulansha Formation and the underlying Keleqinghe Formation which is mainly composed of quarzitic sandstone and mudstone. A variety of magmatic rocks, including dacitic porphyries and basaltic flows, occur within the Linjitang basin, which intruded into the Jurassic strata and are overlain by the Cretaceous strata. One basaltic occurrence was reported to occur about 28 km northwest to the Huoshaoyun deposit, and minor purple-coloured dacite porphyries intruded into the Jurassic limestone unit in the mine district. To the north and southwest of the Linjitang Basin, igneous intrusions including a Triassic granite and a Jurassic-Cretaceous plutonic belt composed of granodiorite were identified, respectively.

Five orebodies were identified, among which orebodies I, II and V are exposed to the surface, whereas orebodies III and IV are concealed. The orebody I is a major sulphide ore zone and occurs at the top of the stratigraphy (Fig. 14B), with reserves of 2.55Mt grading 24.25% Pb and 2.78% Zn. The orebodies II, III, IV and V are all Zn-Pb carbonate ore zones (Fig. 14B), among which the economically most important one is the orebody V with reserves of about 48Mt, grading 23.58% Zn and 5.63% Pb. The orebody V has a north-south extension of 1445m, an east-west extension of 650m, and an average thickness of 12.70m (Dong *et al.*, 2015). The ore minerals are mainly smithsonite and cerussite, which account for about 75% and 25 % of the carbonate ore reserves, respectively. Calcite and quartz are the main gangue minerals. Hemimorphite is occasionally identified in the near-surface area of the massive smithsonite ore zones in an open pit (Li *et al*., 2019).

The massive carbonate ore zone consists of either smithsonite or cerussite, or mixed smithsonite-cerussite ores. Quartz, galena, and calcite are locally associated with the carbonate ores. The smithsonite mineralization has four different styles according to the ore textures and mineral assemblages, namely: *i)* laminated ore composed of smithsonite laminae with rhythmical layers of various crystal sizes, *ii)* massive ores of large euhedral to anhedral crystals and aggregates of fine concentrically zoned crystals coexist with quartz in euhedral and subangular shapes, *iii)* botryoidal ores characteristic of zoned growth and often occur together with vugs that are filled with galena *iv)* vein-type ores containing euhedral to anhedral smithsonite and in width of 400μm to 15cm. The cerussite mineralization is predominantly composed of veined cerussite filling the fractures within or replacing the massive smithsonite mineralization (Li *et al.*, 2019). The lead-dominated sulphide mineralization is composed mainly of galena and traces of sphalerite and pyrite, with minor amounts of calcite and gypsum. Three different styles of sulphide mineralization were also identified, including *1)* laminated ores in which sulphide laminae are composed predominantly euhedral to anhedral galena crystals and subordinately colloform sphalerite and euhedral to anhedral pyrite; *2)* brecciated ores consisting of euhedral to anhedral massive smithsonite ores as clasts and euhedral to anhedral sulphide matrix; and *3)* vein-type ores in which sulphide veins crosscut the limestone and smithsonite and consist mainly of euhedral to anhedral galena that are partly altered to cerussite. Wall-rock alteration close to the zinc carbonate mineralization mainly consists of alteration minerals of siderite and locally ferrihydrite. The contact zone between the carbonate mineralization and host rock of limestone is sharp at local areas, while there is a generally clear separation between the sulphide mineralization zone and the host rock limestone without visible alterations.

Chaqupacha Pb-Zn deposit

The Chaqupacha Pb-Zn deposit is located in the western Fenghuo Shan-Nangqian fold and thrust belt in the Tuotuohe area of central Tibet. It has an inferred mineral resource of 191.3 Mt ores at average grades of 0.6% Zn and 4.2% Pb (Song *et al*., 2019). The deposit is located in the northern Qiangtang

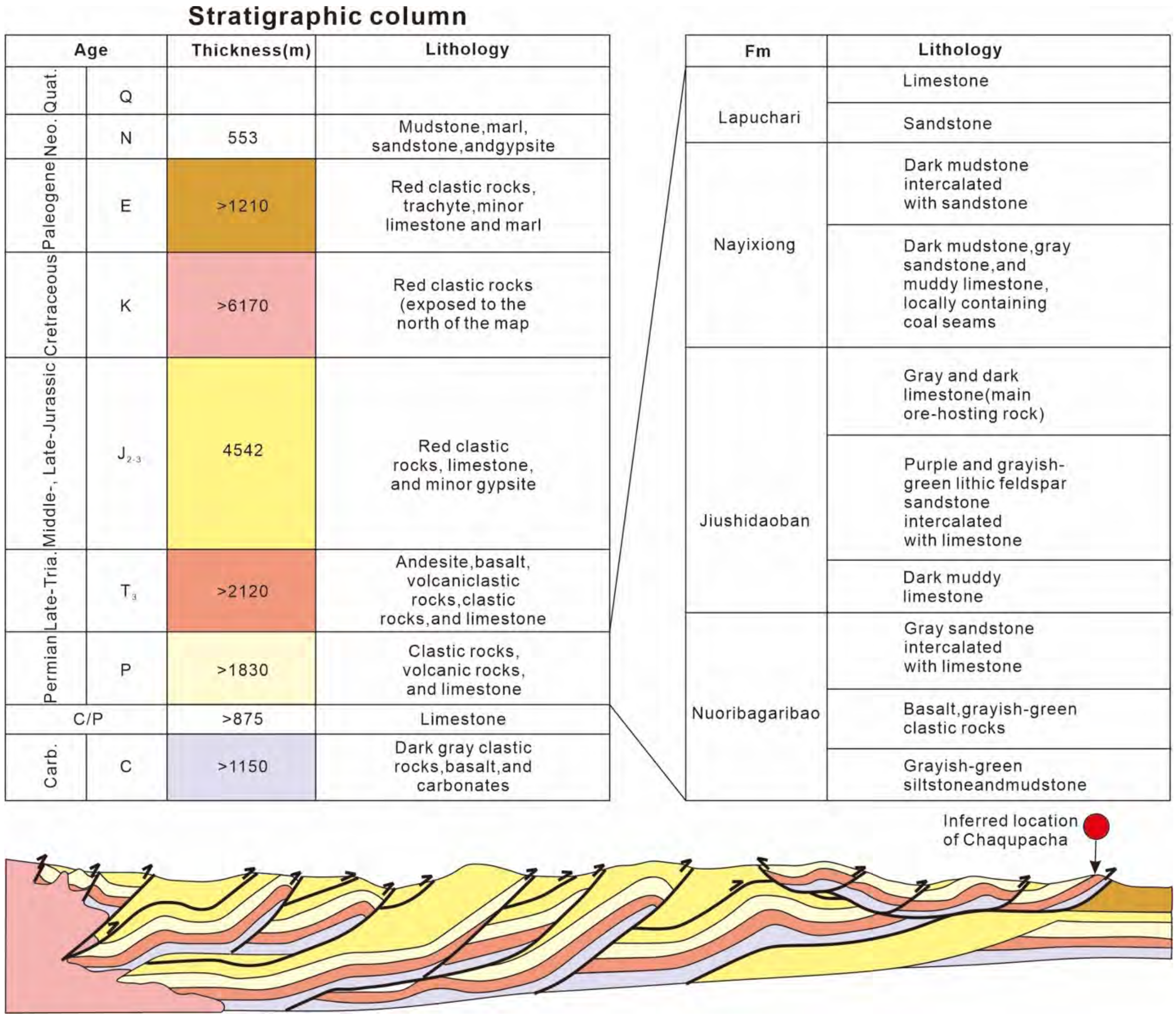

Figure 15: *Stratigraphic column of the Chaqupacha Pb-Zn deposit, in which the late Triassic Jiushidaoban Formation is the main host rock for mineralization. The below sketch map shows the intense thrust and deformation in the region (after Song et al., 2015)*

Terrane (Fig. 9), which is bounded by the Jinsha suture to the north and the Shuanghu suture to the south. The oldest rocks exposed in the Tuotuohe area are the Carboniferous clastic and carbonate strata. The area also has Permian to Triassic carbonate, clastic and volcanic rocks. The Carboniferous to Triassic carbonate rocks host all the major Zn-Pb deposits in the Fenghuo Shan-Nangqian fold and thrust belt. The majority of carbonate-hosted Zn-Pb mineralization, including the Chaqupacha deposit, occur in the Permian limestone (Fig. 10).

The Chaqupacha Pb-Zn deposit is hosted by folded upper Permian strata that include clastic rocks of the Nayixiong Formation and limestone of the underlying Jiushidaoban Formation (Fig. 15). The Jiushidaoban Formation is composed of massive, grey to dark grey limestone, which is bioclastic and lithosclastic grainstone and micrite in composition and contains sedimentary chert lenses within different stratigraphic units of the limestone. In the Tuotuohe area, the Jiushidaoban Formation includes a lower interval dominated by dark micrite and a middle interval dominated by clastic rocks. The Nayixiong Formation conformably overlies the Jiushidaoban Formation limestone to the south at Chaqupacha and is dominated by dark grey, fine-grained clastic rock, muddy limestone and marl in areas where sandstone is interbedded with mudstone and/or siltstone. This formation locally contains coal seams in the Tuotuohe area. Both the Nayixiong and Jiushidaoban formations were thrusted over the red clastic rock of the upper Oligocene Yaxicuo Formation (Fig. 16A). All strata are unconformably overlain by marl and mudstone of the Lower Miocene Wudaoliang Formation. The Cenozoic units in the deposit area include the Eocene to early Oligocene Tuotuohe Formation, the late Oligocene Yaxicuo Formation, and the early Miocene Wudaoliang Formation. The Tuotuohe Formation is exposed in a limited area and consists of gently dipping and red polymictic conglomerate that forms an angular unconformity with the Late Permian strata. The late Oligocene Yaxicuo Formation is dominated by red muddy siltstone containing gypsum veins that were only intersected at the bottom

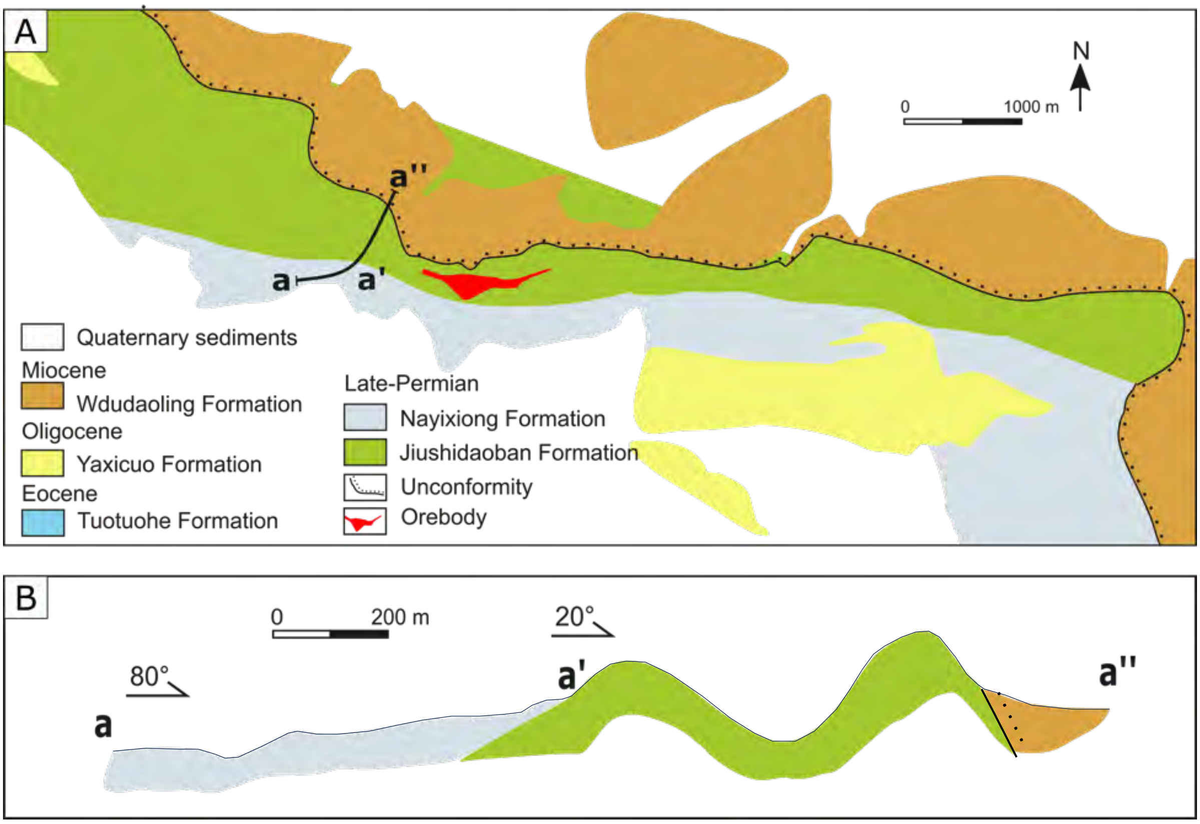

Figure 16:* *(A)* *Geological map of the Chaqupacha Zn-Pb deposit, and* *(B)* *a cross-section through the deposit mainly showing the deformation of Permian strata in the deposit (after Song et al., 2015)

of some drill holes. The early Miocene Wudaoliang Formation consists of, from bottom to top, red calcareous mudstone and light grey marl intercalated with sandstones and evaporites (gypsum). The Wudaoliang Formation shows an erosional unconformity with all the older rocks in the Chaqupacha deposit.

The Late Permian units in the deposit were folded in a diverse direction (Fig. 16B). A group of NWW-striking folds can be linked to the Paleogene folding and thrusting in the Tuotuohe area. The intensely folded strata below surface can be correlated by a carbonaceous limestone marker unit within drill cores. Small north-dipping reverse faults are present in the hanging wall of the south-dipping reverse fault. The rocks in both the hanging wall and footwall of the south-dipping reverse fault are unconformably overlain by the flat to gently dipping early Miocene Wudaoliang Formation. Syenite and diorite intrusions are present in the late Permian sedimentary rocks in the mine area. Zircon U-Pb ages indicate the intrusions are formed at 253.9±4.3Ma and 240.0±3.5Ma, respectively (Li, 2008). The rocks are generally fresh except that feldspar in the syenite is partly altered.

Three types of breccia were distinguished at Chaqupacha, including a palaeokarst breccia, a pre-ore dissolution and collapse breccia, and a late to post-ore dissolution and collapse breccia (Song *et al.*, 2015). The palaeokarst breccia contains clasts of the Jiushidaoban Formation limestone in a marly or muddy matrix which is compositionally comparable to strata of the Wudaoliang Formation. They are interpreted to be formed during the deposition of the Wudaoliang Formation. The palaeokarst breccia mainly occurs in the limestone of the Jiushidaoban Formation. The clast to matrix ratio in the palaeokarst breccia is variable and thus the breccia varies from being clast- to matrix-supported. The breccia clasts are mosaic-textured, either chaotic or well-oriented. They are usually imbricated and have sharp or rounded edges. The pre-ore dissolution and collapse breccia consists of limestone-dominated clasts of the Jiushidaoban Formation and matrix of fine-grained limestone fragments. These breccias are chaotically distributed throughout the entire deposit and are not preferentially associated with any faulting. The majority of these breccias are matrix-supported although a minority is clast-supported. The breccia clasts are usually chaotically oriented in highly variable size and composed of limestone, chert and calcite with sharp boundaries. The fact that chert is present as lenses in the limestone within non-brecciated rocks and is present as pure chert clasts within the breccia suggests that the initial limestone-chert rock underwent chemical dissolution during interaction with fluid. This process resulted in the formation of pre-ore dissolution breccia. The matrix of pre-ore dissolution breccia consists of fine-grained limestone fragments, which underwent partial or total replacement. The dissolution had left open space for filling by sulphides and/or calcite during mineralization. Often the sulphide minerals, mainly sphalerite, form a rim along the clasts, suggesting that the brecciation occurred prior to sulphide precipitation. This leads to the formation of ore-matrix breccias consisting of rounded limestone clasts cemented by sulphides and/or sparry calcite. Furthermore, coexistence of non-mosaic-textured and polymictic breccia clasts, as well as the development of

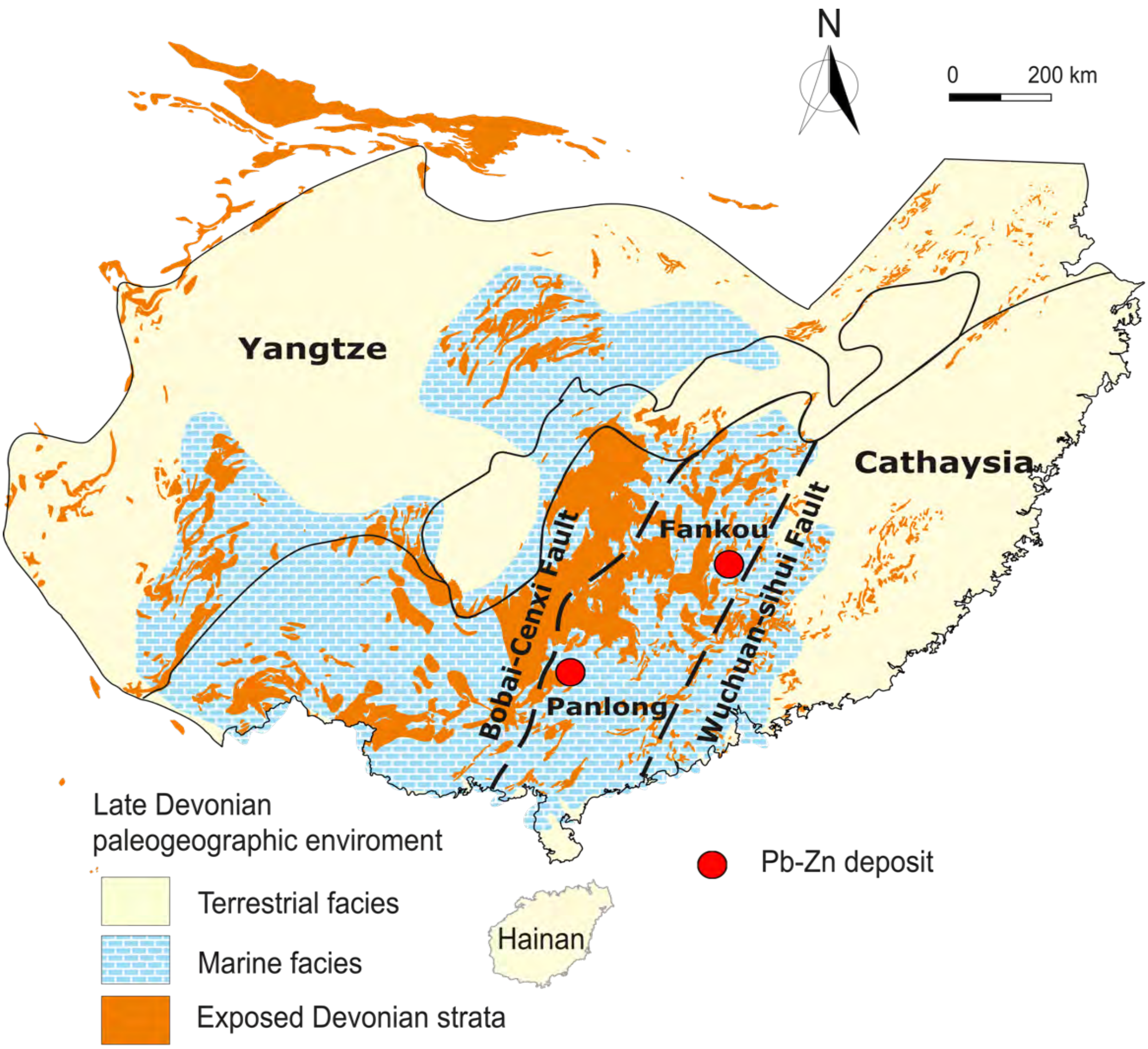

Figure 17: *Geological map of the Devonian strata in South China block, showing where the Fankou Pb-Zn-(Ag-Ga-Ge-Cd) deposit and Panlong Pb-Zn-Ba deposit are located.*

abundant breccia matrix, indicate that a collapse process, in addition to the dissolution process in an earlier stage, was involved in the formation of breccia. This was interpreted to be formed by either warm fluid circulation or subsurface water dissolution at around ambient temperature. The late to post-ore dissolution breccia contains pre-existing ore mineral clasts (mainly galena) in a matrix of sparry calcite and/or fine-grained limestone fragments. The ore clasts have rounded to sub-rounded edges and the matrix contains calcite, fine-grained sulphides, and/or fine-grained limestone fragments, indicating their formation was a result of fluid dissolution and collapse. Apart from the ore clasts, the breccia also contains limestone clasts but lacks limestone-ore clasts. This suggests that the breccia formed after sulphide precipitation, and the brecciation happened during late mineralization stage or post mineralization. The pre-ore dissolution breccia is volumetrically the most abundant and deeply situated, while the palaeokarst breccia is moderately developed at the surface and the post-ore dissolution breccia is rare.

The Pb-Zn orebody is strata bound and discordant, extending for 6 km long (Song *et al.*, 2015). Mineralization is mainly restricted to the limestone of Jiushidaoban Formation, with minor being present in the Wudaoliang Formation. The Pb/Zn ratio for the entire deposit is inferred to be 7.5. Lead mineralization is generally spatially associated with Zn mineralization. The thickness of the Pb-Zn orebody decreases away from the contact zone of the Jiushidaoban Formation and the Nayixiong Formation. High-grade ores are spatially associated with the zones abundant in pre-ore dissolution breccias, although not all this type of breccia is mineralized. In contrast, the mineralization has no close spatial relationship with either the palaeokarst breccias, intact limestone or the syenite. Sulphide minerals mainly include sphalerite, galena and pyrite, and the gangue minerals include calcite and barite. Dolomite is absent, clay minerals and supergene Zn and Pb minerals are not identified. The sulphides occur mainly in the pre-ore dissolution breccias and subordinately in fractures within the intact limestone. Mineralization appears in three styles. Galena and/or sphalerite replace the matrix of the pre-ore dissolution breccia; galena, calcite and minor barite fill in cavities between the pre-ore breccia clasts; and galena and calcite fill in fractures within the intact limestone and form veins. The first two types of mineralization form breccia-type ores, which is the major mineralization style, and the third forms vein-type ores. Three stages of mineralization were further identified based on cross-cutting relationship, mineral assemblages, and textures, namely an early ore stage consisting of galena + calcite + sphalerite + pyrite, a late ore stage mainly consisting of galena + calcite, and a post-ore stage in which buggy or comb-texture calcite co-exists with barite. The late-stage galena and calcite also replaced the marl matrix in the limestone breccia of the Jiushidaoban Formation and in the lower Miocene Wudaoliang Formation, suggesting that the mineralization of Chaqupacha is younger than the ~23 to 16Ma sedimentation.

Carbonate-hosted Pb-Zn deposits in the Cathaysia block

The Cathaysia Block, together with the Yangtze Block, comprise part of the South China Craton. (Fig. 17). The basement of Cathaysia is composed of Palaeo- and Mesoproterozoic rocks which outcrop mostly in the northeast and southwest. Widespread Paleozoic siliciclastic and carbonate successions overlie the basement with an unconformity. Due to the Caledonian orogeny during the Early Paleozoic, the Cathaysia was in a continent-continent collision setting where Late Ordovician to Middle Devonian strata are absent. Instead, granitic intrusion of ages ranging from 480 to 400Ma are widespread in the region. Deep regional faults, including the Wuchuan-Sihui

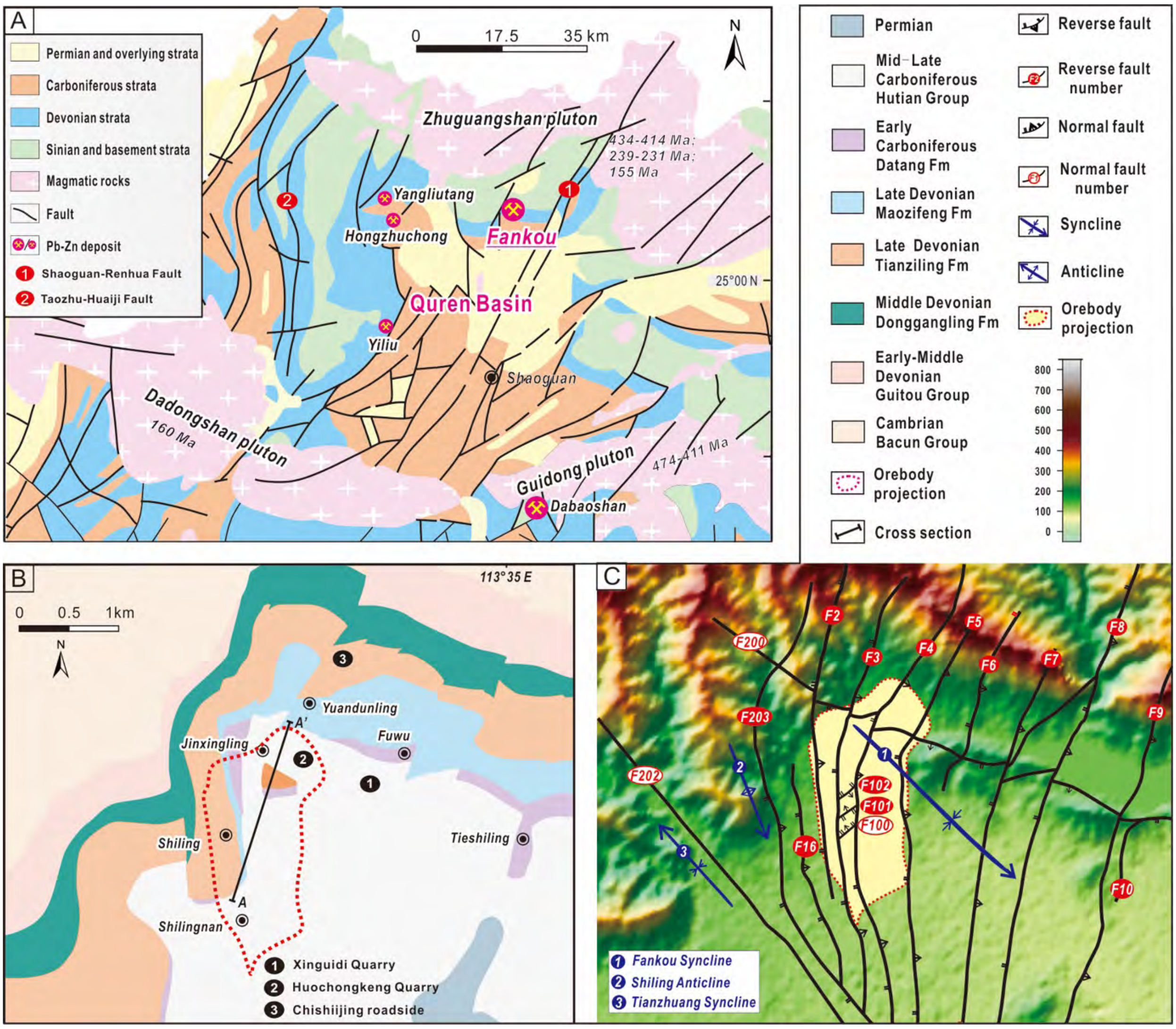

Figure 18: (A) *Geological map of the Quren basin,* ***(B)*** *Geological map of the Fankou Pb-Zn-(Ag-Ga-Ge-Cd) deposit, in which the dashed red line highlights the current mining area, and (C) distribution of major structure on the remote sensing map of the mine area (after Hu et al., 2023)*

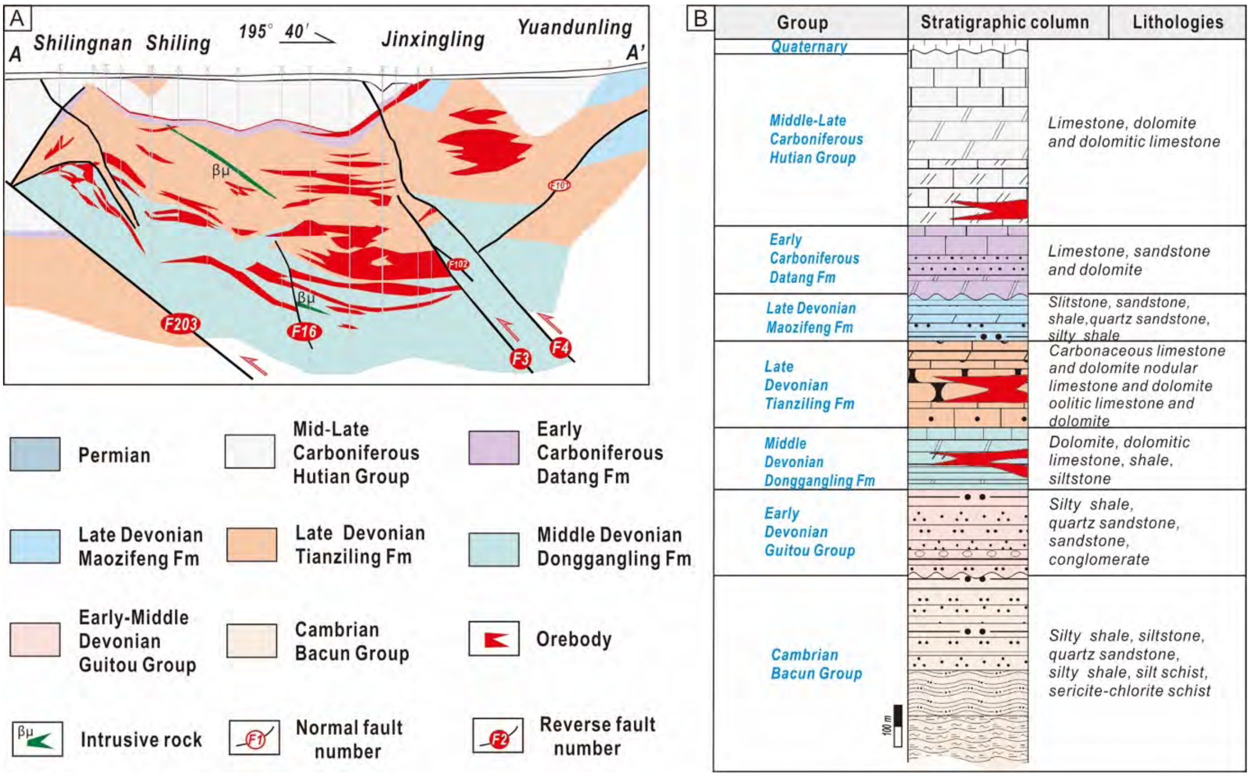

Figure 19: ***(A)*** *A cross-section (indicated in Fig. 18B) through the Fankou deposit to show the primarily strata bound ore-bodies distributing along well-developed fault structures, and* ***(B)*** *a stratigraphic column in the Fankou deposit, showing the main lithological composition and the strata bound nature of mineralization (after Hu et al., 2023)*

and Bohai-Cenxi faults (Fig. 17), were reactivated during major tectonic events and impacted the sedimentation and associated mineralization in the region.

The Devonian to Carboniferous marine sedimentary strata is extensively developed in the region (Fig. 17), dominated by clastic, carbonates and carbonaceous shales in lithological composition. Abundant Pb-Zn sulphide and barite deposits are clustered in the Devonian to Carboniferous strata in the southwest of Cathaysia block and distribute along the regional faults (Hu *et al.*, 2023). Among those Pb-Zn deposits, the Fankou and Panlong are two major Pb-Zn deposits being hosted in dolomite and display both strata-bound and structure-controlled mineralization.

Fankou carbonate-hosted Pb-Zn-(Ag-Ga-Ge-Cd) deposit

Fankou is the third largest Zn-Pb deposit in China, after Huoshaoyun and Jinding containing over 10Mt of Zn+Pb metal in reserves at an average grade of 15% Zn+Pb, and is rich in associated metals including Ag, Cd, Ga and Ge (Hu *et al.*, 2023).

The deposit is located at the northern margin of the Quren Basin, which is filled with folded Late Palaeozoic intercalated marine carbonate and clastic sequences (Fig. 18A). Mineralization is hosted in the Late Devonian to Early Carboniferous carbonate strata, which overlies the basement with an angular unconformity and conformably underlies the Late Carboniferous to Permian marine carbonate rocks (Fig. 18B). The Quren Basin is bounded by a group of regional faults, i.e., the EW-striking Zhuguangshan fault to the north, the Dadongshan-Guidong fault which is now filled with granitic intrusions to the south, the NE-striking Taozhou-Huaiji fault to the west and the Renhua-Shaoguan fault to the east. Inside the basin, two groups of faults have been identified, including NE-striking faults that parrel to the regional Wuchuan-Sihui fault, and NW-striking faults which is smaller in size and cut by the NE-striking faults (Fig. 18C). The faults are episodically activated in correspondence to the major regional tectonic events during the Caledonian, Indosinian and Yanshanian orogenies (Deng *et al.*, 2012; Zhang *et al.*, 2013). In addition to Fankou, several other marine carbonate-hosted Pb-Zn deposits including the Yangliutang, Yiliu and Hongzhuchong are distributed in the north margin of the basin (Fig. 18A), (Hu *et al.*, 2023 and references therein).

The Fankou Zn-Pb deposit comprises three major ore zones from north to south, namely the Jinxingling, Shiling and Shilingnan (Figs. 18A and 19A). Three additional subeconomic ore zones, including the Yuandunling, Fuwu and Tieshiling, are distributed peripheral to the major mineralization zones. Magmatism is in general absent except for a minor occurrence of diabase dykes being identified in drill cores. The Cambrian Bacun Group comprises the basement of the Quren Basin, and has a lithological composition of sandy shale, siltstone and sandstone subjected to low-greenschist facies metamorphism (Fig. 19B). The Lower Devonian Guitou Group unconformably overlies the Bacun basement and contains a sequence of red sandstone interlayered with silty shale and conglomerate, indicative of an oxidizing depositional environment. The overlying Devonian Donggangling and Carboniferous Tianziling formations are the major host rocks for the Pb-Zn mineralization. The Donggangling Formation comprises dolomitic limestone, dolomite, argillaceous shale and siltstone. The Tianziling Formation contains oolitic limestone, micritic limestone, silty shale, siltstone and argillaceous shale. Both the Donggangling and Tianziling formations are characterized by the overall presence of terrigenous clastic quartz, the presence of interlayers of pyrite shale (slate) or pyritiferous silty shale, the abundance of fossils and organic matters, suggesting a relatively reduced depositional environment. The Devonian Maozifeng Formation lies above the Tianziling Formation and consists of fine-grained sandstone and shale with low permeability. On top of the Maozifeng Formation overlies the well-developed Carboniferous Datang Formation, which forms an unconformably cover of the Devonian strata and consists of dolomite, limestone and sandstone. The Permian Qixia and Maoare composedmations, which compose of limestone and shale, occur locally in the southeast of the mining area.

A total of 211 orebodies are concealed below ~300 meter from the ground. The current mining area is concentrated in a narrow area of ~1 km^2 on the surface, extending for ca. 2000m from north to south, ca. 500 m from west to east, and ca. 800 m in depth (Fig. 18B). Mineralization is predominantly hosted in the Middle-Upper Devonian carbonate and partially in the Lower Carboniferous argillaceous carbonate. Faults have a major control on the morphology of orebodies (Figs. 19A and B), which are stratiform, lentiform and irregular in shape. The stratiform orebodies distribute conformably within the sedimentary host rocks, while the lentiform and irregular ones are spatially associated with the fault systems. Mineralization is impacted by deposit-scale folding to some extent. For example, the orebodies in the Jinxingling ore zone are localized in the northern flank of the NW-striking and SW-inclined Jinxingling anticline. The Jinxingling, Shiling and Shilingnan ore zones are suspected to be interconnected by the well-developed fault system at depth.

Three types of mineralization are distinguished in Fankou, including massive pyrite, massive lead-zinc ores, and mixed pyrite and lead-zinc ores (Hu *et al*., 2023). Coarse- to medium-grained sphalerite and galena are the most economic ore minerals in Fankou. Pyrite displays variable morphology changing from finely anhedral to coarsely euhedral grains. In addition, variable amounts of chalcopyrite, siderite, tetrahedrite, silver-rich tetrahedrite, pyrargyrite, argentite and arsenopyrite are concentrated in local areas near the faults. The main gangue minerals are pyrite, quartz, calcite, dolomite, siderite and illite. Pyrite is commonly associated with sphalerite and galena, but pure pyrite zones occur only in local area where beddings are developed or as a massive body. Siderite seldom forms together with pyrite, and both sedimentary and hydrothermal siderite are recognized (Hu *et al*., 2023). The sedimentary siderite is usually grey and fine-grained, while the hydrothermal siderite is yellow and medium-grained. Replacement and open-space filling textures are significant in Fankou. The early fine-grained and disseminated pyrite in the laminated layers are progressively replaced by late coarse and euhedral sphalerite and galena along the fractures. Most of the coarse-grained sphalerite display zoning texture with a dark core and distinct outer zones varying in colour from yellow to white. Mineralization styles include massive, banded, disseminated, veined and brecciated ores. The mineralization styles vary depending on the type of host rocks. For example, laminated pyrite is generally hosted in the pyritic shales, slightly metamorphosed pyritiferous siltstone, micrite containing fine-grain limestone clast or micritic limestone. Whereas the massive pyrite is hosted in dolomitized micritic limestone or sparite limestone, and micritic limestone containing quartz clasts or biodetrius. The Pb-Zn ores are hosted in pyritiferous silty limestone, dolomitized micrite containing limeclasts or sparite limestone containing quartz clasts. Alteration minerals include pyrite, dolomite, calcite, siderite and subordinately a small amount of quartz. Chlorite and barite are also identified to concentrate in the host rocks close to the faults. Siderite alteration is mainly distributed in the northern part of Fankou (Ma, 2002), and siderite usually occurs within the oolite-sparite limestone and sideritic micrite limestone.

Panlong carbonate-hosted Pb-Zn-Ba deposit

The Panlong Pb-Zn-Ba deposit is located in the southeast of the Guizhong Basin at the junction with the Dayaoshan uplift. The deposit belongs to the Xiangzhou-Wu Xuan Pb-Zn-barite metallogenic belt and consists of two ore zones known as Fanshan and Daling (Fig. 20), with total metal reserves of 1.30Mt Pb+Zn grading 2.9% Zn and 0.7% Pb, and 1.26 Mt $BaSO_4$ grading 17% (Niu *et al*, 2017).

The strata developed in the mining area mainly include the Cambrian, Devonian, and Quaternary (Fig. 20). The Cambrian strata only have the lowest unit exposed in the mine area, represented by the flyschoid clastic rocks of the Huangdongkou Formation. The Devonian strata was deposited close to sea or in a platform environment and has a rather intact exposure in the mine area. The Devonian strata lie unconformably over the Cambrian strata and include the Lianhuashan, Yujiang, Shanglun, Ertang, and Guanqiao formations in an ascending order. The Devonian Shanglun Formation is the main host rock of Pb-Zn mineralization and is lithologically composed of dark-grey carbonaceous dolomite and calcareous-siliceous mudstones. The Shanglun Formation overlies the Yujiang and Lianhuashan formations, which consist of gray-white silty mudstone and sandstone. Above the Shanglun Formation lies the Ertang and Guanqiao formations that contain argillaceous limestone and dolomite. The Quaternary strata are mainly composed of brown-red clays.

Faults are well developed in the mine area, including the NEE trending reverse fault F1 and normal fault F3, and the NNE trending fault F2 (Fig. 20). The F1 confines the southeastern boundary of the Guizhong Basin and separates the Cambrian basement from the overlying Devonian carbonate sequences. The post-mineralization F2 dips to NW with an angle of ~80°. It divides the Panlong into two ore zones of Daling and Fanshan, respectively. The F3, together with locally developed

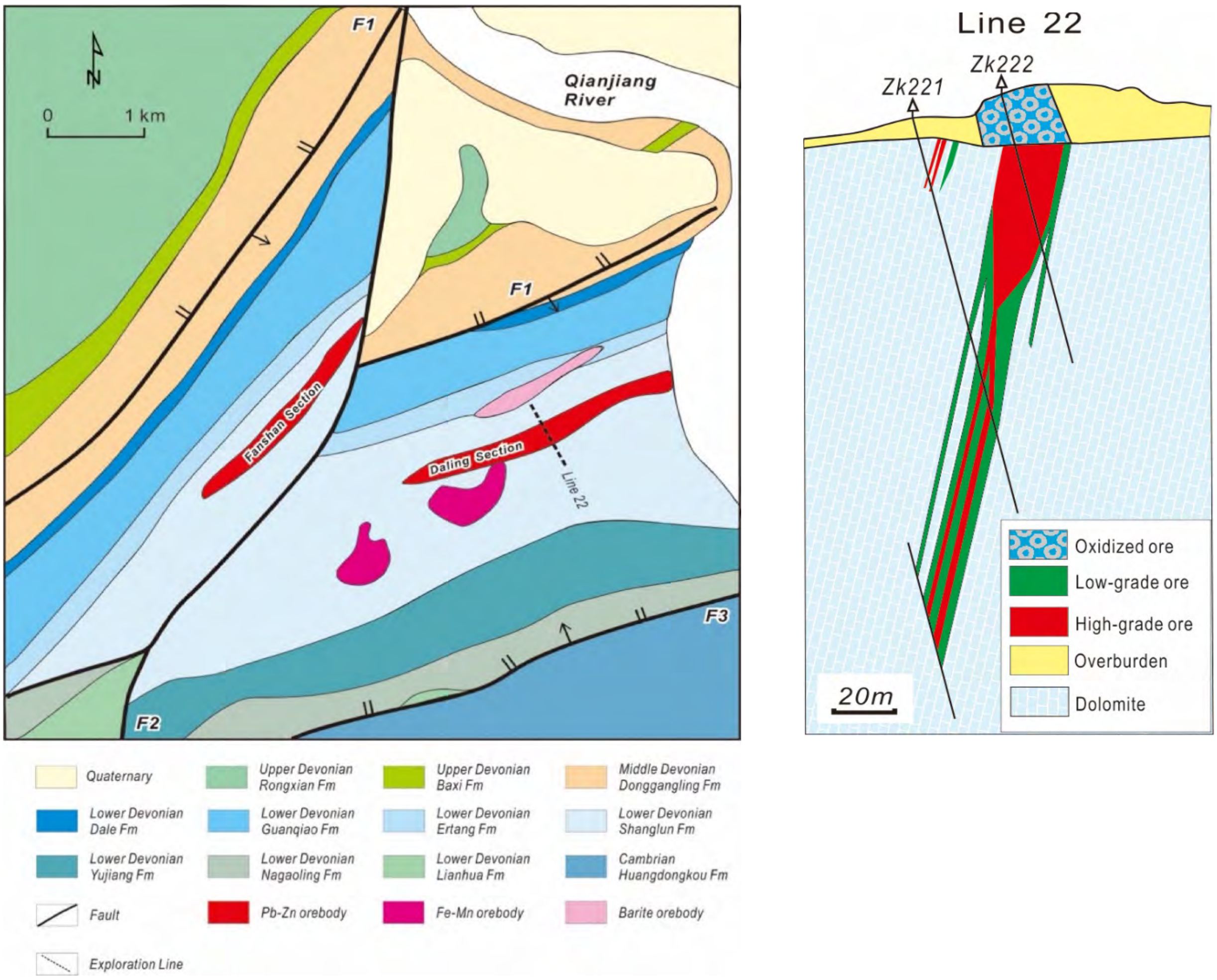

***Figure 20:** Geological map of the Panlong Pb-Zn-Ba deposit (after Niu et al., 2017) and cross-section showing the distribution of orebody*

breccia zones, are secondary structures formed from the movement of major regional Lixiang-Dali fault, representing important channels for the migration and deposition of ore-forming fluids. Magmatic rocks are absent in the Panlong deposit. The NE-striking Daling ore zone stretches ~3.5km in length and 60–80m in thickness and contains 6 multi-layered and stratiform orebodies (Nos. 2, 3, 4, 5, 7 and 8). The No. 2 orebody accounts for more than 95% of the total Pb-Zn reserves of Panlong and dips 75–85° to NNW. In contrast, the NNW-striking Fanshan ore zone comprises several small lenticular orebodies with low Pb and Zn grades. Mineralization is mostly lithological controlled, mostly concentrating in the first carbonate layers deposited during the sea transgression. A multiple-layered architecture was observed for the mineralization, which is hosted in different dolomite layers at various stratigraphy depth of the Shanglun Formation. The thickness of Pb-Zn orebodies is positively correlated with the thickness of the dolomite layers. Pyrite, sphalerite, and galena are the main sulphide minerals. Minor sulphosalt (e.g., tetrahedrite and jordanite) and supergene minerals (e.g., smithsonite, cerussite, calamine, anglesite, and limonite) are also identified. Nonmetallic minerals include barite, dolomite, calcite, and minor quartz. The mineralization consists of massive, brecciated, disseminated, and laminated styles. The ore minerals are characterized by euhedral to subhedral, colloform, framboidal, and replacement textures. Barite and dolomite are mostly formed from hydrothermal alteration, and their occurrence has a close spatial association with Pb-Zn mineralization. Barite is very abundant in the mine area, often forming a massive ore body close to the surface. Barite appears in various textures, including in veins filling faults and fractures, in layers distributing along the strata, or as nodules. Individual barite veins normally extend 80–120m to depth, followed by the appearance of pyrite-lead-zinc mineralization, providing an excellent vectoring tool for exploration.

Controls on the carbonate-hosted Pb-Zn mineralization in China

The carbonate-hosted Pb-Zn deposits in China are formed in diverse tectonic settings and show distinct geological characteristics at regional scale. We summarize the basic geological characteristics of the carbonate-hosted Pb-Zn deposits in the Yangtze and Cathaysia blocks, and the Himalayan-Tibetan orogen as below. Complementary reading of the Pb-Zn deposit geology can be found in several review paper (Zhou *et al.*, 2018; Song *et al.*, 2019; Han *et al*., 2023). Furthermore, a preliminary insight into the controls on the Pb-Zn mineralization in the different metallogenic belt is presented.

The carbonate-hosted Pb-Zn deposits in the SYG triangle show the following geological features:

1) Structure has a major control on the morphology and mineralization styles. Fault system is extremely well developed in the carbonate-hosted Pb-Zn deposits in the SYG triangle. The ore district is framed by several deep regional faults that were reactivated during major tectonic events. Furthermore, several orders of structure exist in the Pb-Zn mineral system of SYG triangle, which control the location of ore deposits, morphology of orebodies and the mineralization styles, respectively.

2) The Pb-Zn mineralization is usually hosted in carbonate layers that contain coarse crystalline dolomite and underlie a capping rock unit with relatively low permeability. Porosity contrast can be an important factor to consider for mineralization. Mineralization in this case is usually strata-bound, and transitions to open space filling and breccia-type towards the main fault. Vein-type mineralization occurs by filling the secondary interlayer fractures and often links different layers of mineralization in the stratigraphy unit. In the deposits where folds and thrusts are developed, mineralization is often hosted by interlayer fractures in the wings and appear as strata bound.

3) Mineralization is commonly comprised of two periods, including a hypogene period in which most of the hydrothermal sulphide ores precipitated and a supergene period forming Fe-Zn-Pb oxide or carbonate ores. The hydrothermal period can be further divided into several stages depending on the mineral assemblages and textures and cross-cutting relationships. Occasionally, a sedimentary period of mineralization is reported (e.g., Daliangzi), characterized by the formation of pyrite in framboids.

4) The ore mineral assemblage is relatively complex. Sphalerite and galena are the main ore minerals. In addition, a variety of copper and silver sulphides/sulphosalts occur and often concentrate in the areas close to faults. In some deposits, chalcopyrite and freibergite are reported as inclusion or exsolution in the sphalerite and galena, respectively (e.g., Daliangzi). Pyrite is abundant and formed throughout the hypogene mineralization stages. Occasionally arsenopyrite is associated with the early stage of hydrothermal pyrite, while marcasite is formed during the main and middle mineralization stage.

5) The gangue mineral assemblage varies among deposits, depending on the lithology of the host rocks and the stratigraphy column. Dolomite and quartz are often the dominant nonmetallic gangue minerals in deposits where siliceous dolostone is the host rock. Fluorite and bitumen are reported for the deposits where the host rocks or the lower stratigraphy units contain phosphorous and organic matters.

6) The carbonate-hosted Pb-Zn deposits have a close spatial associated with the extensive Permian Emeishan continental flood basalts, which are also the host rocks of native Cu deposits (Liu & Lin, 1999; Wang *et al.*, 2006). No other major igneous activities were reported. Zhou *et al*. (2018) suspected that the Emeishan flood basalts provided heat and mantle-source volatiles (e.g., CO_2) to the ore-forming fluids, which can be an important mechanism to account for effective enrichment of metals from fertile rocks. This may somehow explain the enrichment in dispersive elements including Ag, Cd, Ga, Ge, Se and Tl in the sulphide ores of the Pb-Zn deposits in the SYG triangle.

The carbonate-hosted Zn-Pb deposits in the Cathaysia block display many similar geological features to those in the SYG triangle in the Yangtze block, yet there are differences. The main features include:

1) Structural and stratigraphy control on the mineralization is still prominent. Deeply extended regional faults and secondary structures determine the orientation and morphology of orebodies. Mineralization is usually hosted in the carbonate rock units that contain shaly or muddy layers rich in organic matter and sedimentary pyrite. Those ore-host carbonate rock units often overlie siliciclastic rocks such as red sandstones. A change in redox condition for the ore-forming fluids may have played a major role in precipitating ore minerals.

2) Both limestone and dolostone can be the host rock for Pb-Zn mineralization and usually contain abundant intercalated argillaceous layers. The ore mineral assemblage is similar to those reported for the Zn-Pb deposits in the SYG triangle, whereas there are variations among deposits. Pryite, dolomite, calcite and quartz are the main gangue minerals. In addition, barite and Fe-Mn carbonates are well developed, and illite and chlorite are also observed.

3) Both hypogene and supergene mineralization occurred, similar to those deposits in the SYG triangle.

4) The Emeishan flood basalts are not identified in the region, but instead, granitic intrusions are extensively exposed outside the basin.

In contrast, the Pb-Zn deposits in the Himalaya-Tibet orogen differs from those hosted in the South China block in several ways.

1) The mineralization is exclusively hosted in limestone and sandstone, which overlies siliclastic rocks such as sandstone and conglomerates and underlies rock units that has relatively low permeability by containing more muddy and shaly components. This stratigraphy structure is similar to that for the carbonate-hosted Zn-Pb deposits in the SYG triangle and Cathaysia block. Usually either the limestone

host rock or the overlying rock units are rich in organic matters or bitumen, representing a change in redox condition for the depositional environment. It is thus likely that the change in redox condition for the ore-forming fluids may have played a major role in mineralization.

2) Brecciation and replacement textures are predominant. Mineralization occurs either as replacement of the calcite cement in the sandstone or of the calcite matrix in the limestone breccia.

3) Evaporite layers are extensively developed. They show texture of dissolution, replacement and brecciation, and are closely associated with mineralization.

4) The sulphide ore mineral assemblage is relatively simple for most of the deposits, mainly consisting of sphalerite and galena. Pyrite and/or marcasite occurs in all the deposits. Copper and/ or silver-minerals are reported for Jinding, in which the sulphide ore minerals are also relatively enriched in dispersive elements. However, for the other Zn-Pb deposits, the sulphide ore minerals have a rather simple assemblage. The primary gangue minerals are calcite and gypsum, followed by pyrite, barite and quartz, and in some cases, anhydrite. Celestite is abundant in the Jinding deposit.

5) Oxide ore zones are very well developed in the region, represented by the Huoshaoyun deposit. Smithsonite and cerussite are the main oxide ore minerals; hemimorphite is occasionally reported. Different mineralization styles can be observed for the oxide ores, mostly resembling the primary sulphide mineralization styles.

Geological controls on mineralization

Tectonic setting

The Yangtze platform in south China was stable palaeo-geographically from the Late Proterozoic to the end of the Middle Triassic. It formed a stable element in the chaotic palaeogeography of China from the Sinian to the end of the Middle Triassic. During the migration of Yangtze plate from the northeast margin of Gondwana to a suture with Eurasia (Enos, 1995), the Yangtze Platform formed a passive margin of the Yangtze Plate, where it contains the most voluminous and longest record of marine deposition in all of China (Enos, 1995). Thick shallow-water carbonates formed over this vast platform during a prolonged period from about 850 to 230Ma, and they exclusively host the Pb-Zn deposits in the region. The development of a stable and vast carbonate platform in this region, which was essential for exceptional endowment with carbonate-hosted Pb-Zn deposits, is almost comparable to the vast carbonate platform in North America, where Laurentia, a prominent part of Pangea, remained at low latitudes during the Palaeozoic, allowing for the development of vast platform (Leach *et al*., 2001).

In contrast, the Himalayan-Tibetan orogen and its neighboring regions in east Asia were affected by the continent-continent collision and was located in an intracontinental deformation. The collision processes have produced a variety of geological features such as large-scale thrust, strike-slip and normal fault systems, widespread volcanism, leucogranite magmatism, regional metamorphism and formation of intracontinental and continental-margin oceanic basins. The majority of the Pb-Zn deposits in the Himalayan-Tibetan orogen are located in the Qiangtang Terrane and hosted in the carbonate rocks of Carboniferous to Cretaceous age. Although reliable ages of mineralization from directly dating sulphide minerals are not available, paleomagnetic age (23 ± 3Ma, Yalikun *et al*., 2018) and apatite fission track ages (28-25Ma, Li *et al*., 2000) are relatively consistent, which suggest a Cenozoic mineralization formed during a regional transpressional deformation event after the main phase of regional compression during the India-Eurasia continental collision. At Chaqupacha, geological evidence of galena replacing the marl matrix in the pre-ore breccias, and the clasts of the Wudaoliang Formation constrains the timing of mineralization to be younger than the ~23 to 16Ma sedimentation. Considering the Cenozoic tectonic evolution of the Tuotuohe district, Song *et al*. (2019) suggests that the formation of Chaqupacha deposit post-dated regional thrusting and was during E-W crustal extension related to the India-Eurasia continental collision.

Structural control

Formation of epigenetic carbonate-hosted Pb-Zn deposits in basin environment requires atypical tectonic events that cause dense metalliferous brines to ascend kilometers in the crust and deposit ores where fluid-mixing or fluid-rock reactions causes precipitation of the metals. Both the SYG Pb-Zn district and the Pb-Zn deposits in the Cathayasia Block are situated in tectonic zones that are characterized by large-scale overthrust structures, folds, and compressional-shear faults. An extremely well-developed fault network, which is comparable to the ‘fault relay’ system in the Irish-type Pb-Zn deposits), has a major control on the location of Pb-Zn deposits in both districts (e.g., Huize and Fankou). In the SYG Pb-Zn district, both the Xiaojiang and the Qujing-Zhaotong fault zones represent the deep regional deep structure. A series of NE-trending tectonic zones were formed from the sinistral strike-slip movement of the Xiaojiang and Qujing-Zhaotong faults after the Hercynian in NE Yunnan area. These zones are largely composed of NE-trending folds and compressional-shear faults accompanied by NW-striking tensile faults perpendicular to major structures. These shear zones, together with the NW-striking tensile faults, constitute the “Xi-type” ore-controlling structures which are typical ore-controlling structures in the SYG Pb-Zn district (Han *et al*., 2001). Structural control is also prominent for the formation of Pb-Zn deposits in the Cathysia Block. Both Fankou and Panlong deposits are located along the secondary structure that were developed along a crustal fault. The orebodies of Fankou deposit display a narrow band of mineralization parallel to a contemporaneous fault. In areas where rift and fold are well developed, the distribution of ore bodies is mostly controlled by interlayer fractures and/or secondary fractures.

Different from the south China, the most important drive for ascension of ore-forming fluids in the Himalayan-Tibetan orogen is likely to be the regional hydraulic gradient associated with uplift and deformation along basin margins, as well as basin inversion within orogenic belts, which could have produced artesian flow within extensional domains. The carbonate-hosted Pb-Zn deposits in the Himalaya-Tibetan orogenic belt are mostly associated with thrust faults. Although ore-forming fluid migration is ineffective within thrust faults in carbonate-hosted Pb-Zn system, transition from a compressional to a transpressional regime, commonly during uplift of a thrust-and-fold belt, can lead to ore deposition. For example, formation of the Jinding Zn-Pb deposit corresponds to a period of major continental crust movement during the collision of the Indian and Eurasian Plates. The westward thrusts and dome structure were successively developed in the Palaeocene sedimentary rocks in the ore district, and Zn-Pb mineralization appears to have taken place in the early stage of the doming processes.

Breccias

Breccia dissolution is another important mechanism to generate pressure gradient and drive the ore-forming fluids to the focus point. In the Chaqupacha deposit, pre-ore carbonate dissolution-collapse breccias were identified and the breccia zones are strata-bound and penetrate different stratigraphic levels of the limestone of Jiushidaoban Formation, with no preferential controlling by fault structure. The Zn-Pb sulphides in the deposit replaced fine-grained carbonate matrix in pre-ore carbonate dissolution-collapse breccias and filled the open spaces. Moreover, the giant Huoshaoyun deposit contains abundant sedimentary gypsum beds in the carbonate rocks of the Middle Jurassic Longshan Formation, locally occur in the ore zones (Gao *et al*., 2019; Li *et al.*, 2019). In the most important orebody III, ores with residual galena are hosted by breccias which are conformably restricted within a stratigraphic level. This is atypical of carbonate dissolution-collapse breccias that usually have highly variable vertical to lateral dimensions and may penetrate several stratigraphic levels (Loucks *et al*., 2004). It is more likely suggests that the brecciation was caused by replacement of dissolved and collapsed evaporite. Furthermore, brecciation is a common process in dolomite containing anhydrite. Dolomite breccia and some anhydrite breccias are observed in the Jinding deposit, displaying replacement texture subject to ore-forming fluids. It is a process of generating secondary vugs or molds of anhydrite crystals related to the solution, which creates considerable volume for ore-forming fluids accumulation.

Evaporites

Carbonates can be closely related to evaporites in evaporitic basins. Generally, evaporite encompasses a wide range of chemically precipitated salts and includes alkali earth carbonates (Warren, 2006), of which the major ions are Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and CO_3^{2-} in varying proportions, along with other less common ionic constituents such as B, Ba, Sr, Br, Li and Ni and varying amounts of bound or structural water (Warren 2010). Both Jinding and Huoshaoyun, the largest and second largest Zn-Pb deposits in China, contains abundant gypsum layers in the host rock units. In addition, anhydrite and celestine are reported for the Jinding deposit, suggesting intense evaporation associated with generation of porosity and permeability in the host rocks. In the meantime, the meteoric fresh water, probably associated with subaerial exposure in the area due to high relief and arid climate could have dissolved calcite and gypsum, which have led to collapse of surrounding rocks to develop the paleo-karst breccia and additional porosity. Moreover, due to the high reactivity of evaporites, sulphate reduction can become a common process in the presence of organic matters to generate hydrogen sulphide for the precipitation of sulphide minerals.

Organic matter

Geochemical processes involving living organisms or detrital carbonaceous material have often been invoked to explain the preferential enrichment of some metallic elements in organic-rich sedimentary layers, as well as the common association of various organic constituents in some sedimentary ore deposits. Organic matter is widely distributed in the Jingding deposit and occurs mainly as bitumen and crude oil fillings in fractures and dissolved cavities in the ores and host rocks. It is also present as hydrocarbon inclusions in transparent and non-transparent minerals (Xue *et al*., 2007, 2009; Chi *et al*., 2017). In general, the Lanping basin, where the Jinding Zn-Pb deposit is located, was filled with a series of marine sequences with abundant organic matter during the late Triassic. In the Jinding area, the Triassic Sanhedong Formation is mainly composed of marine carbonate rocks, and solid bitumen is present on the surfaces of and fractures in the carbonate rocks, along with the formation of re-crystallised euhedral pyrite in local areas. Further comparison of sulphur isotope composition of the sulphide minerals and solid bitumen suggest that the H_2S in Jinding was mostly produced by microbial sulphate reduction and this mostly likely to have happened in the Triassic strata prior to or during migration of the hydrocarbons to the Jinding dome to form a H_2S-enriched paleo-oil reservoir (Lan *et al.*, 2021). This explains the tabular mineralization in Jinding, which is concentrated in the Jinding dome and hosted in the siliciclastic strata of Early Cretaceous and Palaeocene age. Moreover, silty-argillaceous, and carbonaceous matter is also abundant in the ore-bearing the Devonian strata of Fankou deposit. Generally, the Quren basin, where the Fankou deposit is located, is rich in fossils of invertebrate animals and algae, including brachiopods, lamellibranchia, bryozoa, foraminifera and green and red algae. The aqueous organisms such as planktons, algae and bacteria in the carbonate sediments are important host and source for organic matters. The organic components in the host rock and ores are identical in types and the degree of thermal evolution, suggesting that organic matters could have played an important role during the mineralization (Li *et al.*, 1997).

Conclusions

Marine carbonate-hosted Pb-Zn deposits in China are mostly concentrated in the SYG triangle in the Yangtze block, followed by the Himalayan-Tibetan orogenic belt and the Cathaysia block. The geological characteristics of those deposits display regional variations. The major Pb-Zn deposits located in the Yangtze and Cathaysia blocks are comparable in terms of the mineralization styles of being stratigraphy (i.e., dolostone in certain stratigraphy units) and structure (i.e., well-developed fault system) controlled. The Pb-Zn deposits in the two regions also share similar ore mineral assemblages and are distinctively high in Pb + Zn grade and enriched in dispersive elements such as Ge, Ga, Ag, Cd and Tl. These common features may reflect the control of the geological evolution of South China Platform on the regional Pb-Zn mineralization. However, the Pb-Zn deposits in the Yangtze block are spatially associated with the Permian Emeishan flood basalts, whereas those on the Cathaysia blocks have no definite spatial or genetic links with intrusion rocks. The Pb-Zn deposits in the Himalayan-Tibetan orogenic belt are different from those in the South China block by being hosted in limestone mostly and abundant in evaporite. Brecciation is pervasive and oxide ores are extremely well developed. In general, the Pb-Zn deposits in all the three metallogenic belts are characterized by association with deep regional structures including crustal faults and suture zones, as well as contain sedimentary layers that are rich in organic matters and evaporites. Despite of the extensive studies of Pb-Zn deposits in those regions that mostly focus on geochemistry, we reckon an improved understanding of the geological characteristics of mineral deposits, particularly on structural geology and stratigraphy at both deposit and regional scale, is still very much needed to guide future exploration and develop a complete genetic model.

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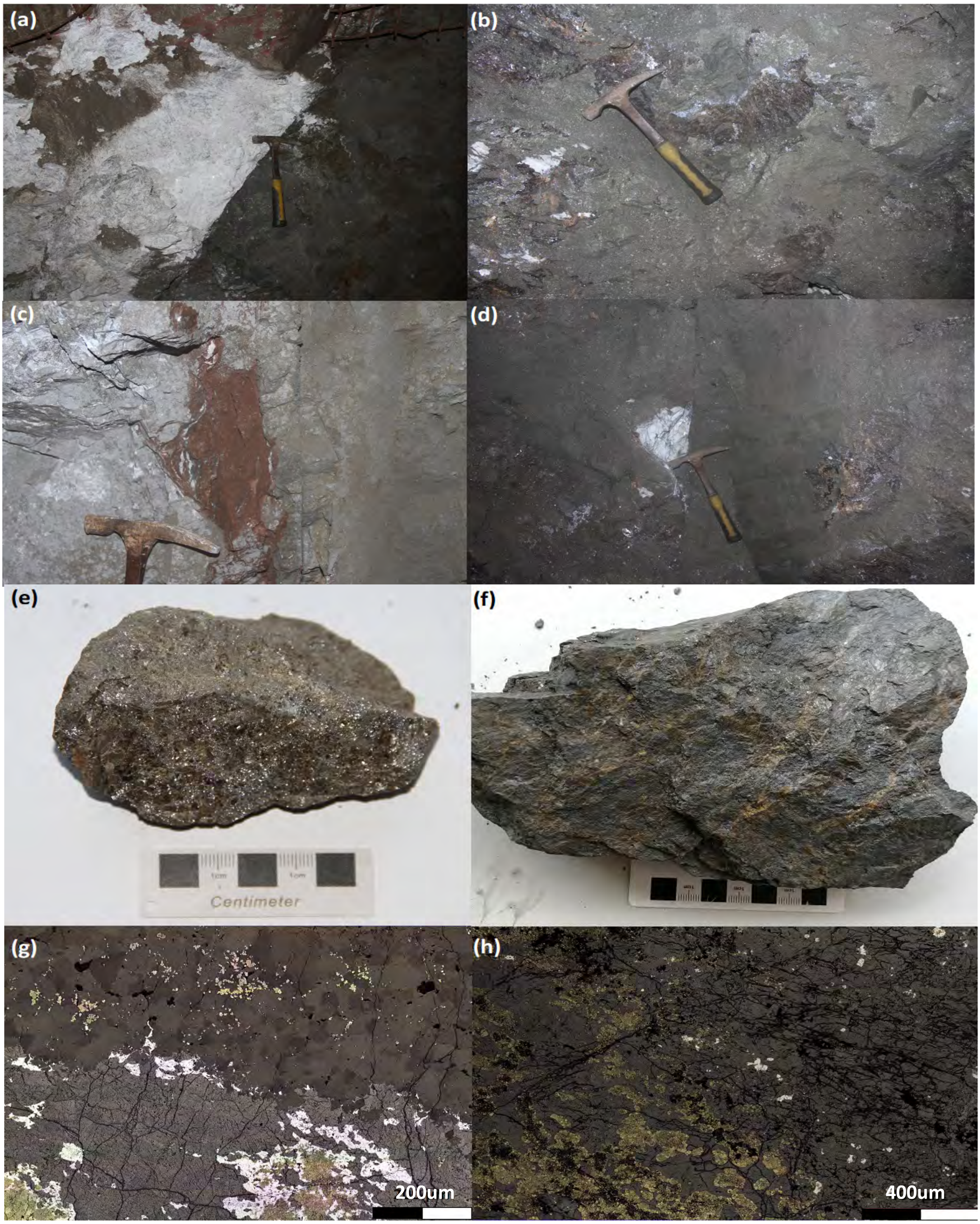

Plate 1: *Geological characteristics of the Huize Pb-Zn-(Ag-Ge) deposit (photos are provided by Jiaxi Zhou)*

(a)*- A sharp boundary between the orebody and strata; re-crystallized dolomite in milky white intergrows with ore minerals in the orebody;* ***(b)****- massive pyrite-sphalerite orebody, in which milky white dolomite clasts are observed; (c)- oxidized ores in rusty red are observed to occur at the margin of sulphide orebody;* ***(d)****- massive pyrite-sphalerite orebody which contains clasts of wall rock;* ***(e)-*** *a massive ore characterized by coarse-grain sphalerite;* ***(f)-*** *a massive ore which contains fine-grain sphalerite and stripes of dolomite;* ***(g)****- reflected light microscopy of disseminated pyrite in dolomite and calcite, as well as pyrite remnants being replaced by galena and massive sphalerite;* ***(h)****- reflected light microscopy of pyrite distributing either in the fractures of sphalerite or as aggregates being enclosed and replaced by sphalerite.*

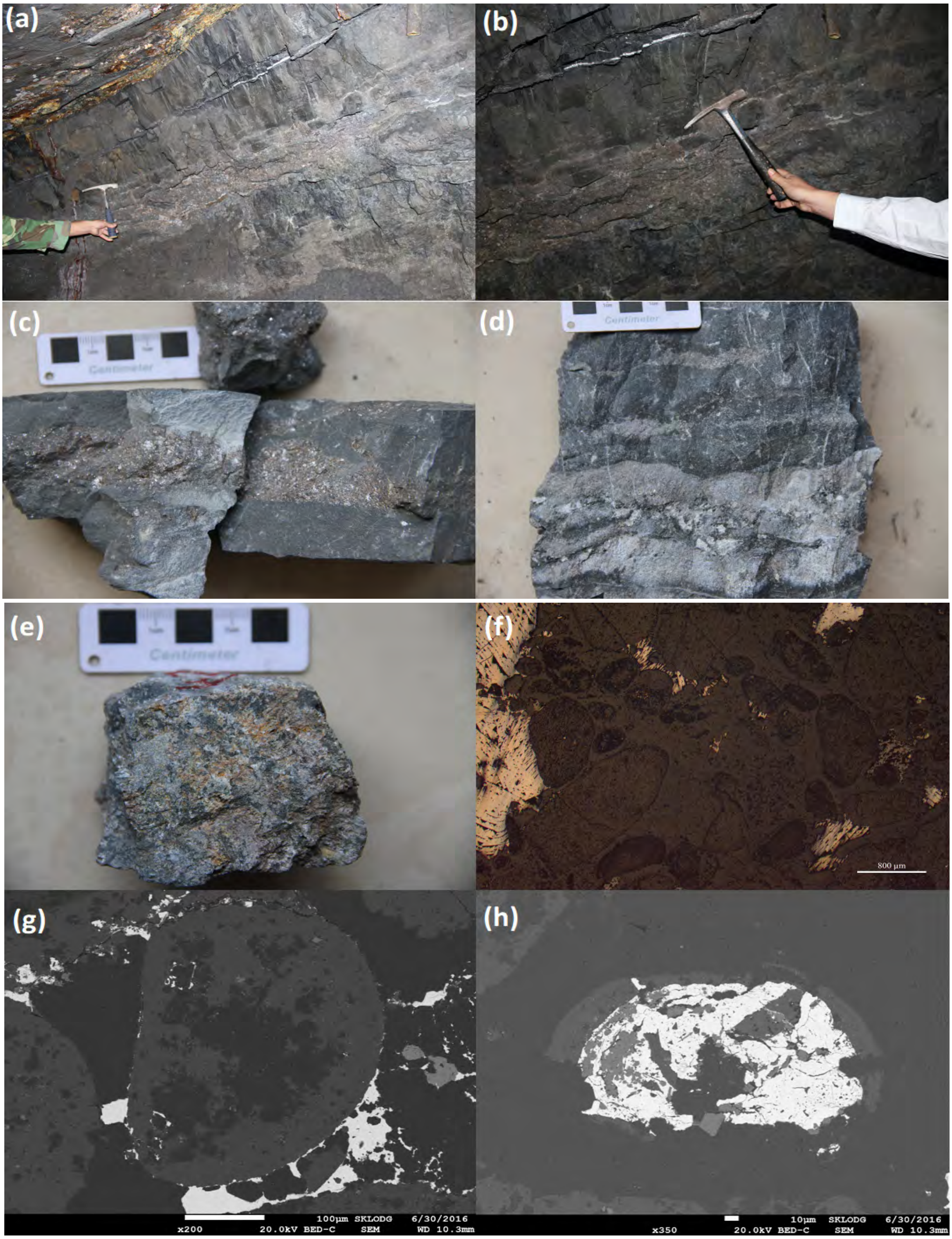

***Plate 2**: Geological characteristics of the Maozu Pb-Zn-(Ag-Ga) deposit (photos are provided by Jiaxi Zhou)*

***(a)**- Stratabound sulphide layers and oxidized orebody in yellow-brown, together with white dolomite layers filling the inter-layer space; **(b)** stratabound sulphide orebody and dolomite in thin veins; **(c)** hand specimen of sulphide ores from the layered orebody; **(d)** multiple layers of mineralization parallel to the stratigraphy units; **(e)**- a hand specimen of sphalerite ore; **(f)**- reflected light microscopy of galena and phosphate nodules being cemented by calcite; **(g)**, **(h)**- scanning electron microscopy pf phosphate nodules being enclosed by calcite and galena, and being partly replaced by galena and calcite, respectively.*

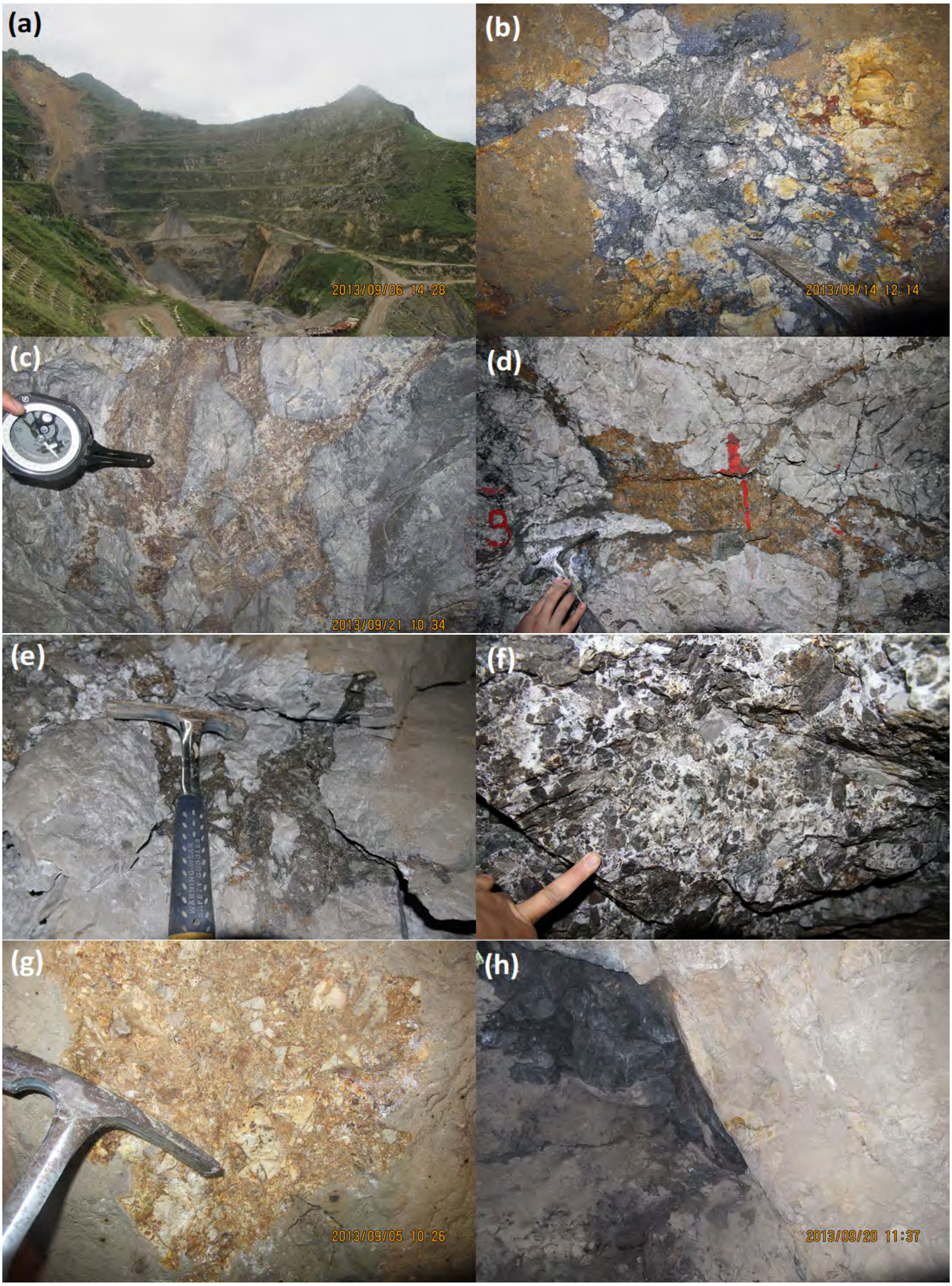

Plate 3: *Geological characteristics of the Daliangzi Zn-Pb-(Cd-Ge) deposit in the Yangtze block (photos are provided by Jiaxi Zhou*

(a)*- Open pit of the Daliangzi Pb-Zn deposit;* ***(b)****- breccia-type ores in the black fracture zone;* ***(c)****- dolomite breccias being cemented by sphalerite and galena;* ***(d)****- mineralization filling the factures of the host rock dolostone, forming nodules and veinlets;* ***(e)****- dolomite breccias being cemented by sphalerite and galena;* ***(f)*** *breccia-type ores in the black fracture zone;* ***(g)****- a sandstone breccia without mineralization;* ***(h)****- a sharp boundary between the black fracture zone and the causative fault*

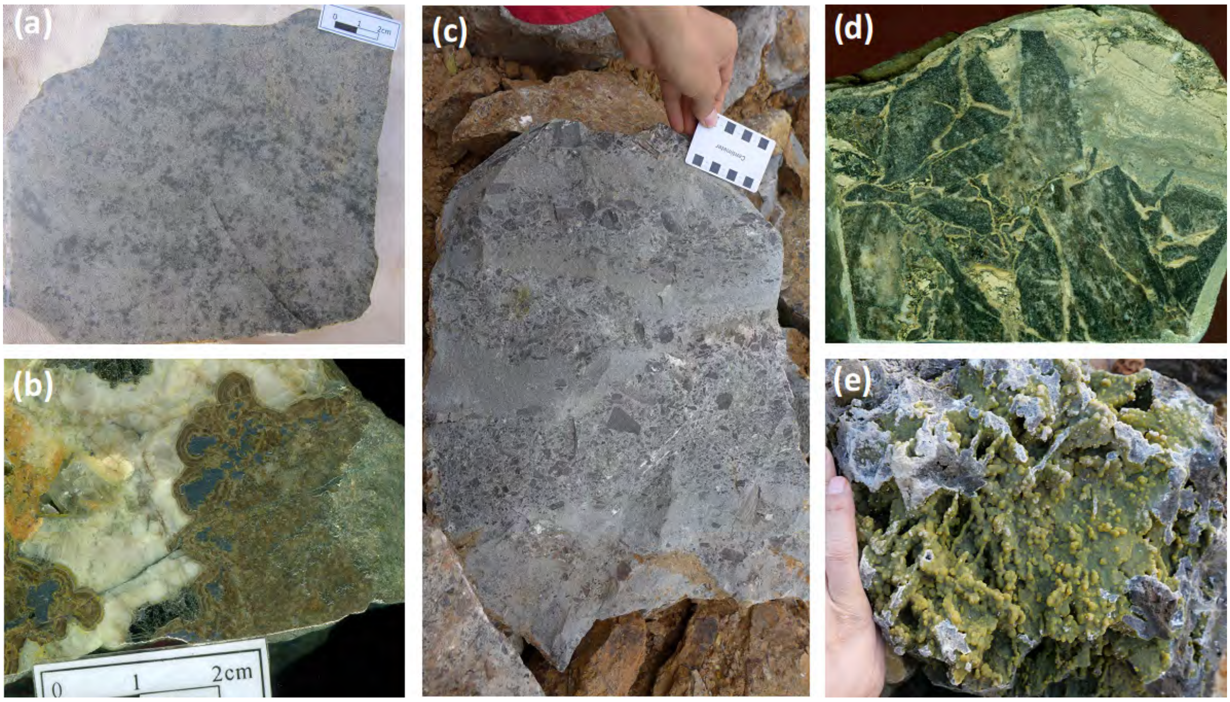

Plate 4: *Geological characteristics of the Jinding Pb-Zn deposit in the Himalayan-Tibetan orogen (photos are provided by Yucai Song)*

(a)*- A hand specimen of disseminated mineralization in the sandstone;* ***(b)****- A hand specimen of open-space filling texture of mineralization in the Beichang ore zone, which is composed of colloform sphalerite and euhedral galena; this texture is closely associated the occurrence of gypsum;* ***(c)****- mineralized sandstone containing limestone breccias;* ***(d)****- mineralized limestone breccias in the Paomaping ore zone, in which sphalerite forms thin rims;* ***(e)****- a supergene smithsonite (hydrozincite?) ore observed at the Beichang ore zone*

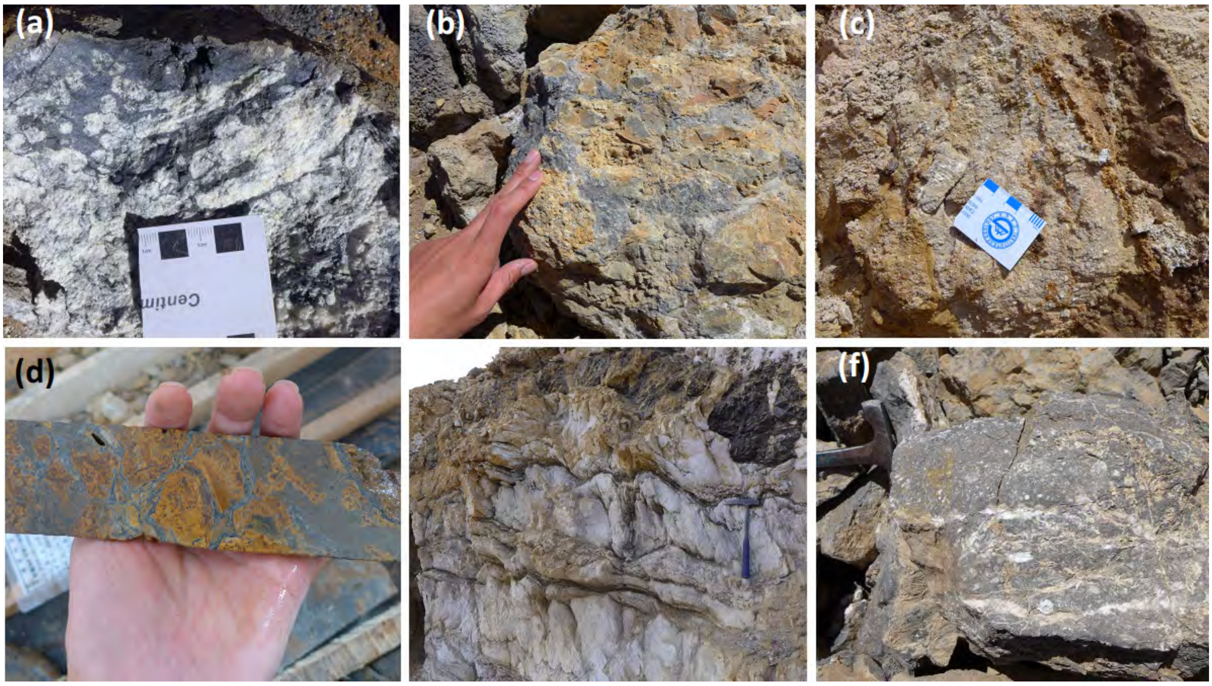

Plate 5: *Geological characteristics of the Huoshaoyun Pb-Zn deposit in the Himalayan-Tibetan orogen (photos are provided by Yucai Song)*

(a)*- A cerussite (in black)-rich ore;* ***(b)*** *and* ***(c)****- smithsonite (in brown yellow)-rich ores;* ***(d)****- a drill core sample showing smithsonite clasts cemented by galena;* ***(e)****- Exposed thick gypsum layers in the mine area;* ***(f)****- the Middle Jurassic Longshan Formation, which is bioclastic limestone in composition and the primary ore-host rock*

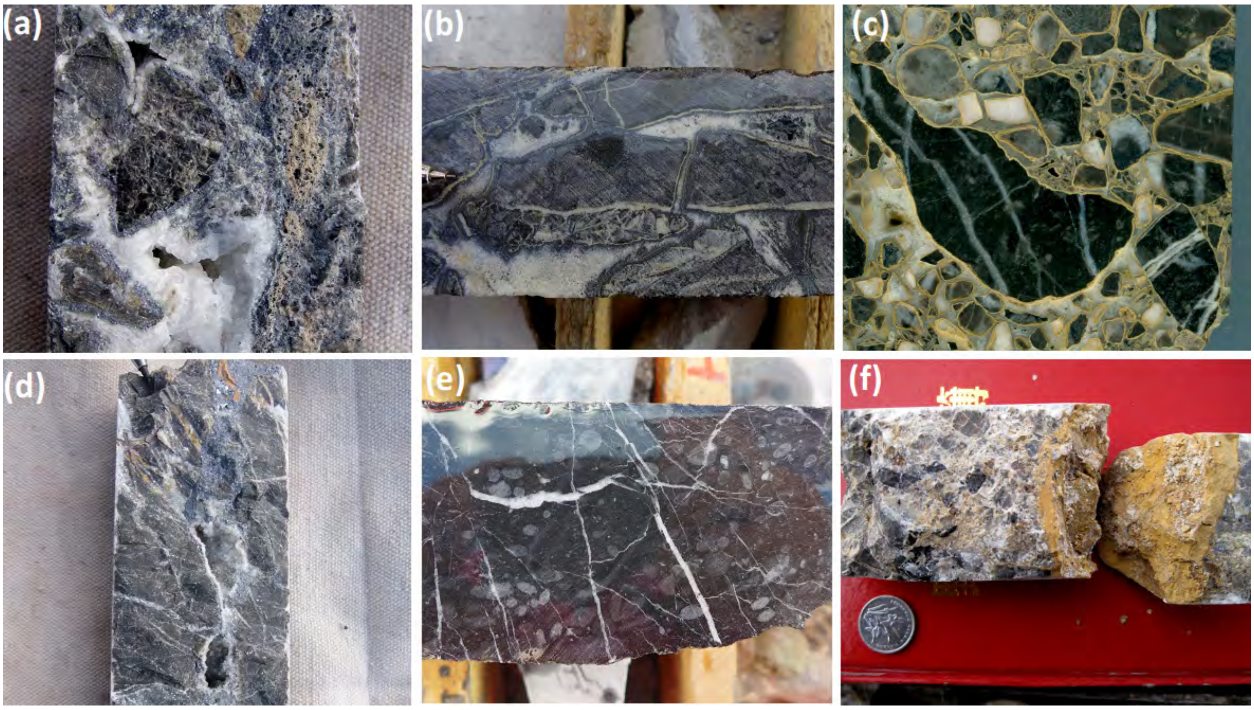

***Plate 6:** Geological characteristics of the Chapupacha Pb-Zn deposit in the Himalayan-Tibetan orogen (photos are provided by Yucai Song)*

***(a)**- Galena-dominant mineralization in the dissolution breccia, which is characterized by galena enclosing the clasts and filling the matrix (Song et al., 2015); **(b)**-mineralized dissolution breccia in the Jiushidaoban Formation; the clasts are enclosed by sphalerite (pale yellow) and galena (dark grey) and cemented primarily by calcite; **(c)**- sphalerite-dominant mineralization in the dissolution breccia, which is characterized by sphalerite in light yellow enclosing the clasts (Song et al., 2015); **(d)**-galena-dominant mineralization as open-space filling in the fractures and cracks of the limestone of the Jiushidaoban Formation; **(e)**- bioclastic limestone of the Jiushidaoban Formation without mineralization (Song et al., 2015); **(f)**- poorly mineralized dissolution breccia, which is hosted in the limestone of Jiushidaoban Formation and contains the muddy Wudaoliang Formation of early Miocene age.*

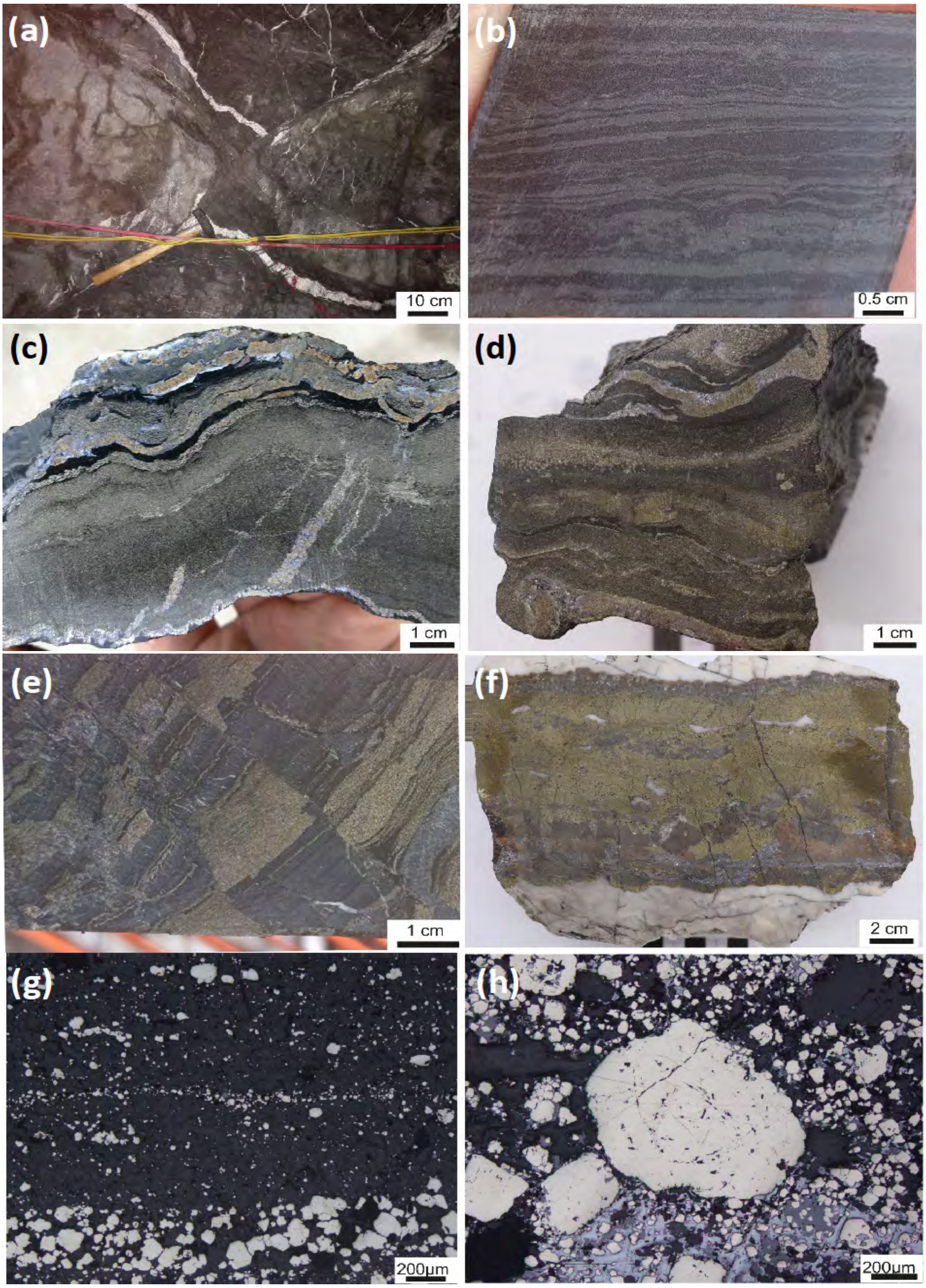

Plate 7: *Geological characteristics of the Fankou Pb-Zn-(Ag-Ga-Ge-Cd) deposit in the Cathaysia block (photos are provided by Zhaobin Hu)*

(a)*- A fault structure which dislocates the limestone strata and intersects the orebody;* ***(b)****- fine-grain pyrite laminas alternating with calcite layers that rich in carbonaceous materials;* ***(c)****- fine-grain massive pyrite layers intergrow with dark layers rich in carbonaceous materials;* ***(d)****- fine-grain pyrite layers alternating with sphalerite + galena layers;* ***(e)****- a micro-structure which dislocates alternating pyrite and sphalerite layers;* ***(f)****- a thick sulphide band that contains massive pyrite, large euhedral sphalerite and fine-grain galena; (g),* ***(h)****- fine-grain and euhedral pyrite disseminated in the argillaceous host rock; some grains show recrystallization with a core-rim texture (Hu et al., 2023)*

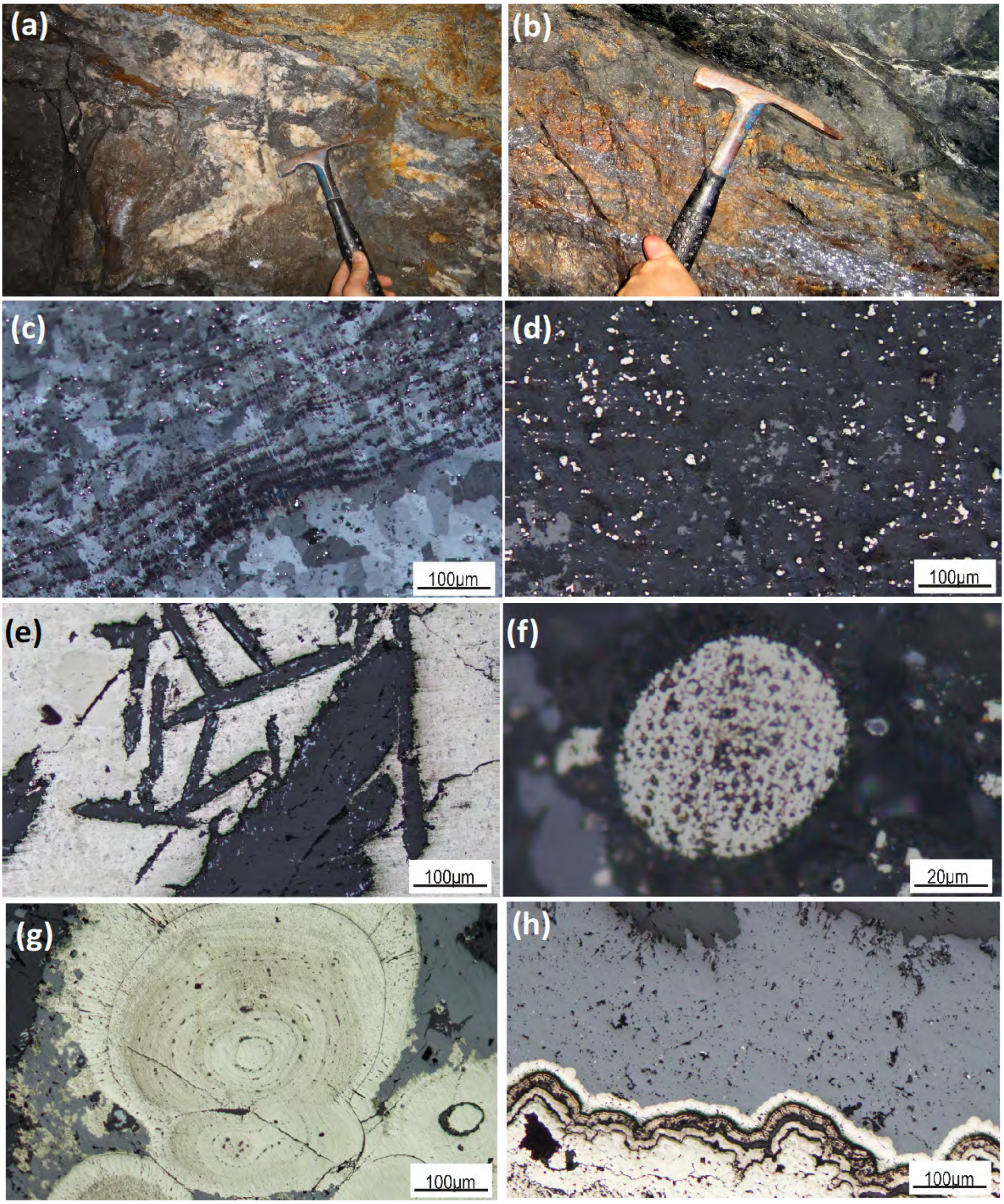

Plate 8: *Geological characteristics of the Panlong Pb-Zn-Ba deposit in the Cathaysia block (photos are provided by Yi Zheng)*

(a)*- Massive sphalerite and galena intergrowing with barite (in whitish pink);* ***(b)*** *massive sphalerite and galena ore body extending along the dolomite strata;* ***(c), (d)****- reflected light microscopy of disseminated pyrite in bright pale yellow colour in the host dolomite;* ***(e)****- reflected light microscopy of barite, which is locally replaced by galena, imbedding in massive pyrite; (f),* ***(g)****- reflected light microscopy of pyrite in framboidal and colloidal shapes, respectively, both are associated with sphalerite;* ***(h)****- colloform Fe sulphides (pyrite + marcasite?) overgrown by banded sphalerite containing carbonate inclusions*