



Structural setting of the Narusongduo Pb-Zn ore deposit in the Gangdese belt, central Tibet

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ARTICLE INFO

Keywords:

Lhasa terrane
Gangdese retroarc
Luobadui-Milashan fault
Structural controls
Linziyong volcanic succession
Narusongduo ore deposit

ABSTRACT

The Narusongduo Pb-Zn deposit is located at the northern boundary of the Luobadui-Milashan fault zone (LMF) in central Tibet and is spatially associated with the Linziyong volcanic succession (LVS). Our study indicates that the regional structural setting was formed by two-stage tectonic events. The first stage, spanning from the late Mesozoic to early Paleocene, is characterized by significant N-S crustal shortening associated with the Cordilleran-type orogeny along the Gangdese arc. The region's Paleozoic-Mesozoic metasedimentary rocks were penetratively strained. Locally deformation was largely partitioned along the LMF. During the second stage (ca. 66–55 Ma), the area was affected by extensive multi-stage Linziyong volcanism, including caldera formation, as well as a coaxial N-S propagative deformation with a distinctive lower shortening rate. We recognized two types of mineralization, both were formed during the second stage. The first type of mineralization (orebody III) is governed by fractures within the extensively deformed Paleozoic carbonate rocks at the LMF's footwall. The overlying LVS, however, includes discrete but numerous mineralized sections. The terminal splays of the ore shoots typify the products of hydraulic fracturing. We propose that the propagative compressive deformation drained fluid reservoirs at depth to higher levels via the "Fault valve" effect. Episodic fluid influxes and mineral deposition formed the time-integrated mineralization. The second type of mineralization (orebody I) is hosted in the LVS in a number of breccia pipes and dykes that were controlled by the structural weaknesses generated by the intersection of the radial and ring fractures. Mineralization occurs as veinlets in the matrix and clasts inside the breccias, which are characterized by multi-stage brittle cracking, fluid injection and mineral precipitation. It is interpreted that the multi-stage magmatism (ca. 66–55 Ma) triggered repeated hydrothermal activities and incremental mineralization within the ore-bearing breccia bodies.

1. Introduction

Hydrothermal mineralization usually occurs in volcanic environments as a result of a variety of processes such as eruption, brecciation, and extensive fluid circulation. (e.g., Hedenquist and Matsuhisa, 1987; White and Hedenquist, 1990; Sidorov et al., 2015; Nadeau et al., 2016; Guo et al., 2020a). In particular, it is considered that volcanic structures

provide pathways for fluid injection and accommodation space for ore deposition, with the assumption that mineralization postdates the volcanism (e.g., Arribas et al., 1995; Stix et al., 2003; Williams-Jones and Heinrich, 2005; Guo et al., 2020a). Nonetheless, recent studies on modern volcanos and magmatic-hydrothermal ore deposits suggest that episodic fluid ingression and brecciation of overlying rocks played crucial roles in fluid depressurization and mineral precipitation (Hattori

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<https://doi.org/10.1016/j.oregeorev.2022.104748>

Received 4 July 2021; Received in revised form 18 January 2022; Accepted 1 February 2022

Available online 5 February 2022

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and Keith, 2001; Maughan et al., 2002; Nadeau et al., 2016).

How compressive deformational structures influenced the ore deposition is another topical issue (Cox, 1995, 2016; Hou et al., 2008; Liu et al., 2011; Zhang et al., 2017). In cases, it has been proposed that (1) the high displacement faults and shearing networks could provide pathways linking the “upstream” fluid reservoirs at depth to shallow crustal level (Cox, 1995; Nguyen et al., 1998; Kenworthy and Hagemann, 2007); (2) The propagative faulting and rapturing triggered repeated high flux fluid activities (Boullier and Robert, 1992; Cox, 2016; Zhang et al., 2017); (3) The fault- and fold-related dilation system along with fluid-driven growth of fracture permeability provided “downstream” space for the precipitation of the ores (Sibson et al., 1988; McCuaig and Kerrich, 1998; Cox et al., 2001, 2005).

However, structural controls on the formation of ore deposits hosted in fault zones, which are affected by intensive volcanism, are less clear and may vary significantly. The fluid localization and mineralization within these systems could be associated with the margin of a caldera, its

interior structures, and adjacent regional structures (e.g., Lipman et al., 2015; Garden et al., 2017). In addition, the regional structural setting, particularly the temporal and spatial relations between the tectonic deformation and caldera-forming events, exert crucial influences on the mineralization patterns. For example, it is noted that post-caldera regional faults could reactivate the ring faults of the volcanic edifice and promote the localization of later-stage fluid flow (Rytuba et al., 1990; Elston, 1994; Rytuba, 1994). Nonetheless, calderas commonly result from multi-stage magmatism which may continue for several million years (Elston, 1994; Acocella, 2007). Therefore, large-scale centric volcanism overprinting a pre-existing regional structural discontinuity would (1) induce repetitive magmatism and fluid ingress focusing on the regional structural weakness and (2) form relatively intact volcanic loads that may blanket later-stage fluid influx (Tramparulo et al., 2018 and references therein). This complexity highlights the necessity of investigation on the structural settings of this type of ore deposits.

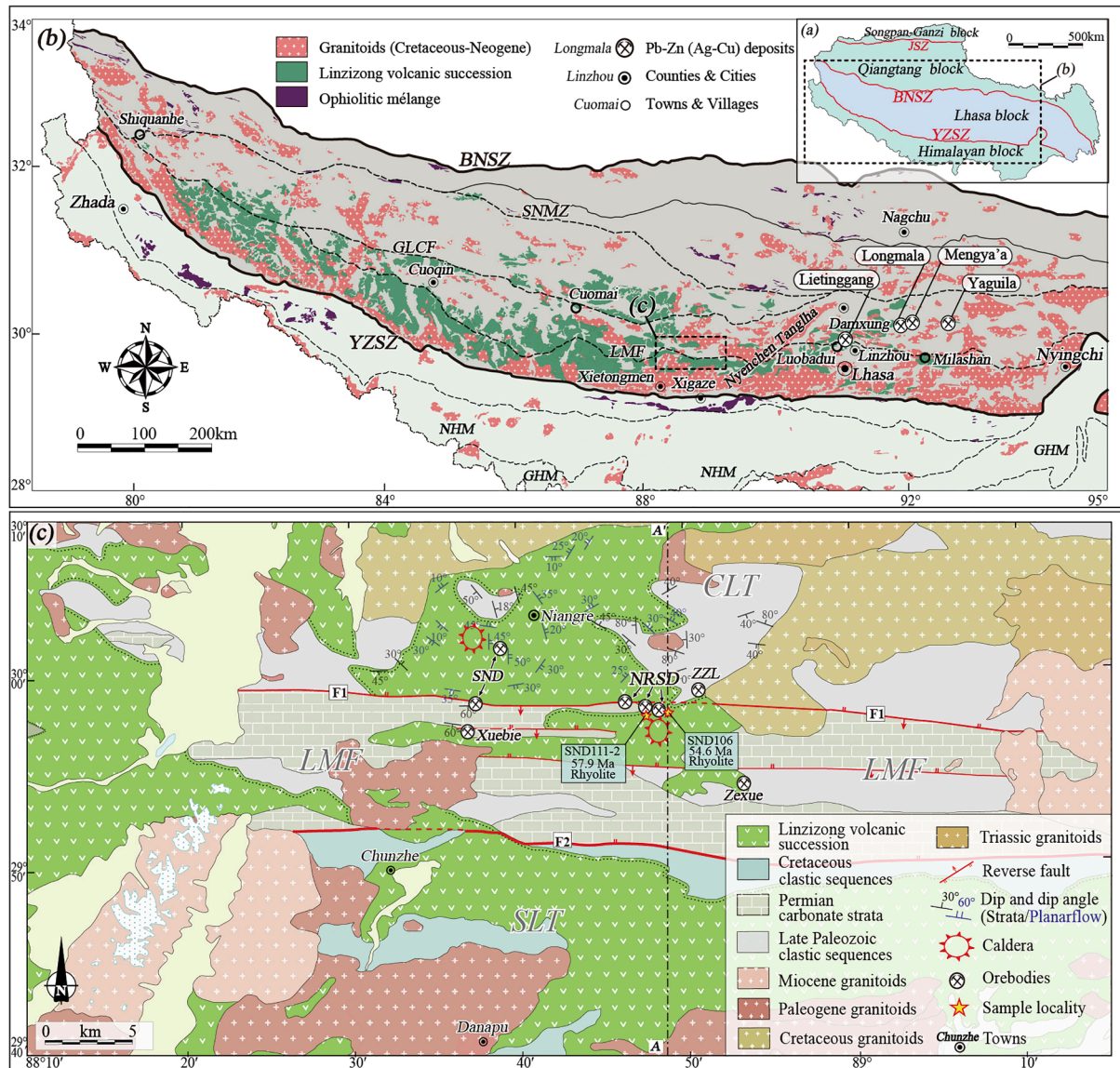


Fig. 1. (a) Inset showing the tectonic subdivisions of the Tibetan plateau (after Liu et al., 2019). (b) Simplified geological map of the Gangdese belt and adjacent regions (modified from C.G.S., 2019; Liu et al., 2019). Abbreviations: BNSZ = Bangong-Nujiang suture zone; GHM = Greater Himalaya; GLCF = Gar-Lunggar-Cuomai Fault; LMF = Luobadui-Milashan fault; NHM = Northern Himalaya; SNMZ = Shiquanhe - Nam Tso mélange zone; YZSZ = Yarlung Zangbo suture zone; (c) Detailed geological map of the Narusongduo region (compiled from C.G.S., 2019 and unpublished report of the Deep Resources Program). The dashed line indicates the location of the cross-section in Fig. 2. Abbreviations: LMF = Luobadui-Milashan fault, CLT = central Lhasa sub-terrane, SLT = southern Lhasa sub-terrane, NRSD = Narusongduo, SND = Sinongduo, ZZL = Zhazhalong.

The Pb-Zn (Ag-Cu) deposits in the Gangdese *retro*-arc zone (GRAZ) are important components of the Tethyan metallogenic domain (Richards, 2011; Tang et al., 2014, 2016; Hou et al., 2015; Yang et al., 2015a, 2016; Zheng et al., 2015; Fu et al., 2017). Voluminous Pb-Zn deposits were identified in the eastern segment of the GRAZ and interpreted as being controlled by the Gangdese *retro*-arc thrust-fold systems (Wang et al., 2010; Ding, 2017; Fu et al., 2017). In contrast, the western GRAZ, characterized by extensive Cenozoic eruptive magmatism and significant crustal shortening (Kapp and DeCelles, 2019; Zhu et al., 2019), hosts fewer deposits (Fig. 1). However, examples from other world-class metallogenic domains suggest that the combination of compressive deformation and intensive volcanism provides favorable conditions for ore deposition (e.g., Bissig et al., 2002; Richards, 2013). Recently, a series of Pb-Zn (Ag-Cu) deposits were discovered in the western GRAZ (Ji et al., 2012, 2014; Tang et al., 2016; Ding et al., 2017; Zhou et al., 2017, 2020). Yet, their structural settings are still unclear because of the scarcity of data. For instance, although vital for understanding the structural evolution and metallogeny of the GRAZ, the thrusting polarity of the LMF is variously interpreted as north or south vergent based on observations at different locations (Murphy et al., 1997; Kapp et al., 2007a). Nevertheless, limited data on the temporal and spatial relations between the LVS and LMF hampered further discussion on their control on the mineralization (Tang et al., 2016). In addition, how these structures control the deposit-scale fluid migration, redistribution and localization still await further investigation.

The Narusongduo Pb-Zn deposit displays obvious spatial association with the regional thrust-fold system and the Linzizong volcanic edifice (Ji et al., 2012, 2014; Ji, 2013), comparable with several economically significant deposits worldwide (e.g., Redwood, 1987; Cunningham et al., 1994; Milési et al., 1999; Klemm et al., 2008). Previous studies focused on ore geology, geochemistry and geochronology (Ji et al., 2012, 2014; Ji, 2013; Yang et al., 2015b; Gong et al., 2019; Zhou et al., 2020), whilst its structural setting is still largely unknown. In this study, we conducted (1) geological mapping and structural analyses to reveal the structural frame of the Narusongduo region; (2) field and microscopic observations to investigate the characteristics of the fracture and void systems and their controls on the mineralization, and present (3) a discussion on the possible mineralization model with the newly obtained structural and zircon U-Pb chronological data. They provide new insight into the structural controls on Pb-Zn mineralization in the Gangdese *retro*-arc zone. This contribution also sheds new light on our understanding of the generation of ore deposits in a compressional deformed site affected by intensive volcanism.

2. Geological background

It is widely accepted that the Tibetan Plateau is a tectonic collage composed of several east-west trending allochthonous blocks that accreted to the southern margin of Eurasia since the early Paleozoic (Allègre et al., 1984; Dewey et al., 1988; Yin and Harrison, 2000). The Lhasa terrane delineated by the Indus-Yarlung suture in the south and the Bangong-Nujiang suture in the north is the southern edge of the Eurasia continent (Fig. 1a; Zhu et al., 2009, 2011, 2019; Pan et al., 2012; Liu et al., 2019). Based on the distribution of crystalline rocks, volcano-sedimentary covers, and major tectonic boundaries, the Lhasa terrane is subdivided into the northern, central, and southern sub-terrane by several E-W striking fault zones or mélange belts (Fig. 1b; Pan et al., 2012; Liu et al., 2019). The Narusongduo (NRSD) region straddles the boundary between the southern and central Lhasa sub-terrane and is truncated by the Luobadui-Milashan fault zone (LMF) (Fig. 1c).

The northern Lhasa subterrane comprises minor Triassic sedimentary rocks, Jurassic-Cretaceous sedimentary strata, and abundant Cretaceous volcanic rocks. The eruptive ages of the volcanic sequence are constrained between ca. 130 and 110 Ma by zircon U-Pb dating (Zhu et al., 2011). A Cretaceous batholithic complex composed of granodiorites, diorites, and mafic dykes is exposed along the northern Lhasa sub-

terrane (Pan et al., 2012; Zhu et al., 2013; Liu et al., 2019). Ages obtained by sericite Ar-Ar and zircon U-Pb methods indicate that they were emplaced during ca. 140–110 Ma (Kapp et al., 2007b; Zhu et al., 2011, 2016; Haider et al., 2013; Volkmer et al., 2014). The igneous rocks are either described as products of the northward subduction of the Neo-Tethyan oceanic plate (Kapp et al., 2005, 2007b) or alternatively related to the southward subduction of the Bangong-Nujiang Ocean lithosphere (Zhu et al., 2016).

The central Lhasa subterrane is considered as a microcontinent with a Precambrian basement that underwent multi-stage metamorphism during the Neoproterozoic, late Triassic, and Cenozoic (Zhu et al., 2011). Early Paleozoic carbonate rocks, Carboniferous to Permian meta-sedimentary rocks, and Mesozoic volcano-sedimentary sequences unconformably overlie the crystalline basement. Mesozoic plutons that were emplaced between ~ 215 Ma and ~ 95 Ma discretely extend for ca. 1200 km (Pan et al., 2012; Liu et al., 2019).

The southern Lhasa subterrane is characterized by composite intrusive rocks that mainly formed from ca. 210 Ma to 10 Ma (Zhu et al., 2015, 2017; Wang et al., 2020) and eruptive rocks including the Jurassic Yeba Formation, Jurassic-Cretaceous Sangri Group, and Paleogene Linzizong volcanic succession (LVS; Mo et al., 2005, 2008; Zhong et al., 2013; Zhu et al., 2015, 2019; Ma et al., 2017b). The magmatic rocks that formed since 140 Ma in the southern Lhasa terrane are designated as the Gangdese arc and thought to have formed during the northward subduction of the Neo-Tethyan oceanic slab and the ensuing India-Asia collision (Kapp et al., 2007a; Ding et al., 2014; Zhu et al., 2019). The massive Cretaceous-Paleogene Gangdese batholiths mainly consist of granites, granodiorites, and diorites (Mo et al., 2005; Zhu et al., 2011). The LVS is exposed along the boundary of the southern and central Lhasa sub-terrane (Mo et al., 2008). Detailed stratigraphic studies on the LVS near the Linzhou basin divided the volcanic successions into the Dianzhong, Nianbo, and Pana Formations from bottom to top (Liu, 1993; Dong et al., 2005). The reported eruptive ages of the LVS range from ~ 69 Ma to ~ 43 Ma (He et al., 2007; Lee et al., 2009, 2012; Zhu et al., 2015, 2019; Liu et al., 2018). In the eastern Gangdese, the weakly deformed LVS in the Linzhou region unconformably overlies the strongly folded Mesozoic clastic rocks. Timing of the deformation is constrained at ~ 72–69 Ma by the youngest dated volcanic rocks of the Cretaceous strata (Sun et al., 2012) and the oldest zircon U-Pb age obtained from the base of the overlying Dianzhong formation (Zhu et al., 2017).

The E-W trending Luobadui-Milashan fault (Fig. 1b) between the central and southern Lhasa sub-terrane is regarded as part of the Gangdese *retro*-arc thrust system (Kapp et al., 2007a) or as a *retro*-arc fault-uplift zone (Pan et al., 2012). Previous investigations on the eastern Gangdese imply that the Gangdese *retro*-arc zone is a propagative northward thrust system active during the late Cretaceous to Eocene (Kapp et al., 2007a; Pan et al., 2012; Kapp and DeCelles, 2019). These E-W trending thrusts dip to the south and generally juxtapose the Carboniferous-Permian strata above the Mesozoic and younger rocks (Pullen et al., 2008). The LMF in the eastern Gangdese, however, is represented by a series of N-dipping thrust nappes (Kapp et al., 2007a). Some authors interpreted this structure as a folded N-directed thrust belt involved in the evolution of the so-called Lhasa-Linzhou ramp anticline (Kapp et al., 2007a; Pullen et al., 2008).

The LMF to the west of the Nyenchen Tanglha range was less investigated, and its geometric and kinematic features are not clear. For example, it has been argued that the LMF to the south of Cuoqin county juxtaposed the Paleozoic units southwardly over the Jurassic-Cretaceous sequences (Murphy et al., 1997). Some geologists thus proposed that the LMF, along with the south-dipping Gar-Lunggar-Comai Fault (GLCF), form a fan-shaped pop-up structure (Murphy et al., 1997). In contrast, others suggested that the western segment of the LMF was formed by north-vergent thrusting and then locally folded and reversed (Kapp et al., 2003, 2007a). In addition, recent structural and seismic studies demonstrate that the Gangdese magmatic belt in the Xigaze-Xietongmen

region is dominated by north-vergent folding and thrusting, which differs from the proposed structural model for its eastern segment (Guo et al., 2018; Liu et al., 2019; Yang et al., 2021). In this case, a question emerges as to how the LMF in the Narusongduo area was deformed.

The Gangdese magmatic arc hosts numerous porphyry copper polymetallic deposits and is known as the Gangdese porphyry copper belt, constituting a principal part of the Tethyan metallogenic domain (Richards, 2009, 2015; Tang et al., 2010; Zheng et al., 2010, 2014; Zhong et al., 2012; Hou and Zhang, 2015; Hou et al., 2015; Yang et al., 2015a; Lang et al., 2019). Recently, a series of Pb–Zn (Ag–Cu) deposits were explored in the Gangdese retro-arc zone (Fig. 1b, c) and are described as a part of the Gangdese retro-arc Pb–Zn–Ag–Cu metallogenic belt (Wang et al., 2010; Ji et al., 2012; Tang et al., 2016; Ding et al., 2017; Fu et al., 2017; Ma et al., 2017a; Zhou et al., 2017, 2020). This belt is near parallel to the Gangdese porphyry copper belt and can be subdivided into eastern and western segments by the NNE–SSW striking Nyenchen Tanglha range. The deposits in the eastern part (Yaguila, Mengya'a, Longmala, and Lietinggang deposits) are generally hosted in carbonate rocks, with ore-forming ages ranging from ~ 62 Ma to ~ 42 Ma (Wang et al., 2010; Gao et al., 2011; Fu et al., 2014, 2015; Yang et al., 2014; Ma et al., 2017a). The published evidence indicates that these hydrothermal deposits were commonly controlled by thrust-fold systems (Tang et al., 2014; Wang et al., 2015). In contrast, the major deposits (e.g., Sinongduo, Narusongduo, and Zexue deposits) in the western segment are hosted both in the carbonate strata and the LVS (Ji et al., 2012; Li et al., 2019a; Guo et al., 2020b). Available ore-forming ages in the western GRAZ range from ~ 65 Ma to ~ 55 Ma (Ji et al., 2014; Ke et al., 2017; Li et al., 2019a), highly comparable with the duration of the Linzizong volcanism. In addition, several deposits are reported to be controlled by the volcanic structures and related to the brecciation of the host rocks (Ji et al., 2014; Li et al., 2019a).

3. Geology of the Narusongduo region

We carried out geological mapping in the Narusongduo region

(Fig. 1c) and structural analysis along a ca. 30 km north–south section covering major lithological units and significant structures (Fig. 2). In the following paragraphs, we first briefly elaborate on the lithologies, then describe the thrust-fold system and volcanic structures in this region.

3.1. Map units

Map units in the Narusongduo region range in age from the late Carboniferous to Quaternary. The oldest rocks in the study area are the late Carboniferous–early Permian *meta*-sedimentary rocks known as the Angjie or Laga Formation (Figs. 1c, 2 and 3). This unit reaches over 100 m in thickness and mainly consists of gray and dark gray *meta*-sandstone and slate with minor thin carbonate interlayers (Liu et al., 2019). The clastic rocks contain lithic fragments and quartz and feldspar grains, with a fine interstitial matrix and cemented by clay minerals (Liu et al., 2019). These Paleozoic strata are highly deformed and occasionally metamorphosed (Fig. 4a–b). The argillaceous cement is commonly transformed into sericite, while the quartz grains are generally recrystallized (Liu et al., 2019). The foliations and stretching lineations are defined by the aligned planar and elongated minerals within the rocks (Fig. 4c).

These clastic strata are overlain by over 300 m thick mid-Permian carbonate strata with siltstone interlayers (C.G.S., 2019). These light gray ridge-forming fine-grained carbonate rocks are characterized by massive structures and generally deformed (Fig. 5a–c). In addition, the carbonate rocks are locally recrystallized and infilled by calcite veinlets (Fig. 4d). The siltstone interlayers are also highly deformed and fractured, with visible sericitization and quartz recrystallization (Shi et al., 2016).

The Paleozoic rocks are unconformably covered by the Paleogene volcanic succession assigned to the Dianzhong Formation and minor Nianbo Formation (Fig. 4e–f). These volcanic-clastic successions are widely exposed in the Narusongduo region with up to 1000 m thickness (Shi et al., 2016). Several lenticular conglomerate layers can be

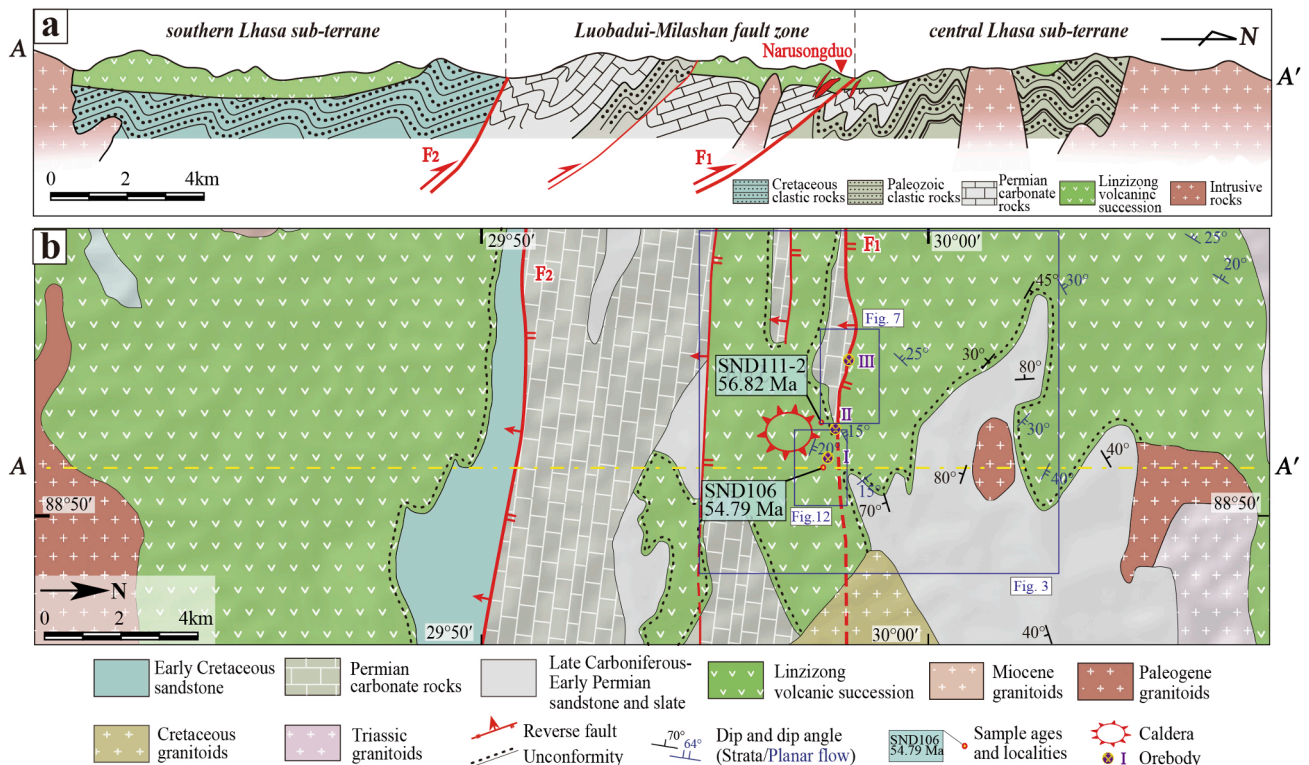


Fig. 2. Cross-section (a) and structural map (b) of the Narusongduo region. The dashed line (AA') on the structural map shows the location of the cross-section.

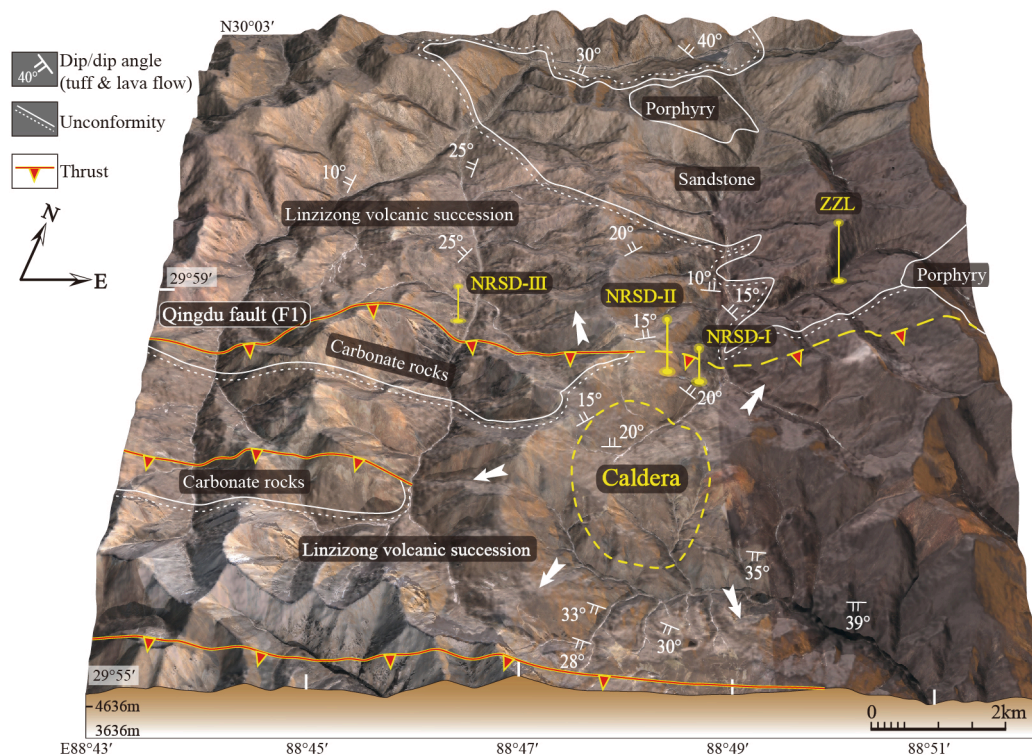


Fig. 3. Perspective structural and topographic features of the Narusongduo ore deposit. The satellite image was taken from Google Earth Pro.

identified at the bottom of the LVS (Fig. 4e; Shi et al., 2016). Previous studies and our geological mapping distinguished four eruptive cycles within the region (Shi et al., 2016). Each cycle could be further divided into sedimentary and volcanic packages. The sedimentary packages consist of fluvial sequences with pyroclastic intercalations. The fluvial beds are mainly composed of sandstone, siltstone and tuff, while mudstone and cherts are also recognized (C.G.S., 2019). The clastic rocks contain poorly to moderately sorted pyroclastic and terrigenous grains filled with interstitial detritus and cemented by calcareous and argillaceous materials (Shi et al., 2016). The volcanic units are generally made up of volcanic lava flows with pyroclastic interlayers. The eruptive rocks are mostly andesitic, dacitic, and rhyolitic in composition and reddish, brown, and white in color. They display porphyry texture featured by feldspar and quartz phenocrysts and lithic fragments embedded in a groundmass composed of glass, fine-grained felsic minerals, and vitric pyroclasts. (Fig. 4h-i; Shi et al., 2016).

3.2. Thrust-fold system

The LMF in the Narusongduo region is represented by several sub-parallel south-dipping thrusts within an E-W trending fault zone whose width varies between 5 and 7 km (Figs. 2, 3, 5a-c; C.G.S., 2019). In the northern margin of the thrust zone, strongly deformed Permian carbonate rocks thrust northwards on the Linzizong volcanic rocks along the south-dipping Qingdu fault (F1). The southern margin of the fault zone is marked by the south-dipping Mainong thrust (F2), which juxtaposes strongly folded Cretaceous clastic rocks in the hanging wall against Permian carbonate rocks in the footwall (Fig. 2). The rock slice sandwiched between these two significant faults, is dominantly composed of fossil-bearing Permian carbonate rocks and minor upper Carboniferous-lower Permian slate (Fig. 2). These Paleozoic units are strongly folded with axial planes dipping to the south (Fig. 5a-b), and unconformably overlain by the weakly deformed LVS (Fig. 5d). Two south-dipping reverse faults extend discontinuously within the LMF between the faults F1 and F2 (Figs. 2, 3, 5c). The northern one juxtaposes the Carboniferous-Permian meta-clastic and carbonate rocks

northwards against the Paleogene LVS. In contrast, the southern south-dipping thrust cuts both the Paleozoic sequences and the LVS. These thrusts are considered as part of the imbricate structure within the LMF (Fig. 1c).

To the north of F1, the outcrops of the Paleozoic strata are made up of meta clastic rocks, while Permian carbonate rocks are also recorded by the drill core data from the footwall of fault F1 (Shi et al., 2016). The Paleozoic sequences were deformed into several E-W trending tight folds with shallowly plunging hinges (Fig. 5e). The geometric features of the deformed strata include recumbent isoclinal and box folds (C.G.S., 2019). These structures constitute an anticlinorium with an axial plane dipping steeply to the south and wavelengths up to 8 km (Fig. 2). The tightly folded Paleozoic sequence is unconformably overlain by the LVS composed of medium to thick-bedded felsic lava and tuffaceous rocks (Fig. 5f). The LVS was involved in the fault-related folds in a 1 to 2 km wide E-W trending zone right to the north of F1 (Fig. 5a-b). In comparison, the volcanic rocks further to the north are nearly undeformed (Fig. 6a-b). This spatial structural trend indicates propagative deformation during the lifespan of Linzizong volcanism. At the northern end of the cross-section and the core of the anticlinorium, the Paleozoic clastic rocks were intruded by Triassic and Paleogene granitoids (Fig. 2).

3.3. Volcanic-related structures

The LVS within the LMF covers a region with E-W length of over 20 km and N-S width of 2–6 km and sporadically overlies the thrust faults within the LMF (Fig. 1c). The weakly deformed volcanic succession comprises rhyolites, dacites and minor andesites. Eruptive structures, such as lava flows, diatremes, and volcanic pipes are well preserved (Fig. 6a-d). The felsic lava flows are ca. 0.5 to 15 m in thickness, and unconformably covered by later volcanic sequences, implying multi-phase volcanism (Fig. 6a-d). A caldera was identified in the Narusongduo region based on the radial dips of the lava flows away from the caldera and ring-shaped geomorphological features (Fig. 1c). The volcanic rocks are crosscut by voluminous steep fractures that are subdivided into the radial and ring-shaped groups according to their spatial

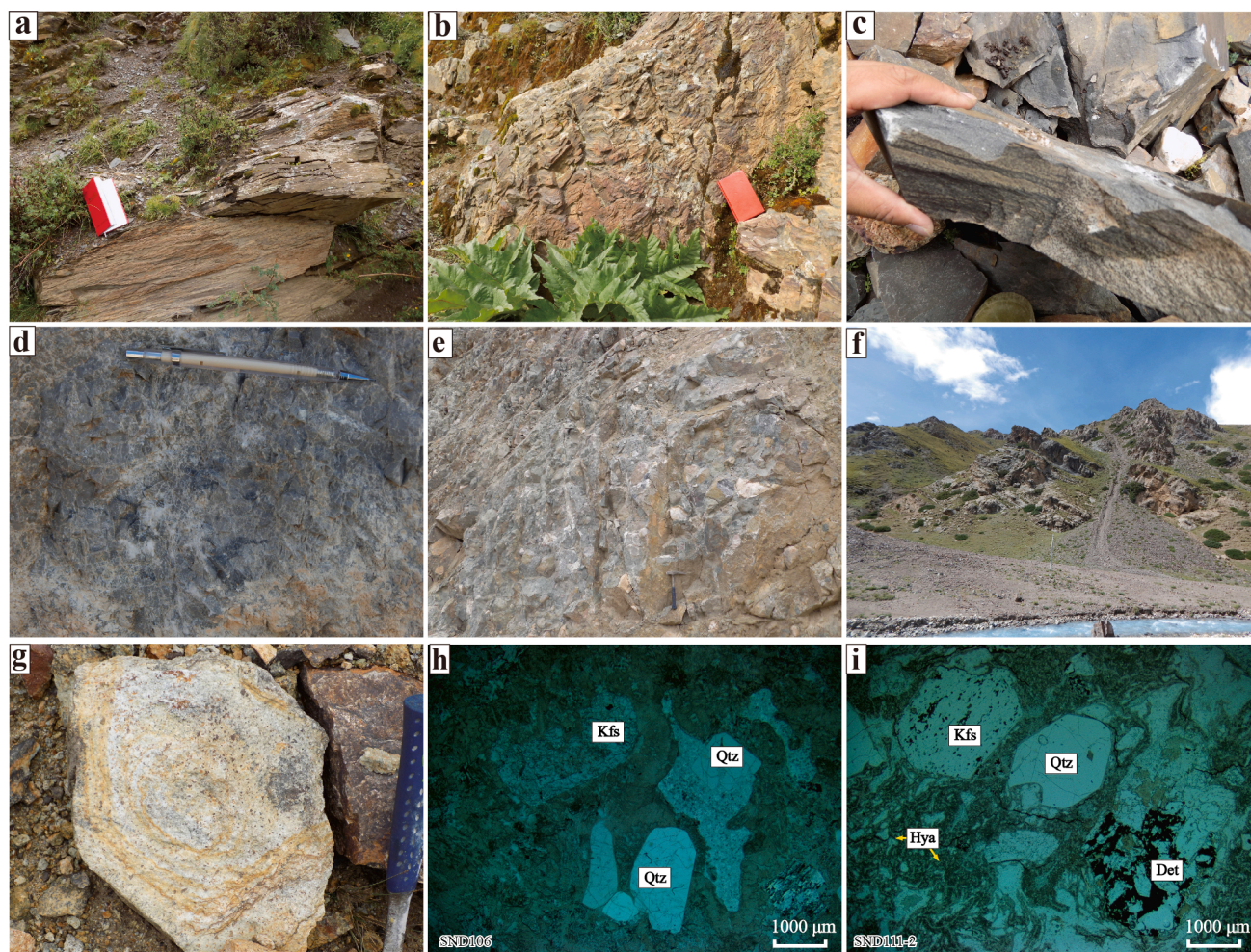


Fig. 4. Field and thin section photos of the major lithological units exposed in the Narusongduo region. (a) Slaty cleavages in the Carboniferous-Permian metaclastic rocks; (b) Folded foliations in the Paleozoic metaclastic rocks; (c) Oriented felsic minerals in the Paleozoic slates; (d) Slightly recrystallized carbonate rocks crosscut by calcite veinlets; (e) Conglomerate layers at the bottom of the LVS; (f) Gently dipping Linzizong volcanic succession; (g) Porphyritic rhyolite collected near the Narusongduo caldera; (h) Quartz and feldspar phenocrysts in the non-deformed rhyolite; (i) Feldspar, quartz, lithic fragments and vitric pyroclasts in the non-deformed rhyolite.

relations to the lava flows (Figs. 3 and 6).

Several volcanic pipes with elliptical cylindrical shapes are noticed on the northern slope of the Narusongduo caldera (Fig. 12). These pipes consist of fine-grained porphyries, lavas, and minor pyroclastic rocks and are interpreted as volcanic plugs. Their borders are usually characterized by steep sheeted fractures (Fig. 12a and 13). Most of the plugs are characterized by brecciation, alteration, and formation of secondary minerals, indicating fluid influx after the solidification of the rocks (Ji et al., 2012).

The LVS to the north of the F1 fault comprises dacitic to rhyolitic volcanic and pyroclastic rocks attributed to the Dianzhong Formation. This unit is unconformably overlain by the Nianbo Formation represented by minor reddish felsic volcanic rocks, and tuffaceous sandstone has also been noticed (C.G.S., 2002; Ding, 2017). These volcanic rocks are locally involved in the thrust-fold system and underlain by the anticlinorium composed of Paleozoic sequences (Fig. 2). The volcanic structures exposed in the northern section include lava flows dipping mildly to the east and steeply dipping fractures with E-W or NNE-NNW strike (Fig. 2). These structures are thought to be genetically linked to the Sinongduo caldera further to the west (Fig. 1c).

4. Structural controls on mineralization

Three main orebodies are identified in the Narusongduo ore deposit,

the orebodies I, II, III (Figs. 1 and 2). Orebody I is hosted in the LVS and orebody II occurs near the unconformity between the LVS and the Permian carbonate rocks (Fig. 3). Both orebodies are closely related to volcanic structures and breccia bodies. Orebody III is located at the footwall of F1 and was mainly hosted by Permian carbonate rocks beneath the LVS cover (Figs. 7–9). The F1 fault and fault-related folds are the primary structures controlling the mineralization in orebody III (Figs. 7–10; Yang et al., 2015b).

4.1. Structural discontinuities within the thrust-fold system

The nearly E-W trending F1 fault zone comprises a 10–20 m wide lenticular breccia zone (Fig. 10a–c) and a wider damage zone (Fig. 10a, g–i). The rocks in the lenticular breccia zone were broken into several lenticular “crackle breccias” (Woodcock and Mort, 2008) along the network of joints (Fig. 10b–c). The long axes of the brecciated rock occurrences are largely parallel to the dip of the fault plane, and no obvious rotation was observed (Fig. 10c). The fractures between the fragments are filled by carbonate minerals and sulfides that are concentrated in dilational jogs (Fig. 10d). These “boudinage” structures may have formed by episodic fluid ingress and hydrothermal “self-sealing” of fractures (Cox et al., 2005). The fault plane’s continuous permeable fracture network could have offered a conduit for fluid recharge from deeper reservoirs to higher crustal levels.

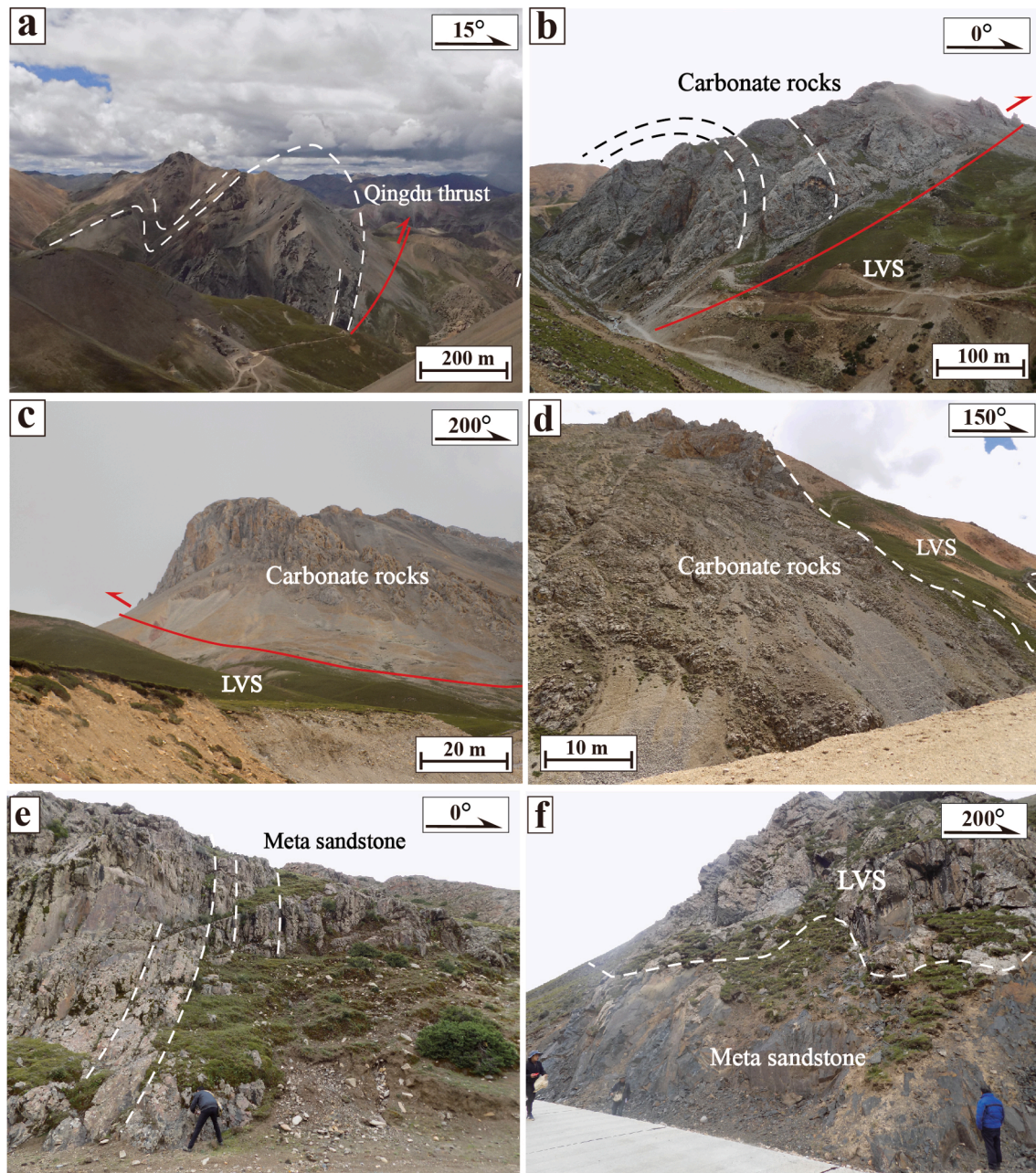


Fig. 5. Field photos of the thrusts and folds in the Narusongduo region: A view of the fracture system associated with the Qingdu (F1) thrust. (a-b) Tightly folded carbonate strata thrust northwardly on the LVS at the Qingdu thrust (F1), note that the carbonate rocks at the hanging wall is covered by the volcanic rocks further to the south; (c) A view of a thrust within the LMF zone to the south of the Narusongduo caldera, note that the ridge-forming carbonate rocks (Xiala Fm.) are thrust northwardly over the LVS; (d) The carbonate rocks in the LMF are unconformably overlain by the LVS; (e) The northern flank of an isoclinal anticline within the Paleozoic metasandstone to the north of the Qingdu thrust; (f) Unconformity between the Paleozoic sandstone and the overlying LVS.

The damage zone contains centimeter- to meter-sized rock blocks separated by well-developed fractures (Fig. 10a). Although small-scale folds were occasionally observed, most original beddings were unrecognizable due to substantial shortening and deformation. The damage zone of F1 shows a variable N-S width between ca. 20 to 100 m. There is no distinct boundary between the damage zone and the fault-related fold system.

The Paleozoic carbonate rocks exposed at the hanging wall of F1 are strongly folded and penetratively deformed, whereas drilling at the footwall reveals that the carbonate rocks are also highly strained (Figs. 8 and 9). The Paleozoic sequences were deformed into isoclinal or reverse folds with south-dipping axial planes (Fig. 5a-c) and voluminous joints and tensional fractures are well developed (Fig. 10e-f). The conjugate

shear joints observed in the field can be subdivided into two groups based on their occurrences and spatial relations to the beddings. Sub-vertical joints of the first group exhibit NNE-SSW and NNW-SSE strike and probably formed at the early stage of folding in response to the N-S compression. They display clear vertical continuity and provide structural control on the N-S trending river valleys (Fig. 10e-f). The second group of joints with strikes sub-parallel to the fold axial plane was observed in the folds' N-S cross-sections. This kind of joints occasionally evolved into low displacement reverse faults (Figs. 5a-b and 10e-f). Moreover, tensional fractures with E-W strikes developed at the outer limbs of the folds (Fig. 10e-f). These fractures along with the bedding-parallel slip dilations form up composite fracture systems with considerable vertical extension and abundant terminal splays.

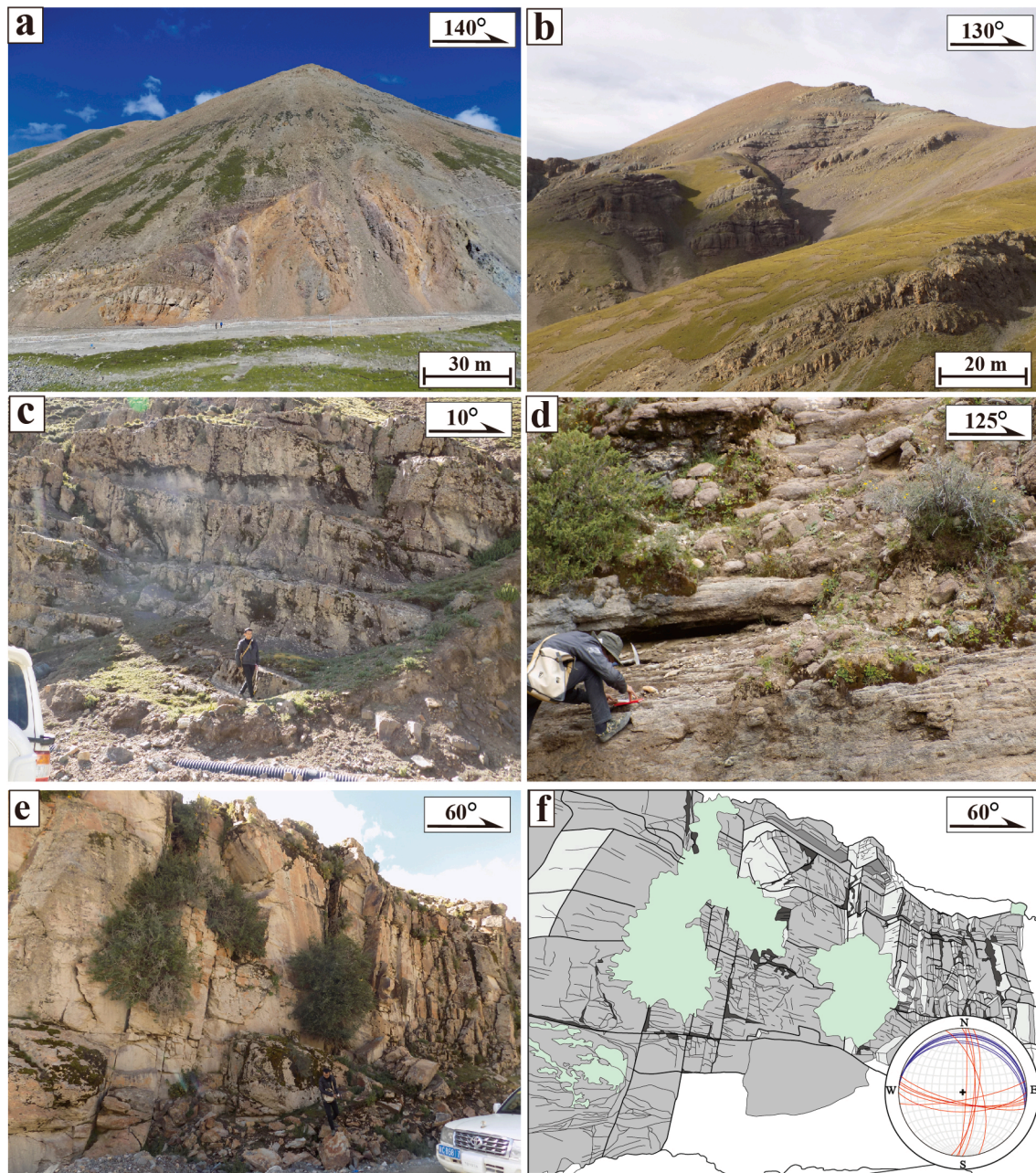


Fig. 6. Field photos of the volcanic structures in the Narusongduo region: (a) Lava flows near a diatreme at the northern side of the caldera; (b) A distant view of the volcanic succession dipping gently to the north at the northern side of the Narusongduo caldera; (c) Thick lava flows dipping gently to the north; (d) Pyroclastic sequences to the northwest of the caldera; (e-f) An outcrop view of the lava flow that shows its internal structures. As shown by the equal-area lower hemisphere projection plot, the steeply dipping joints (red arcs) could be subdivided into two groups, one with approximately E-W strikes and another with N-S strikes. The lava flows (blue arcs) dip gently to the NNE.

The Linzizong volcanic rocks at the hanging wall were generally undeformed and variably weathered (Figs. 5d and 10e-f). The LVS within the fault-related fold zone at the footwall is locally folded but less fractured in comparison with the underlying carbonate strata (Fig. 2).

4.2. Alteration and mineralization within the F1 fault zone

The fractures within the fault-fold zone controlled the distribution of the mineralization. Nevertheless, other structural surfaces such as the beddings and unconformity surface also provide space for ore deposition (Figs. 7–9; Shi et al., 2016). In addition, drill core data records discrete mineralized sections within the LVS overlying the deformed Paleozoic strata (Figs. 8 and 9). Mineralization in the lenticular breccia zone is

represented by discontinuous bands and cement between the rock blocks. The occurrence of the sulfide ores in this zone was controlled by geometric irregularities such as jogs and fracture intersections. As a result, the ore assemblages usually wedge out along the fault dip (Fig. 10d). As to the damage zones and folds near F1, the fracture networks of the thrust-fold system provide first-order control on the mineralization. The mineralization is well developed along the fracture network and forms a complex stockwork (Figs. 10g-i and 11). Calcite, quartz, and sulfides such as sphalerite, galena, pyrite, and chalcopyrite are among the minerals present in the veins (Fig. 11).

Hydrothermal alteration can be recognized at the boundaries between the veins and country rocks (Figs. 7–9). The carbonate rocks are characterized by skarnization and marbleization, while the volcanic

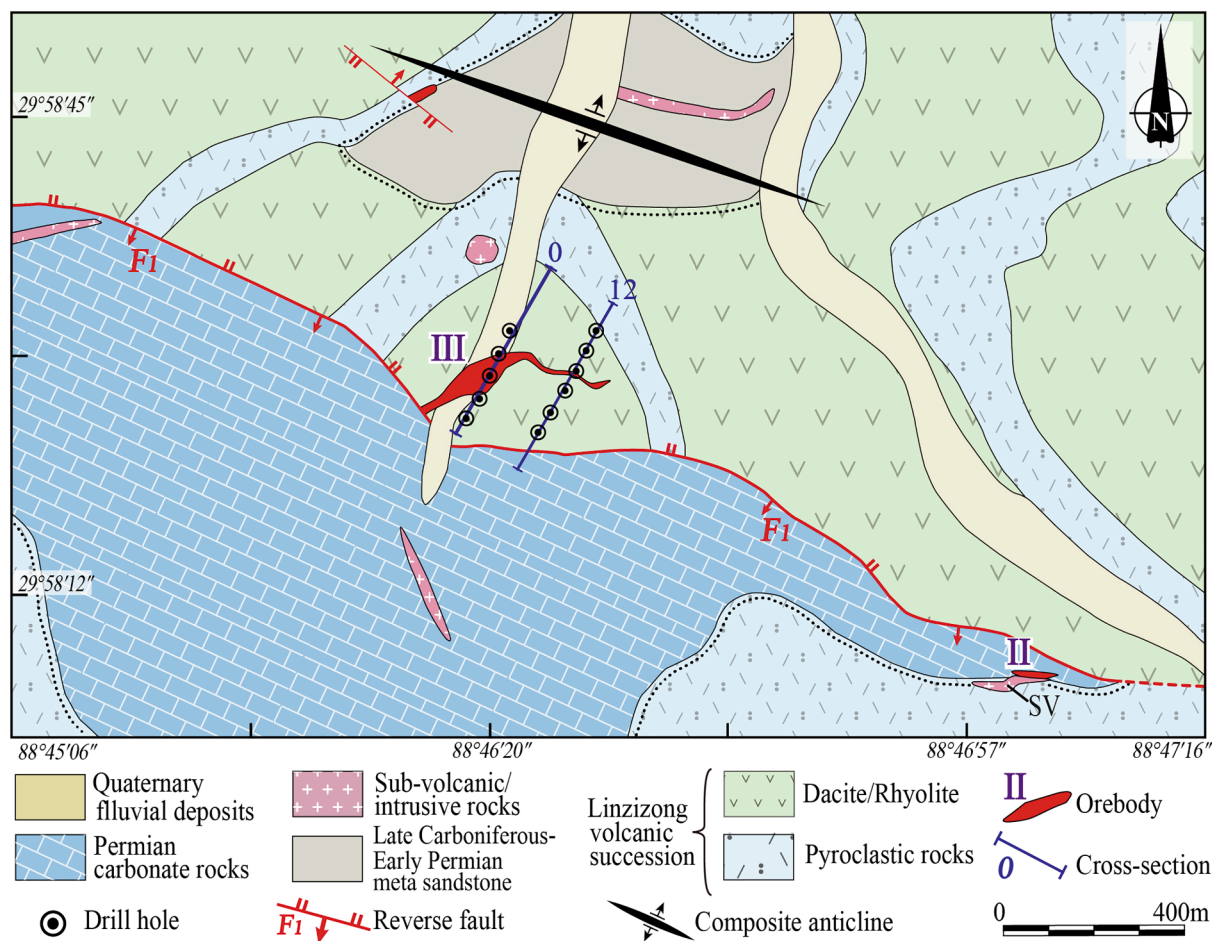


Fig. 7. Geological map of the No. III orebody in the Narusongduo ore deposit (modified from Shi et al., 2016).

covers were affected by chloritization, epidotization and sericitization (Shi et al., 2016). Microscopic observations reveal that the hydrothermal minerals occur in fractures and dilated zones with no preferred orientations (Fig. 11). Typical features of hydraulic fracturing, such as splayed veinlets and jigsaw boundaries between fragments, are visible (Fig. 11). In addition, carbonate-rich country rocks and earlier precipitated minerals are commonly fractured and filled by later-stage calcite, quartz and sulfides, suggesting that multi-stage hydraulic fracturing and fluid influxes formed the ore deposition (Fig. 11g-i).

4.3. Volcanic structures' control on the orebodies

Orebody I is hosted in several breccia pipes and dykes at the northern slope of the Narusongduo caldera. The breccia bodies are composed of rhyolitic rocks and porphyritic subvolcanic rocks and are structurally controlled by the steeply dipping radial and ring-shaped fractures related to the Sinongduo caldera.

The No. I-1 breccia pipe is well exposed by the mining operation (Fig. 12). The surface exposure of the breccia pipe is elliptical with an E-W striking long axis of 112–120 m and an N-S maximum width of 45 m. The northern border of the pipe is marked by several sheeted fractures that dip steeply to the south, and some of them evolved into low displacement normal faults (Fig. 13a-b). Drilling data reveal that the breccia pipe dips to the south with dip angles between 70°–80° and is more than 300 m in depth (Fig. 12c; Shi et al., 2016).

The volcanic rocks near the breccia pipe are intensely fractured. The ring-shaped and radial fractures separate the rocks into blocks (Fig. 13c-d). It is noteworthy that the fracture system is connected with the breccia pipe and hosts several breccia dykes with N-S or NNW-SSE

strikes (Fig. 12b; Shi et al., 2016). These minor dykes with lengths of 5–20 m and widths of 0.2–2 m are lithologically similar to the pipe. Brecciation occurred in the pipes and along the fractures in the surrounding volcanic rocks, implying that the brecciation postdates the formation of the fracture system.

The fragmented country rocks and early-stage fluid-related minerals are embedded in and cemented by matrixes composed of sulfides, lithic debris, calcite and quartz. Some of the specimens contain polymictic fragments that possibly underwent milling, mixing, and forceful transportation (Fig. 14a). Nevertheless, some of the shattered wall rock fragments are characterized by triangular-acute angle textures and jigsaw boundaries that are suggestive of in-situ brecciation and mineral infilling (Fig. 14b-i; Taylor, 2009). Sericitization, silicification and kaolinitization were observed in the matrix and at the borders of the fragments (Figs. 14 and 15; Shi et al., 2016).

4.4. Mineralization in the volcanic and subvolcanic rocks

Fluid ingress and ore precipitation are concentrated both in the dilational voids of the breccia pipes and the intersecting zones between the radial and ring-shaped cleavages (Figs. 13-15). Fluid-related alterations such as greisenization, silicification, kaolinitization and chloritization are prevalent in the country rocks (Yang et al., 2015b). Ores hosted in the volcanic and subvolcanic rocks display veined, disseminated and massive structures and were superimposed by multi-stage hydraulic fracturing and fluid injections (Fig. 15). Country rocks and preexisting minerals were cracked, and the fissures were infilled by later-stage minerals (Fig. 15d-f). These features indicate multi-cycle hydrothermal activity and breaching of the fluid pathways.

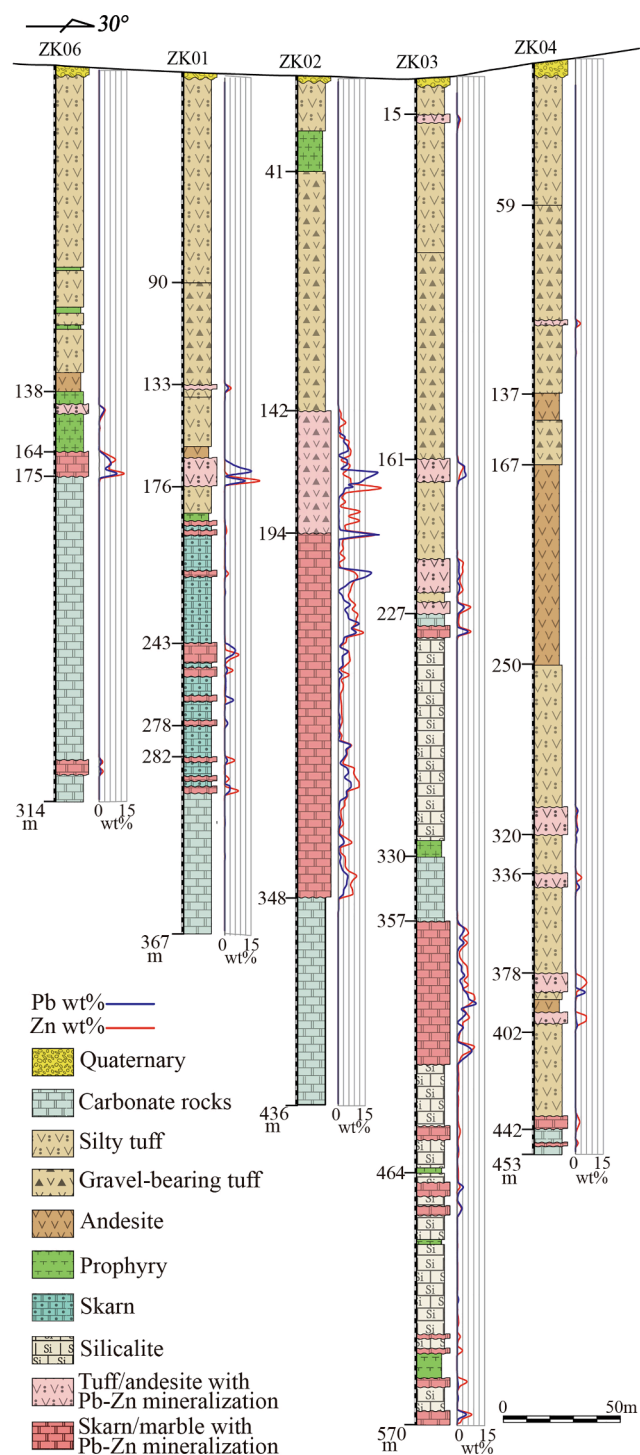


Fig. 8. No. 0 drilling profile of the No. III orebody in the Narusongduo ore deposit (modified from Shi et al., 2016).

Over 20 different ore minerals were identified in the specimens collected from these two orebodies. The economic ore minerals include galena, sphalerite, native silver, chalcophyrite, and tetrahedrite (Ji, 2013). Microscopic observations demonstrate that the sulfide ores infilled the fissures with dilational jogs in the greisenized porphyry country rocks (Fig. 16). Nevertheless, the sulfides are usually shattered and infilled by later-stage minerals (Fig. 16b-f). These micro-structures also point towards multi-cycle brecciation and ore precipitation.

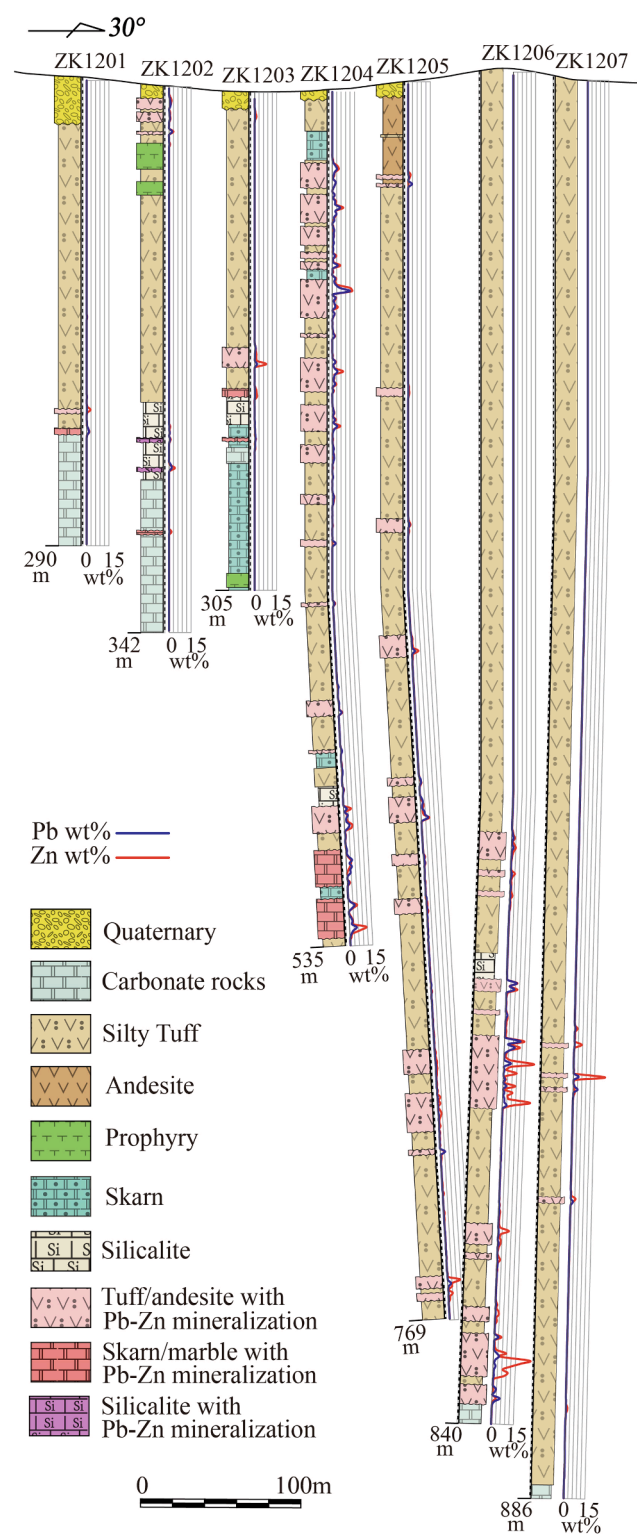


Fig. 9. No. 12 drilling profile of the No. III orebody in the Narusongduo ore deposit (modified from Shi et al., 2016).

5. Zircon LA-ICP-MS U-Pb geochronology

5.1. Samples and methods

Two crystal-rich rhyolite samples were collected from the northern slope of the Narusongduo caldera. To avoid the effect of fluid-present alteration, the collected samples are free of veinlets and metamorphic

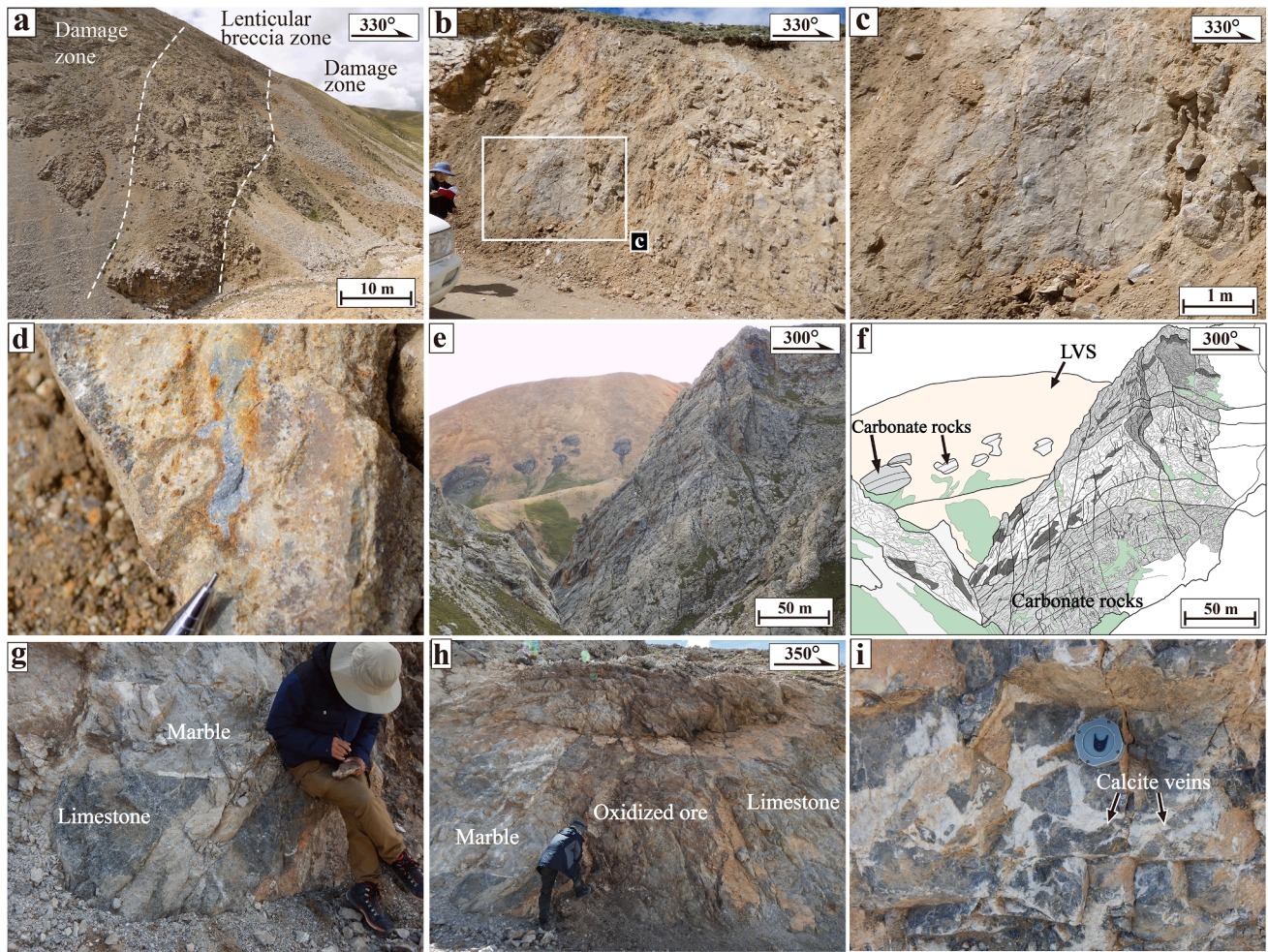


Fig. 10. Photos of the fracture systems and mineralization in the thrust-fold belt. This diagram includes photos shot at several N-S trending valleys crosscutting the thrust-fold belt. (a) A panoramic view of the fault zone of the Qingdu thrust. The fault zone comprises a lenticular breccia zone and a wider damage zone; (b-c) Photos of the breccia zone that marked by two sets of fractures, the asymmetry of the blocks suggests a north-vergent thrusting; (d) Sulfide ores infilled in the dilational jogs within the breccia zone, note that ore vein wedges out along the extension of the fractures; (e-f) A view of multiple sets of fractures in the carbonate rocks at the hanging wall of the Qingdu thrust. Note that the NNE-SSW and NNW-SSE striking fractures control the river valley; (g) Field photo showing the marbleization developed along the conjugate joints within the carbonate rocks; (h) Mineralization and marbleization developed along the steep fracture within the folded carbonate rocks in close proximity to F1; (i) Breccias at the terminal plays of the alteration zones typify the products of hydraulic fracturing.

overprint. Moreover, the samples were taken from the gently dipping volcanic sequences that are not involved in the N-S shortening. These samples display porphyry textures with euhedral to subhedral phenocrysts of feldspar, quartz and lithic fragments, included in a groundmass composed of glass, vitric fragments and fine-grained quartz and feldspar (Fig. 4h-i). An interstitial texture could be observed with the fissures in K-feldspars filled up with secondary quartz and feldspar. The samples are characterized by rhyolitic textures and the phenocrysts are commonly wrapped by quartz ribbons (Fig. 4h-i). However, the grains are randomly oriented with no signs of dynamic recrystallization or crystal distortion, suggesting that they were not subjected to simple shearing deformation.

The samples were crushed to the 200 μm fraction and conventional heavy liquids and magnetic separation was used to separate the heavy and ferromagnetic minerals. The zircon grains were then hand-picked and mounted on epoxy mounts that were polished to expose the internal structures of the grains. Cathodoluminescence (CL) images were taken at Nanjing Hongchuang Geological Service by using a Gatan Mono CL 3 + Fluorescence Spectrometer attached to a Quanta 400 FEG scanning electron microscope.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analyses were conducted at the Analytical Lab of the Tianjin

Center, China Geological Survey by using an Agilent 7900 ICP-MS coupled with a New Wave 213 nm laser ablation system with which a laser beam of 24 μm diameter and 5 Hz frequency was used. The experimental and instrumental procedures were as described by Jackson et al. (2004). The raw data were processed by an in-house software package ICPdataCal version 11.7 (Liu et al., 2013), corrected for common lead (Andersen, 2002), and then visualized and plotted by Isoplot 3.70 (Ludwig, 2008).

5.2. Zircon U-Pb results

Zircon grains from the two aforementioned samples are colorless and transparent (Fig. 17a, c). They have euhedral and narrow shapes with aspect ratios up to 5.0. Their clear oscillatory zoning and homogeneous texture, together with relatively high Th/U ratios suggest an igneous origin (Corfu et al., 2003; Corfu, 2013) (Fig. 17a, c; Table 1). Only one dated grain (No. 09) from sample SND111-2 yielded a Carboniferous apparent age (332.7 ± 5.3 Ma), the rest of the zircons yielded concordant results and consistent $^{206}\text{Pb}/^{238}\text{U}$ apparent ages (SND106: 65–54 Ma; SND111-2: 68–57 Ma). For sample SND106, seven out of twenty-four analyses yielded consistent and concordant apparent ages, and a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 54.6 ± 1.0 Ma (MSWD = 0.31; Fig. 17b) was

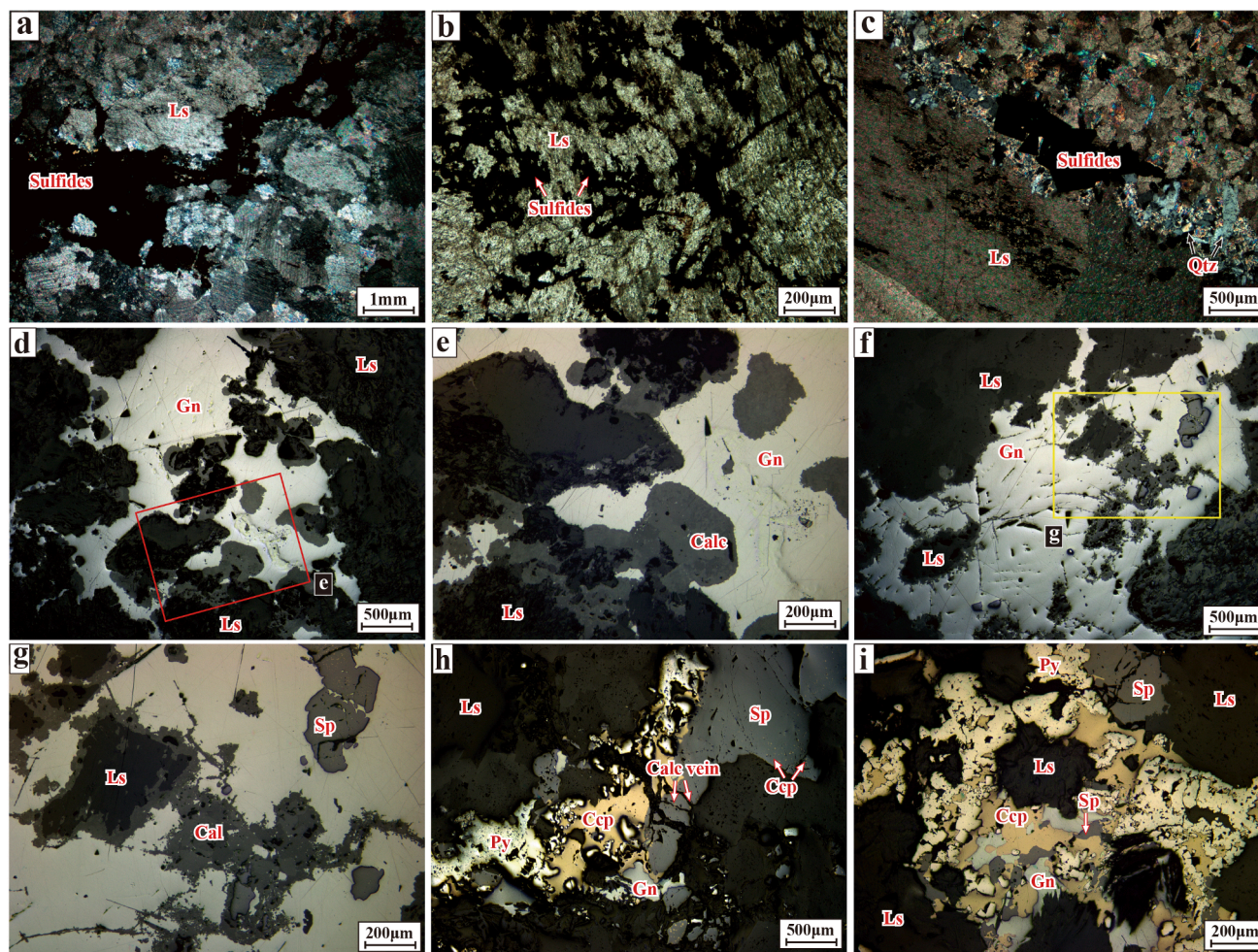


Fig. 11. Photomicrographs of the ores hosted in the carbonate rocks: (a) sulfide minerals (crossed polarizers) infilling the fractures in the carbonate rocks. The jigsaw-fit between the fragments and lithic fragments engulfed by the sulfide minerals are typical of hydraulic fracturing; (b) sulfide infillings in (plane polarizers) the randomly distributed fracture network in an ore-bearing carbonate rock; (c) infilling of sulfide and quartz veins within the cracks of the carbonate wall rock (crossed polarizers); (d-e) two stages of fluid-present fracturing are noticed in a polished section. The first stage is featured by fragments of carbonate wall rocks in a matrix composed of later-stage calcite. During the second stage, the assemblages were further brecciated and infilled by galena; (f-g) multi-stage structural and fluid superimposition in a polished section. The irregularly fractured carbonate wall rocks and sphalerite grains are engulfed by later-stage galena. The assemblages are further cracked and infilled by calcites; (h-i) complex infill overprinting and brecciation within a specimen from the mineralized carbonate rock. The wall rocks have been strongly brecciated and infilled by various types of minerals. It could be noted that the later-stage minerals break through preexisting sulfides. Abbreviations: Calc-calcite, Ccp-Chalcopyrite, Gn-Galena, Ls-Carbonate rocks, Py-Pyrite, Sp-Sphalerite.

calculated. A total of seven zircons from sample SND111-2 yielded consistent apparent ages with a mean age of 57.9 ± 1.0 Ma (MSWD = 0.28; Fig. 17d). Both are interpreted as the eruption ages of the dated rocks.

6. Interpretation and discussion

6.1. Structural evolution in the Narusongduo region

The structural history of the Narusongduo region is still a matter of discussion, primarily due to limited access and structural data. Based on our new data and recently published large-scale geological maps (C.G.S., 2019), it is possible to subdivide the late Mesozoic-Cenozoic structural evolution of the Narusongduo region into two stages.

6.1.1. N-S Crustal shortening prior to the Linzizong volcanism

Regional N-S crustal shortening developed pervasively in the Gangdese *retro*-arc zone (Murphy et al., 1997; Kapp et al., 2007a). It has been proposed that the Gangdese *retro*-arc thrust-fold belt accommodates over 200 km of N-S shortening in the Lhasa terrane (Kapp et al.,

2007a, 2019). Our field mapping shows that the N-S crustal shortening affected the Paleozoic-Mesozoic rocks in the Narusongduo region, causing penetrative deformation. As mentioned, the structural evolution of the Narusongduo region is still a matter of debate (Ji, 2013; Ji et al., 2014; Yang et al., 2015b, 2021; C.G.S., 2019). This debate centers on three correlated issues: (1) the definition of the LMF in this region; (2) the geometry and polarity of the thrust-fold system; and (3) the timing of the main stage of the N-S crustal shortening.

From our mapping in the Narusongduo region and recent publications, it becomes clear that the central Lhasa sub-terrane is characterized by tightly folded and partially foliated Paleozoic sequences that constitute an anticlinorium with south-dipping axial plane (Fig. 1c; C.G.S., 2019; Yang et al., 2021). On the other hand, the southern Lhasa subterrane comprises dominantly composite Mesozoic-Cenozoic intrusions and minor folded Mesozoic strata (C.G.S., 2019; Liu et al., 2019; Yang et al., 2021). Despite the occasional presence of fractures and faults, a regional tectonic discontinuity has yet to be discovered within these sub-terrane. The E-W trending LMF running between these two tectonic units is composed of a stack of imbricate nappes truncated by several southward dipping thrust faults that cut the Paleozoic basement,

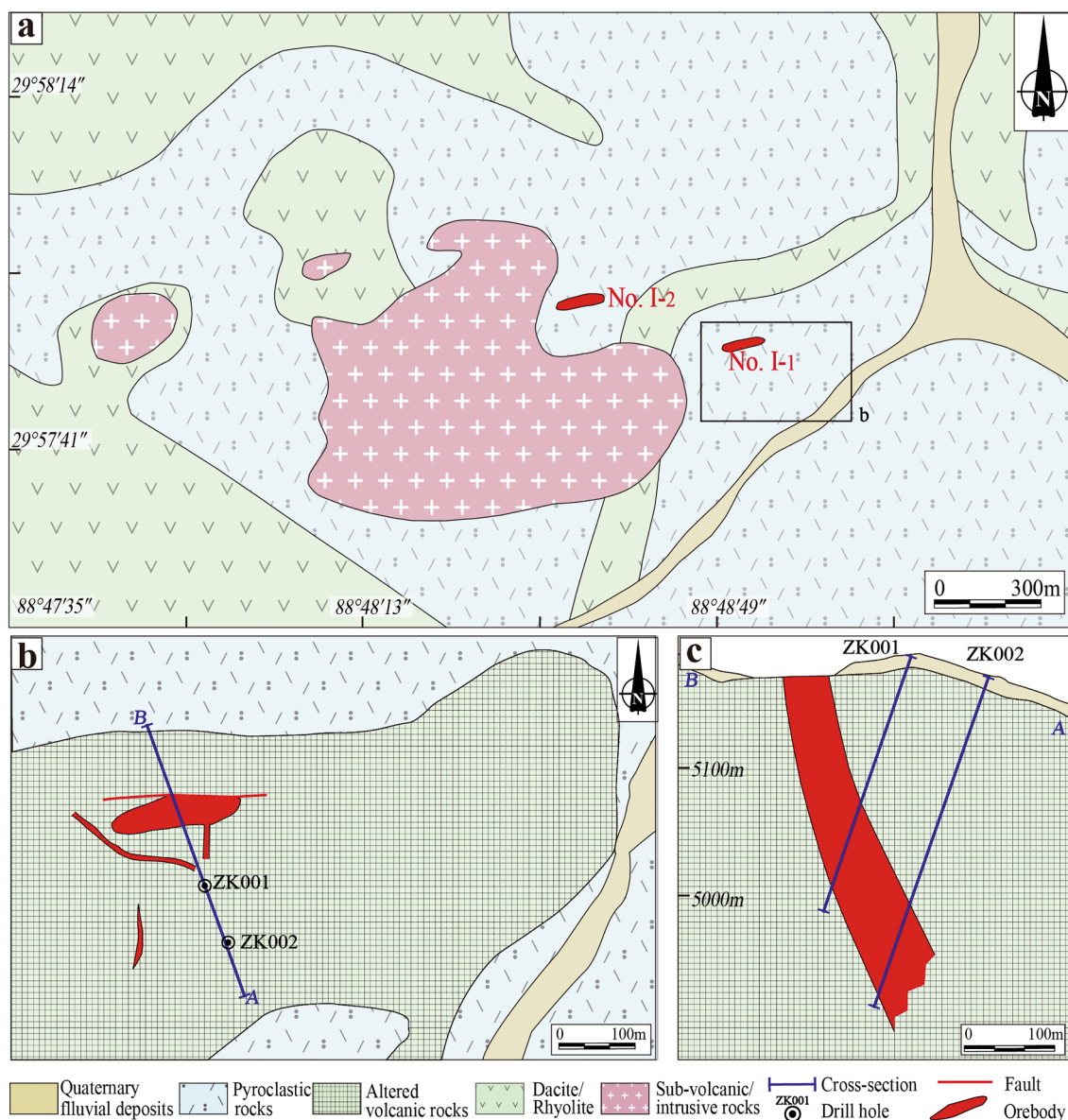


Fig. 12. (a) Geological map of the No. I orebody in the Narusongduo ore deposit; (b) Geological map of the No. I-1 breccia pipe of the orebody I; (c) Cross-section of the No. I-1 breccia pipe, note its elliptical cylindrical shape (modified from Shi et al., 2016).

the LVS cover, and the Mesozoic intrusive rocks. The fault zone is delineated by the Qingdu fault (F1) to the north and the Mainong fault (F2) to the south. They could be traced for over 80 km from west to east (C.G.S., 2019; Liu et al., 2019). Considering these distinct lithological and structural features, we define the imbricate thrust-fold system between the Qingdu and Mainong thrusts as the LMF in the Narusongduo region. The architecture of this segment of the LMF is comparable to its eastern extension to the north of Linzhou city, which comprises a stack of imbricate thrust sheets (Kapp et al., 2007a).

Previous studies suggested that the LMF to the north of Linzhou city thrusts towards the south. These structures were interpreted as folded and reversed N-verging thrusts at the northern flank of a ramp anticline (Kapp et al., 2007a; Pullen et al., 2008). Similar southward thrusting features were also found in the LMF near the Coqin basin further to the west (Murphy et al., 1997). Despite the lack of structural data, it has been inferred that the LMF in between the Coqin and Linzhou regions is characterized by southwards thrusting (Kapp et al., 2007a). Our observations and recent literature, however, reveal that the LMF in the Sinongduo-Narusongduo region is characterized by north-vergent

thrusting and folding. The northward polarity of the thrusts is supported by (1) the asymmetry of the folded strata within the nappes and the foreland; (2) the Paleozoic basement thrusting northwards against the Cenozoic volcanic rocks; and (3) the slickensides and steps on the fault planes indicative of top-to-the-north motion (Yang et al., 2021).

Unlike the intensely deformed Paleozoic-Mesozoic units in the Narusongduo region, the overlying LVS was weakly deformed or even undeformed. In addition, the thrust faults within the LMF are occasionally covered by the LVS (Fig. 1c). The timing of this N-S contraction is thus roughly constrained by contact relations between the Paleozoic strata and overlying LVS. However, precise dating of this event is difficult due to the lack of structural and chronological constraints. In addition, structural reactivation, volcanism, and hydrothermal fluid activity in the study area further hampered direct thermochronological dating (Reiners and Brandon, 2006). It is noteworthy that the LMF to the north of Linzhou city was also covered by weakly deformed LVS. The timing of this deformation event was constrained between 72 and 69 Ma by zircon U-Pb dating (72 Ma) on a volcanic layer in the folded Cretaceous sequences (Sun et al., 2012) and an andesitic layer at the base of the

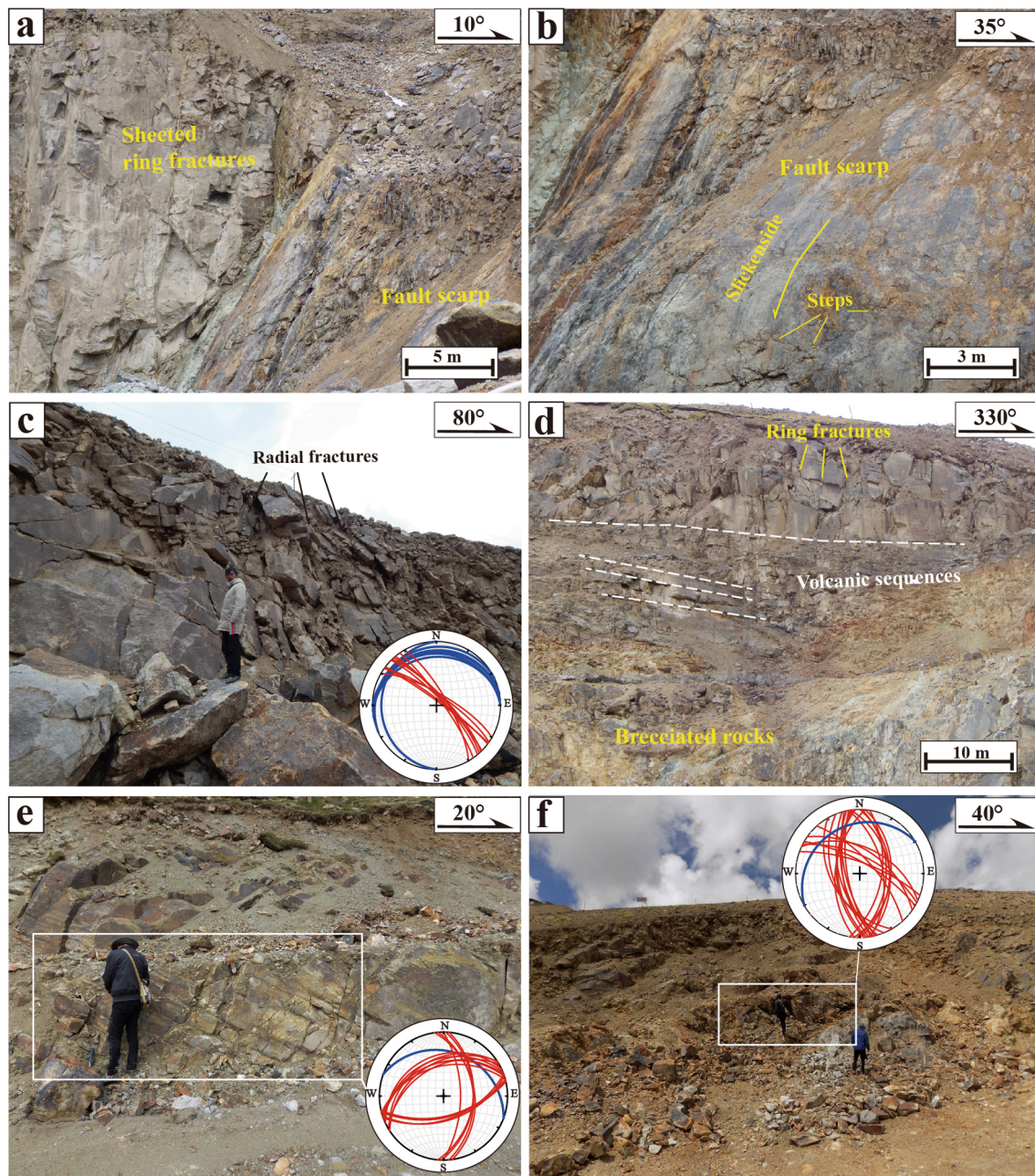


Fig. 13. Photos of the ore-controlling volcanic structures. (a) Marginal sheeted fractures and steep normal fault at the northern border of the No. I-1 breccia pipe; (b) A view of the plane of the normal fault along the northern margin of the No. I-1 breccia pipe, note the slickensides and steps; (c) Intense steep radial fractures crosscutting the volcanic rocks near the breccia pipe; (d) A view of the fractured volcanic succession overlying the brecciated and mineralized rocks; (e-f) Volcanic rocks in the vicinity of orebodies I and II are highly fractured. Equal-area lower hemisphere projection plots show the preferred orientations of lava flows (blue arcs) and fractures (red arcs).

overlying LVS (69 Ma) (Zhu et al., 2017). We take these chronological data from the LMF for reference and tentatively propose that the strong N-S shortening in the Narusongduo region took place during the Cretaceous-early Paleogene.

In summary, the first episode of deformation preserved in the Narusongduo region is characterized by regional N-S crustal shortening during the late Cretaceous-early Paleocene (Fig. 18a). This tectonic event was probably a consequence of the establishment of a Cordilleran-type continental margin at the southern Lhasa terrane (Ding and Lai, 2003; Kapp and DeCelles, 2019).

6.1.2. Linzizong volcanism and propagative tectonic deformation

The Gangdese magmatic arc experienced extensive high-K calc-

alkaline magmatism during ca. 70–44 Ma, producing the massive Gangdese batholith and the LVS (Harris et al., 1986; Mo et al., 2008; Zhu et al., 2009, 2011, 2017, 2019; Liang et al., 2010; Zhang et al., 2010; Ma et al., 2015, 2017c; Yang et al., 2016; Kapp and DeCelles, 2019). In the Narusongduo region, this stage of magmatism is represented by the widely distributed Linzizong volcanic rocks. Previous zircon U-Pb dating results suggest that these eruptions in the Narusongduo region occurred during ca. 66–60 Ma (Ji et al., 2012; Ding, 2017; Ding et al., 2017). Our new zircon U-Pb ages reveal that certain rhyolites in the Narusongduo region erupted later around 58–55 Ma. Considering that the LVS can be subdivided into four eruptive cycles and are interlayered with fluvial sedimentary rocks (Shi et al., 2016), we propose that multi-stage volcanism superimposed the Narusongduo region from the early

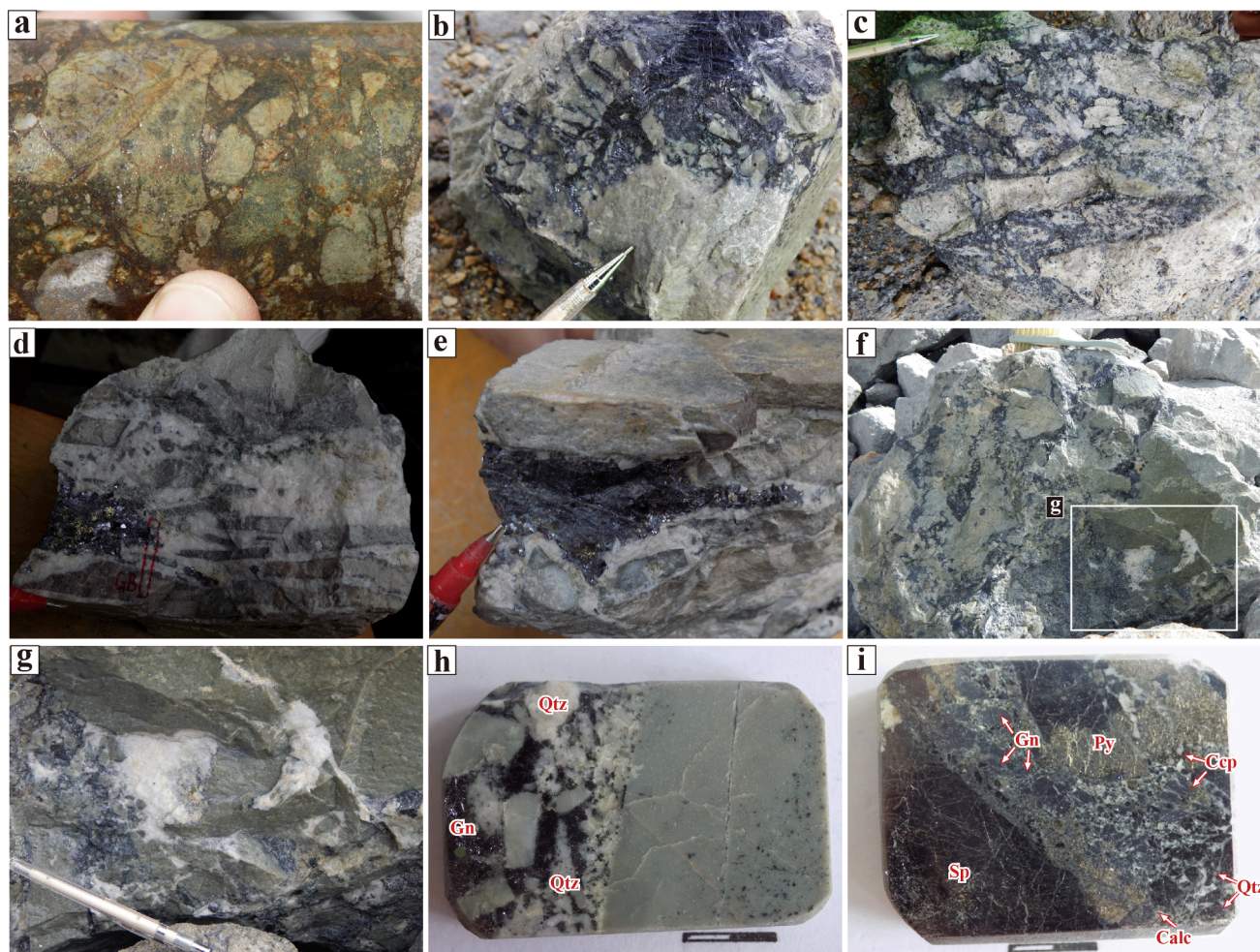


Fig. 14. (a) A close look at the polymict breccia obtained from orebody I at the elevation of ca. 5000 m. The specimen contains differentially rounded and altered fragments with various sizes and origins, and a composite matrix comprising fine groundmass and fluid-related minerals; (b) volcanic rock infilled by sulfides typifies the product of hydraulic fracturing and immediate ore precipitation; (c) photo showing the complex sequential infilled accompanied by fracturing in a brecciated rock. Later-stage sulfide veins form a network developed along the cracks within the wall rocks and the quartz clusters; (d-e) Brecciated porphyritic rocks infilled by quartz and sulfides. The wall rocks fractured into sheeted fragments that are typical of decompressive shock textures; (f-g) photos of a rock specimen typical of multi-stage fluid-related brecciation. The assemblages of volcanic fragments and sulfide cements were further shattered and infilled by later-stage quartz stocks; (h) specimen with typical multi-stage brecciation. The fragments of the volcanic wall rock are surrounded by quartz and sulfides. Note the sharp boundary of the breccia, and the fissures propagated in the bulk wall rocks; (i) specimen that experienced at least three stages of fluid ingress and brecciation. The spherulite assemblages were shattered into banded but isolated fragments. The cracks between these fragments were infilled by chalcopyrite, pyrite and galena. These later-stage sulfides, however, were also broken into pieces that were cemented by minute calcite and quartz veins.

Paleocene to early Eocene (ca. 66–55 Ma).

The tectonic setting of the Linzizong volcanism is still vigorously debated (Mo et al., 2008; Lee et al., 2009; Zhu et al., 2015, 2019). However, research in the eastern Gangdese suggests that the *retro*-arc contraction continued till mid-Eocene and propagated northward with decreasing magnitude (Kapp et al., 2007a; Pullen et al., 2008). Thus, it can be questioned if the Narusongduo region experienced propagative N-S compressive deformation during the period of the Linzizong volcanism. Our structural mapping demonstrates that the LVS within the LMF was locally crosscut by thrust faults. In addition, the LVS in the LMF's footwall exhibits a regional trend toward more gentle deformation characteristics away from the fault zone. Furthermore, muscovite ^{40}Ar - ^{39}Ar ages of 54–52 Ma were obtained from the LMF to the south of the Sinongduo deposit, slightly younger than the eruptive ages of the Linzizong volcanic rocks (Yang et al., 2021). It is thus reasonable to propose that the Narusongduo region was subjected to propagative N-S compressive deformation during and after the Linzizong volcanism. On the other hand, the F1 fault was locally buried by the Linzizong volcanic rocks that erupted between 58 and 55 Ma (C.G.S., 2019; Fig. 17). The

Linzizong volcanic rocks, except for those in close proximity to the thrust faults, are largely undeformed (Fig. 6). These observations suggest that reactivated thrusting in the study area was characterized by multiple pulses of lesser magnitude. The pop-up and overturned structures recorded in the western and eastern extensions (Murphy et al., 1997; Kapp et al., 2007a) of the LMF have not been identified yet in the Narusongduo region, indicating that the study area was less affected by deformation during the late Cretaceous-Paleogene N-S crustal shortening compared to the LMF's western and eastern segments. In summary, around 65–55 Ma ago, the region experienced extensive Linzizong volcanism and pulsed N-S contraction with a decreased shortening rate (Fig. 18b). It is noteworthy that the ongoing convergence between the Indian and the Eurasian continents since ~ 55 Ma induced widespread lithospheric shortening and multi-stage propagative deformation in the hinterland of the Tibetan plateau (Li et al., 2015). In specific, some researchers suggest that the Narusongduo region experienced propagative N-S contraction since 55 Ma (Yang et al., 2015b). This hypothesis, although lacking chronological and field evidence, highlights the necessity of examining the post-mineralization structural overprints

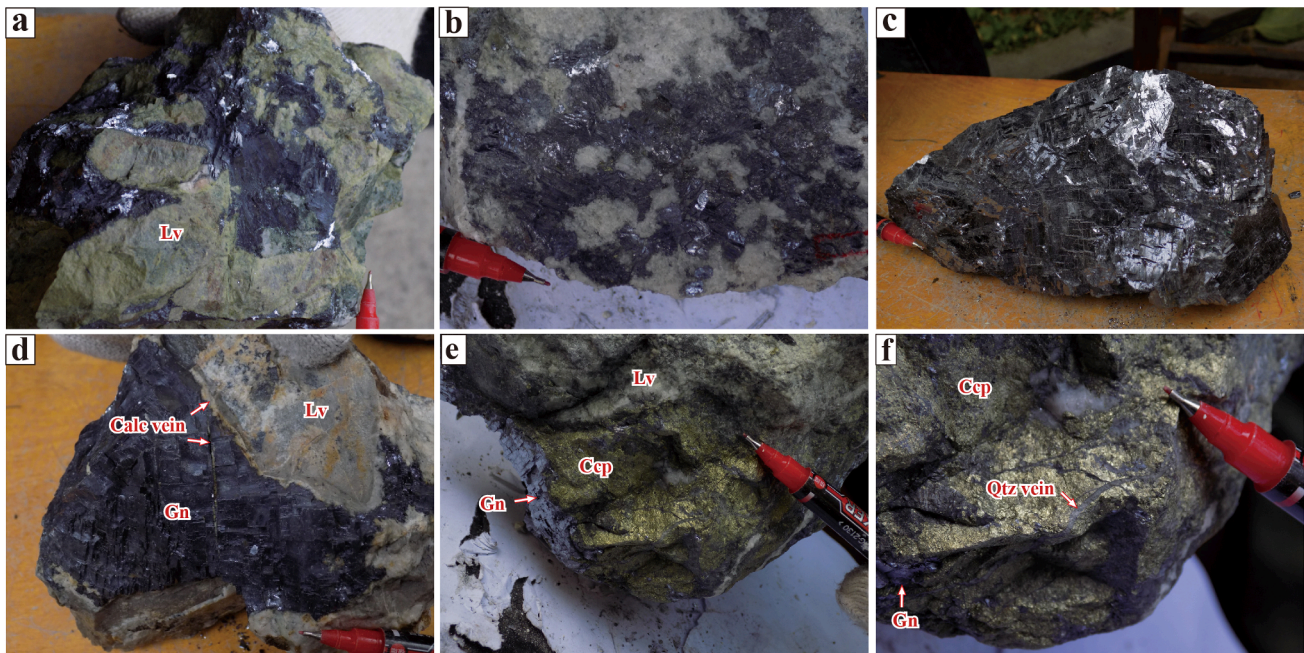


Fig. 15. Photos of the ores hosted in the Linzong volcanic rocks. (a-b) Irregular fragments in a brecciated porphyritic rock cemented by sulfides. Note that the cracks in the fragments are filled by sulfide veinlets. Alteration commonly developed in the felsic rocks whereas the brown protolith is locally preserved in the interior of large fragments; (c) massive sulfide ore collected from orebody I; (d) brecciated porphyritic wall rocks infilled by sulfides (mostly galena as indicated by the cleavages). Calcite veinlets infilled the cleavages in the sulfides; (e-f) multi-stage brecciation and hydrothermal overprinting in a specimen collected from orebody I. The volcanic country rock was first fractured and infilled by chalcopyrite, the galena is deposited later and reshaped the boundaries of the chalcopyrite assemblage and the country rocks. Lastly, all the pre-existing assemblages are cracked and infilled by quartz veins. Abbreviations: Lv-(Sub)volcanic rocks; Calc-calcite; Ccp-chalcopyrite; Gn-Galena; Qtz-Quartz.

during future investigation.

6.1.3. Formation of structural discontinuities in the LVS and the strongly folded basement

Structural discontinuities, including fractures, fissures and faults, may enhance rock permeability (Sibson, 1996; Evans et al., 1997). Furthermore, the intrinsic porosity and deformational behavior of certain rock types may have an impact on their permeability (Cox et al., 2005).

Structural analyses in our study area disclosed two sets of fractures with preferred orientations in the folded Paleozoic strata. The first group of NNE-SSW and NNW-SSE striking conjugate joints are widely developed within the carbonate rocks near the fault zone, resulting from the early-stage N-S compressive deformation. The second group of tensional and conjugate shearing joints with approximate E-W strikes were formed during the folding of the strata under coaxial compressive stress. These two types of fractures and the folded beddings formed complex conduit systems with considerable along-strike and vertical connectivity.

Some of the fractures within the LVS near the footwall of the thrusts could be related to the compressive deformation. However, most of the fissures and fractures within the LVS show radial and tangential attitudes with respect to the volcanic center, and can accordingly be grouped into the radial and ring-shaped groups. These fractures can be formed due to volcanic activity (e.g., inflation, deflation and caldera-collapse), edifice load, or local cooling contraction (Komuro, 1987; Marti et al., 1994; Acocella, 2007). Most of these fractures and fissures are featured by tensional rupturing, limited along-strike extension and negligible displacement. Some of the ring-shaped fractures on the northern side of the volcanic edifice developed into high-angle normal faults, probably induced by differential collapse (Fig. 13a-b).

In general, the brittle rock failures within the Paleozoic-Mesozoic units resulted dominantly from the regional compressive tectonic deformation, whereas the fractures and faults in the LVS are primarily

associated with the volcanic-tectonic stress. Furthermore, experimental studies indicate that compressive deformation of the carbonate rocks may induce cataclasis and growth of microcracks parallel to maximum principal stress (Vajdova et al., 2004, 2010). These dilations could then facilitate subsequent hydrothermal activity. By comparison, pores in the argillaceous and tuffaceous rocks tend to be sealed by fine-grained clasts and fine matrix during compressive deformation (Cox et al., 2005). These differences of deformational and mechanical features may yield crucial control on later-stage fluid influxes and mineralization.

6.2. Mineralization in the compressive deformational structures

The LMF is the first-order ore-controlling structure in the Narusongduo region, hosting the Sinongduo, Narusongduo, Xuebie and Zexue ore deposits (Fig. 1c; C.G.S., 2019). Recent field mapping and drilling data point out that the Qingdu fault (F1) and related folds are key structures that controlled the mineralization of orebody III in the Narusongduo deposit (Yang et al., 2015b; C.G.S., 2019; Liu et al., 2019). However, how the fault zone promotes fluid ingress and mineralization is hitherto not clear. In addition, the structural factors that controlled the distribution and accommodation of fluid-related mineralization are rarely discussed. Nevertheless, the role of the distinct structural and lithological characteristics of the Paleozoic rocks and the LVS on the control on mineralization patterns requires further discussion.

The Qingdu fault (F1) contains a lenticular breccia zone and a damage zone (Fig. 8a-c; Caine et al., 1996; Faulkner et al., 2010). The lenticular breccia zone is characterized by oriented clasts and a well-connected fracture network developed along the dip of the fault plane. The damage zone of F1 is composed of a complex organization of rock blocks with no preferred orientations and a matrix comprising calcareous, and siliceous minerals and fault gouge. These structures display remarkable connectivity along the fault dip and may have provided pathways for fluid redistribution from the reservoirs in the depth to the

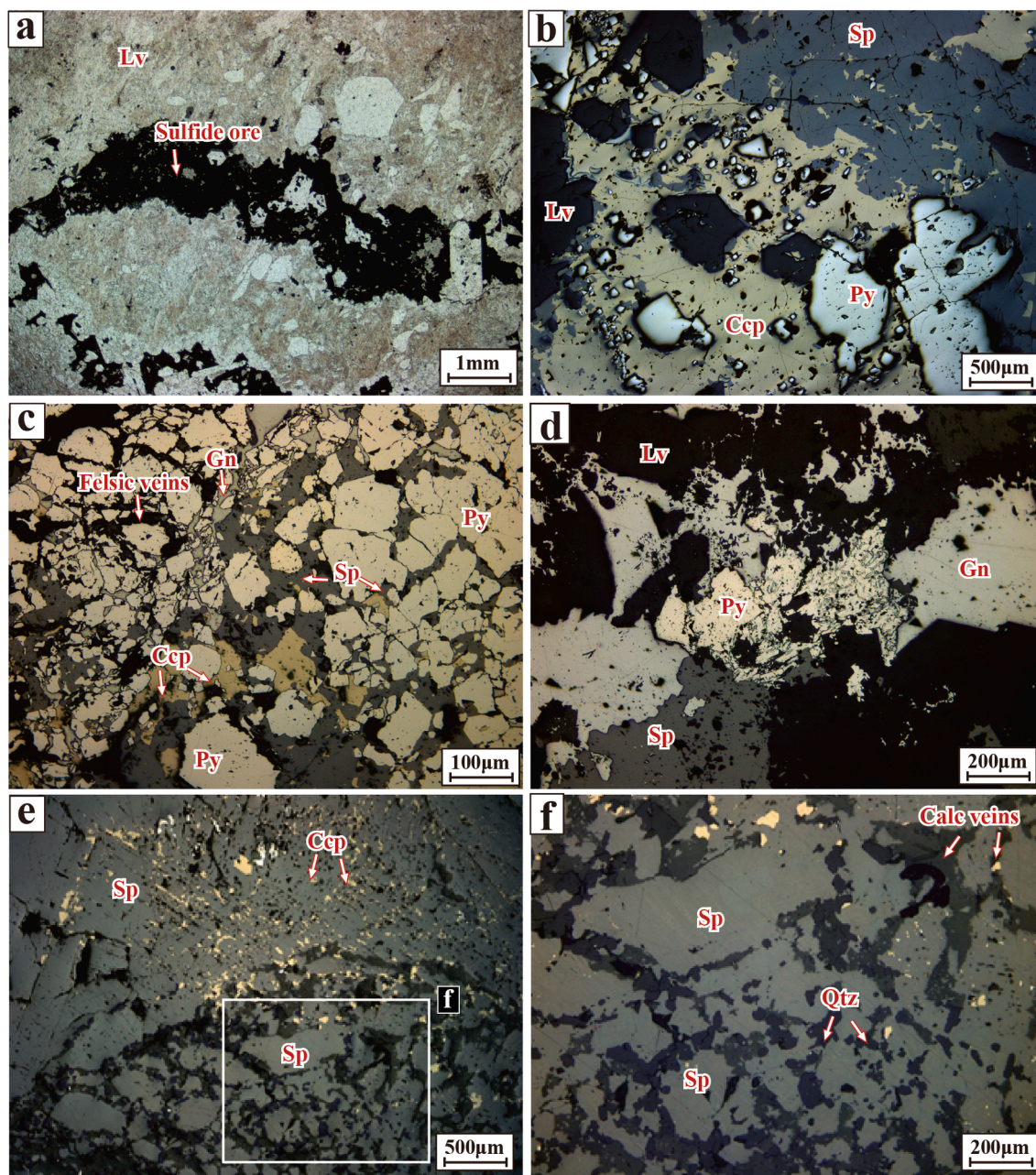


Fig. 16. Photomicrographs illustrating the mineralization in the Linzizong volcanic rocks. (a) A plane-polarized thin section photo showing the irregular fractures and sulfide veins within a mineralized porphyritic volcanic rock; (b) microscopic view of multi-stage brecciation and mineral deposition in a polished section. The wall rock and the pyrite are fragmented and engulfed by the sphalerite and galena matrix. The sequential relation between the sphalerite and galena assemblages is difficult to restore. (c) Polished section as an example for multi-stage fluid superimposition. The pyrite is fragmented and infilled by veinlets composed of chalcopyrite, galena, sphalerite, and felsic minerals. The chalcopyrite is crosscut and surrounded by the sphalerite, and superimposed by later injected galena and felsic minerals; (d) fragmented country rock and pyrite are embedded in a matrix composed of galena and sphalerite. (e-f) Example of a sphalerite assemblage that is brecciated into several angular fragments with jig-saw fit boundaries. The voids between the fragments are infilled by later-introduced calcite and quartz. Abbreviations: Ccp-chalcopyrite; Gn-Galena; Lv-(Sub)volcanic rocks; Py-Pyrite; Sp-Sphalerite.

deposits at higher crustal levels. The fractures in the lenticular breccia zone are mostly filled and cemented by fault gouge composed of clay minerals and calcite, whereas sulfides are usually preserved in discontinuous voids, such as the dilational jogs. These phenomena can be explained by the “fault-valve” model (Sibson et al., 1988; Boullier and Robert, 1992; Cox, 1995). This model implies that fault rupture events resulted in sudden permeability enhancement and rapid fluid ingress, which was followed by deposition of fluid-related minerals and self-sealing of the fracture network. The episodic “valve opening” repeatedly tapped the fluid into the fault zone and formed the incremental

mineralization (Cox, 1995).

Compressive faults are not usually preferred places for mineral deposition (Caine et al., 1996). Instead, fault damage zone and fault-related folds can promote fluid migration and provide favorable accommodation for mineralization (e.g., Rowland and Simmons, 2012). Field observations in the Narusongduo region demonstrate that fluid-related alteration and mineralization occurred extensively in the deformed and fractured carbonate rocks in close proximity to the F1 fault (Fig. 10g-i). Fluid percolation and overprinting concentrated in the sections with higher densities of structural discontinuities. The fluid-

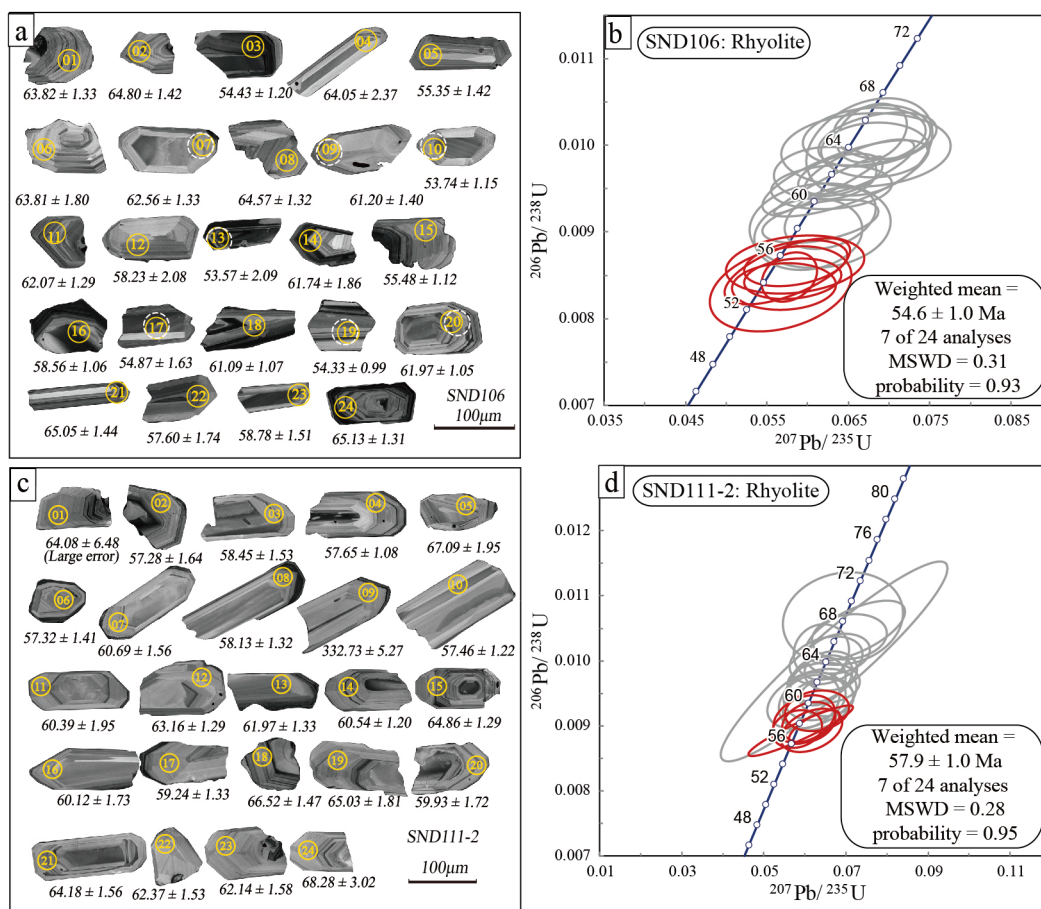


Fig. 17. Zircon CL images (a, c) and U-Pb concordia diagrams (b, d) of the volcanic rocks at the northern slope of the Narusongduo caldera. See text for details.

related alteration and mineralization commonly developed along the steeply dipping permeable fracture systems, and are separated from the country rocks by sharp boundaries (Fig. 10g-h). We thus propose that the nucleated and connected fracture systems acted as the main pathway for fluid percolation. Nevertheless, the mineralized or altered zones, which usually wedge out upward, are characterized by randomly distributed terminal splays and extensive fluid-related brecciation (Fig. 10i). These observations imply that hydraulic fracturing also contributed to the growth of the fracture system accommodating the fluid influxes. The country rocks hosting the hydrothermal minerals were usually broken into polymict breccia fragments during later-stage fluid-driven mechanical overpressurization, indicative of multi-stage fluid overprinting (Fig. 11). The successive fluid-ingression events were controlled by the deformational fractures and occupied the same zone of structural weakness (Fig. 10; Shi et al., 2016). The growth of the fracture network is highly comparable with the “ordinary percolation model” (Cox et al., 2005), in which the regional N-S compressive strain plays a vital role.

Information obtained from extensive exploration drilling revealed that much mineralization is hosted in the deformed carbonate rocks or the unconformity between them and the overlying LVS. The ores are spatially associated with marbleization, silicification or skarnization. Therefore, it has been proposed that this deposit is a skarn-type ore deposit (Ji et al., 2012, 2014). However, numerous discrete mineralized sections with high ore grades are observed in the LVS several meters to several hundred meters above the unconformity. In addition, both the field observation and the drilling data demonstrate that the mineralization is featured by steep occurrences and limited lateral extensions. We therefore propose an updated model to explain the mineralization patterns within different lithologies. The steeply dipping fracture

systems in the strongly deformed carbonate rocks provide the principal fluid conduits and exert main controls on the alteration and mineralization. The strongly deformed and porous carbonate rocks provided ample accommodation space for ore deposition. By contrast, the gently dipping LVS with less fracture density and porosity likely acted as a mechanical barrier during fluid flow. Nevertheless, the eruptive fractures and fissures along with the locally developed deformational joints within the volcanic sequences also provide less prominent conduits for the fluid introduction. This could explain the discrete mineralization and alteration assemblages within the LVS.

6.3. Mineralization in the volcanic structures

It has been observed that the mineralization in orebody I is mainly hosted in steep breccia pipes and dykes, which share similar lithological characteristics with the rhyolitic wall rocks. The surface outcrops of the breccia pipes parallel to the E-W strike of the long axes of the ring-shaped fractures (Fig. 1c). The sharp contacts between the breccia bodies and the wall rocks imply that the brecciation was controlled by these E-W trending structural discontinuities. Drilling at orebody I also documented that the ore-hosting breccia pipe dips steeply to the SSE, in accordance with the dips of the ring-shaped fractures (Fig. 12c; Yang et al., 2015b). Another group of fractures within the brecciated volcanic rocks strike N-S and perpendicularly intersect with the ring-shaped structures. They are interpreted as the radial group in respect to the volcanic center. Several meter-scale breccia dykes with occurrences parallel to the radial or ring-shaped tensional fractures were identified in the vicinity of the major orebodies. In summary, the occurrence of the ore-hosting breccia bodies was controlled by radial and concentric ring-shaped tensional fractures related to the Narusongduo caldera. The high

Table 1

LA-ICPMS zircon U-Pb isotopic results from the volcanic rocks from the Narusongduo region.

Analysis	Corrected ratios and errors						Corrected ages and errors						²³² Th/ ²³⁸ U	Conc. ^b
	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ		
SND106 Rhyolite														
SND106.01	0.04978	0.00341	0.06828	0.00437	0.00995	0.00021	184.5	159.6	67.1	4.3	63.8	1.3	1.06	95
SND106.02	0.04807	0.00394	0.06696	0.00499	0.01010	0.00022	102.6	194.0	65.8	4.9	64.8	1.4	1.08	98
SND106.03	0.04854	0.00192	0.05776	0.00225	0.00848	0.00019	124.2	78.7	57.0	2.2	54.4	1.2	0.67	95
SND106.04	0.04912	0.00362	0.06762	0.00511	0.00999	0.00037	153.4	172.7	66.4	5.0	64.1	2.4	2.47	96
SND106.05	0.04995	0.00521	0.05846	0.00559	0.00862	0.00022	194.5	99.5	57.7	5.4	55.4	1.4	1.50	96
SND106.06	0.04898	0.00535	0.06719	0.00688	0.00995	0.00028	147.1	256.1	66.0	6.8	63.8	1.8	1.14	97
SND106.07	0.04940	0.00413	0.06642	0.00443	0.00975	0.00021	166.7	195.6	65.3	4.4	62.6	1.3	1.20	96
SND106.08	0.04942	0.00396	0.06859	0.00480	0.01007	0.00021	167.8	187.0	67.4	4.7	64.6	1.3	1.28	96
SND106.09	0.04749	0.00445	0.06246	0.00439	0.00954	0.00022	73.9	222.9	61.5	4.3	61.2	1.4	1.45	99
SND106.10	0.05012	0.00394	0.05708	0.00422	0.00837	0.00018	211.2	200.0	56.4	4.1	53.7	1.1	1.86	95
SND106.11	0.04659	0.00319	0.06216	0.00417	0.00968	0.00020	28.5	164.2	61.2	4.1	62.1	1.3	0.93	99
SND106.12	0.04921	0.00473	0.06157	0.00573	0.00907	0.00032	157.8	225.2	60.7	5.6	58.2	2.1	1.42	96
SND106.13	0.04977	0.00594	0.05671	0.00575	0.00834	0.00033	183.4	259.2	56.0	5.5	53.6	2.1	0.83	95
SND106.14	0.04871	0.00620	0.06463	0.00672	0.00962	0.00029	133.8	299.1	63.6	6.6	61.7	1.9	1.35	97
SND106.15	0.04861	0.00393	0.05854	0.00421	0.00864	0.00017	127.9	145.4	57.8	4.0	55.5	1.1	1.07	96
SND106.16	0.04893	0.00421	0.06156	0.00470	0.00912	0.00017	144.3	202.0	60.7	4.6	58.6	1.1	1.14	96
SND106.17	0.04880	0.00357	0.05752	0.00508	0.00855	0.00025	138.2	171.7	56.8	5.0	54.9	1.6	1.91	97
SND106.18	0.04797	0.00370	0.06298	0.00490	0.00952	0.00017	97.7	182.5	62.0	4.8	61.1	1.1	1.85	98
SND106.19	0.05016	0.00368	0.05819	0.00394	0.00846	0.00015	211.2	165.7	57.4	3.8	54.3	1.0	0.68	94
SND106.20	0.04807	0.00301	0.06403	0.00341	0.00966	0.00016	102.7	147.9	63.0	3.4	62.0	1.0	1.16	98
SND106.21	0.04856	0.00201	0.06790	0.00284	0.01014	0.00022	126.7	97.3	66.7	2.8	65.0	1.4	1.24	97
SND106.22	0.04856	0.00365	0.06010	0.00439	0.00898	0.00027	126.7	176.8	59.3	4.3	57.6	1.7	0.89	97
SND106.23	0.04971	0.00277	0.06278	0.00368	0.00916	0.00024	181.3	130.0	61.8	3.6	58.8	1.5	0.97	95
SND106.24	0.04941	0.00294	0.06917	0.00392	0.01015	0.00020	167.1	139.1	67.9	3.9	65.1	1.3	1.46	96
SND111-2 Rhyolite														
SND111-2.01	0.04734	0.00854	0.06715	0.01823	0.00999	0.00102	64.9	644.5	66.0	17.3	64.1	6.5	1.20	97
SND111-2.02	0.04615	0.00542	0.05896	0.00846	0.00892	0.00026	5.7	124.5	58.2	8.1	57.3	1.6	1.04	98
SND111-2.03	0.04763	0.00444	0.05981	0.00490	0.00911	0.00024	80.7	221.4	59.0	4.8	58.4	1.5	1.33	99
SND111-2.04	0.05021	0.00401	0.06219	0.00407	0.00898	0.00017	204.6	185.4	61.3	4.0	57.6	1.1	1.14	94
SND111-2.05	0.05009	0.00657	0.07225	0.00800	0.01046	0.00030	199.0	304.5	70.8	7.8	67.1	1.9	1.08	94
SND111-2.06	0.05001	0.00464	0.06158	0.00495	0.00893	0.00022	195.2	215.7	60.7	4.9	57.3	1.4	1.17	94
SND111-2.07	0.04778	0.00412	0.06231	0.00497	0.00946	0.00024	88.2	204.7	61.4	4.9	60.7	1.6	1.45	99
SND111-2.08	0.04873	0.00387	0.06086	0.00429	0.00906	0.00021	135.0	186.5	60.0	4.2	58.1	1.3	1.23	97
SND111-2.09 ^c	0.05473	0.00185	0.39974	0.01375	0.05297	0.00084	401.4	75.6	341.5	11.7	332.7	5.3	0.10	97
SND111-2.10	0.04706	0.00358	0.05809	0.00401	0.00895	0.00019	52.1	181.5	57.3	4.0	57.5	1.2	1.14	100
SND111-2.11	0.04753	0.00628	0.06169	0.00717	0.00941	0.00030	76.2	313.8	60.8	7.1	60.4	1.9	2.31	99
SND111-2.12	0.04885	0.00336	0.06631	0.00421	0.00985	0.00020	140.5	161.4	65.2	4.1	63.2	1.3	1.13	97
SND111-2.13	0.04850	0.00439	0.06459	0.00577	0.00966	0.00021	123.8	213.0	63.6	5.7	62.0	1.3	0.97	97
SND111-2.14	0.05015	0.00343	0.06524	0.00433	0.00944	0.00019	201.9	158.6	64.2	4.3	60.5	1.2	1.32	94
SND111-2.15	0.04883	0.00356	0.06809	0.00507	0.01011	0.00020	139.8	171.0	66.9	5.0	64.9	1.3	0.83	97
SND111-2.16	0.04726	0.00435	0.06106	0.00491	0.00937	0.00027	62.4	219.3	60.2	4.8	60.1	1.7	2.53	100
SND111-2.17	0.04938	0.00438	0.06286	0.00516	0.00923	0.00021	166.1	207.0	61.9	5.1	59.2	1.3	1.12	96
SND111-2.18	0.04950	0.00419	0.07080	0.00603	0.01037	0.00023	171.7	197.8	69.5	5.9	66.5	1.5	0.87	96
SND111-2.19	0.04579	0.00353	0.06401	0.00446	0.01014	0.00028	-13.4	186.4	63.0	4.4	65.0	1.8	1.04	97
SND111-2.20	0.04902	0.00419	0.06313	0.00568	0.00934	0.00027	148.9	200.2	62.2	5.6	59.9	1.7	1.10	96
SND111-2.21	0.04719	0.00468	0.06510	0.00584	0.01001	0.00024	58.8	236.2	64.0	5.7	64.2	1.6	1.33	100
SND111-2.22	0.04777	0.00351	0.06403	0.00500	0.00972	0.00024	87.8	174.3	63.0	4.9	62.4	1.5	1.12	99
SND111-2.23	0.04732	0.00331	0.06320	0.00443	0.00969	0.00025	65.6	166.8	62.2	4.4	62.1	1.6	1.06	100
SND111-2.24	0.04721	0.00666	0.06932	0.00967	0.01065	0.00047	60.1	336.4	68.1	9.5	68.3	3.0	0.98	100

Notes:

a. $\rho_r(\%) = (\sigma_2(207\text{Pb}/235\text{U}) + \sigma_2(206\text{Pb}/238\text{U}) - \sigma_2(207\text{Pb}/206\text{Pb})) / (2 * \sigma(206\text{Pb}/238\text{U}) * \sigma(207\text{Pb}/235\text{U}))$.b. "Concordance" = $(1 - \text{abs}((207\text{Pb}/235\text{U}) - (206\text{Pb}/238\text{U}))) / ((206\text{Pb}/238\text{U})) * 100$.

c. Analyses in shadow are not shown on the concordia diagram.

density of structural discontinuities and the intersection of multiple groups of fractures likely facilitated fluid introduction and brecciation.

Brecciated rocks with highly comminuted polymictic fragments are discovered by drilling at the No. I-1 breccia pipe (Fig. 14a). The clasts within these breccias are differentially rounded and abraded, indicative of forceful transportation (Taylor, 2009). In contrast, economic mineralization is often found in breccias with a jigsaw-fit structure and curved and branched fractures, indicating rapid pressure release, in-situ brecciation, and limited clast migration. (Sillitoe, 1985; Cox, 1995). At the outcrop scale, the breccias consist of lithic clasts with a sulfide matrix that are commonly fractured into fragments during later-stage fluid influx. The cracks between these fragments are filled and sealed by later-stage hydrothermal minerals, forming polymict hydrothermal breccias (Figs. 14 and 15). It could also be noticed under a microscope that both

the wall rocks and the earlier-stage minerals are cracked and infilled by later-stage minerals (Figs. 14i and 16c-f). The sharp jig-saw contacts between different generations of sulfide minerals indicate successive hydraulic fracturing and multi-stage mineral precipitation. In summary, these shreds of evidence advocate that the ore-bearing breccia bodies experienced repetitive infiltration of pressurized fluids, brecciation of wall rocks and self-sealing of the fracture system (Cox et al., 2005; Cas et al., 2011).

The ore-bearing breccia pipes are in close proximity to several cylindrical porphyry intrusions that are interpreted as ore-related (Ji et al., 2012, 2014; Ji, 2013; Yang et al., 2015b). They were emplaced during 62.54 ± 0.77 Ma to 62.47 ± 0.91 Ma and related to the mineralization events, according to previously published studies (Ji et al., 2012, 2014). On the other hand, Argon dating on the sericite obtained from the ore-

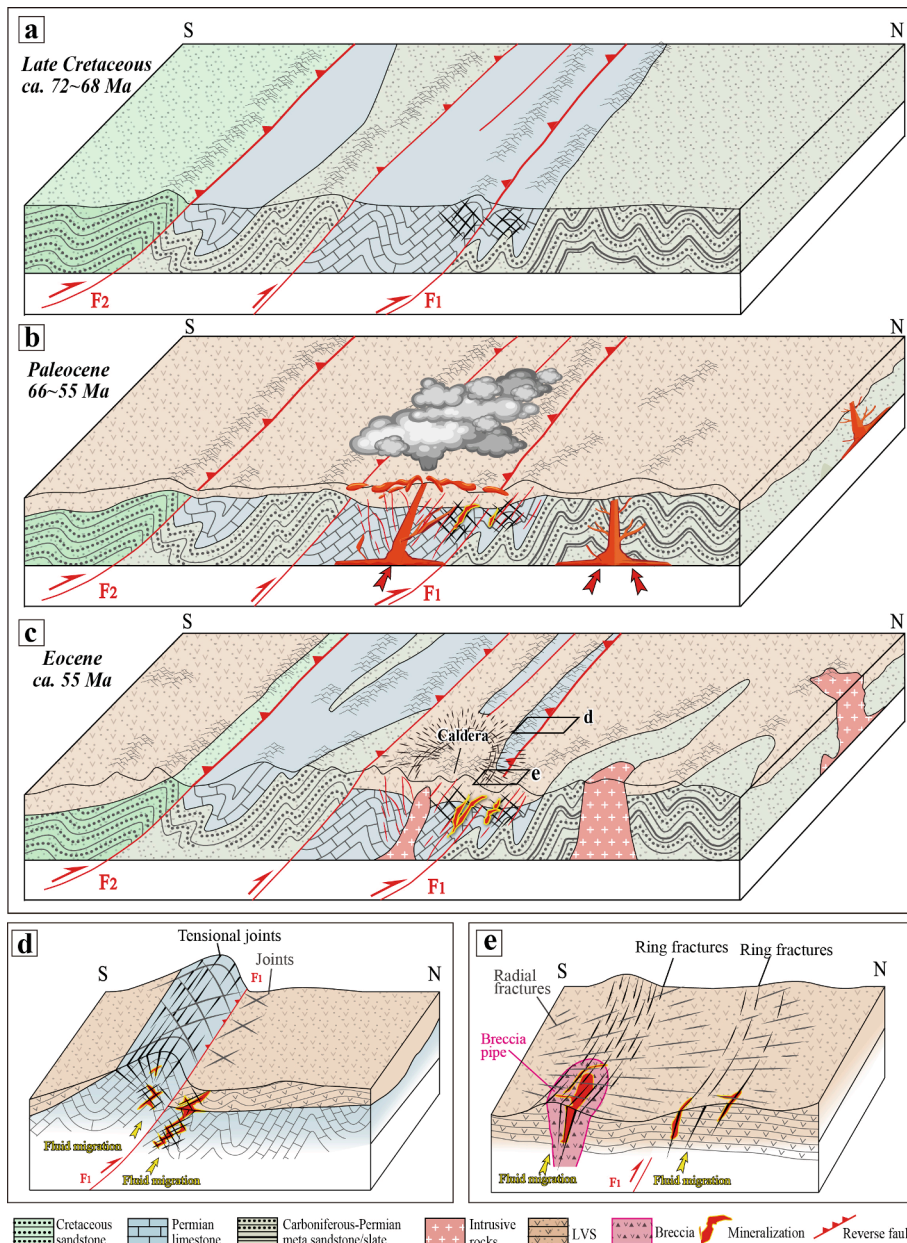


Fig. 18. Conceptual formation model of the ore-controlling structures in the Narusongduo region. (a) Late Cretaceous–Early Paleocene Cordilleran orogeny induced N–S crustal shortening in the Narusongduo region in the Gangdese *retro*-arc. The pre-Cenozoic lithological units within the LMF are deformed into a north-vergent thrust-fold system. Active deformation and development of fracture systems enhanced the permeability of the carbonate rocks; (b) at ca. 66–55 Ma, the LMF in the Narusongduo region is superimposed by propagative N–S compressive deformation and multi-stage volcanism. The volcanic structures provide conduits and accommodation space for fluid migration and mineral deposition. Hydrothermal activity concentrated at the fault-fold zone and volcanic conduits and induced pulsed hydraulic fracturing, decompression and mineral deposition; (c) the long-lived interplay between structural deformation, volcanism, and hydrothermal ingress eventually formed the time-integrated economic mineralization in the fault zone and the volcanic-related breccia bodies; (d) conceptual model of the structural controls on the mineralization in orebody III. The ore-forming fluids migrated along the fault structures and percolated through the fault zone and associated folds. The mineralization was hosted mainly in the fractures formed during the tectonic deformation; (e) structural factors controlled the mineralization in orebody I. The intersection between different sets of volcanic fractures permitted the fluid migration and the formation of the steeply dipping ore-bearing breccia bodies.

bearing breccia yielded an age of 57.81 ± 0.66 Ma, approximately 4 Ma younger than the intrusive magmatism (Yang et al., 2015b). In addition, our newly obtained zircon U–Pb ages of the volcanic wall rocks gave an even slightly younger range of 58 ± 1 Ma to 55 ± 1 Ma (Fig. 17). It is well-established that single intrusion-cooling events and the duration of ore depositional processes are short-lived (several 10^4 – 10^5 years) (Glazner et al., 2004; Chiaradia et al., 2013; Karakas et al., 2017). A magmatic or hydrothermal system that appears to have lasted for millions of years is hence probably characterized by several successive magma and hydrothermal pulses (Schoene et al., 2012; Bucholz et al., 2017). Therefore, the relative wide age range of these deposits as outlined above also suggests that the Narusongduo region experienced multi-stage magmatism and incremental hydrothermal activity during the Paleocene to Eocene (Ji et al., 2012, 2014; Shi et al., 2016; Zhou et al., 2020).

In summary, we here introduce a conceptual formation model for the ore-controlling structures in orebody I. In the early stages of magmatism, large-scale eruption and subsequent collapse formed the Narusongduo caldera and subordinate fractures. At the sites with more intense

deformation, the densely-occurring ring-shaped fractures intersect with the radial fractures and lithological surfaces, adding complexity and increasing permeabilities of the fractured wall rocks. The fracture systems may further have been affected by local normal faulting, renewed magmatism, and later-stage fluid influxes. The subvolcanic intrusions, welded volcanic rocks and infilled fluid-related cements, formed steep volcanic plugs that blocked the pathway for potential subsequent fluid migration. On the other hand, the long-lived magmatism triggered repeated overpressurized hydrothermal fluids that took advantage of the pre-existing complex structural fabric. Pressure-driven hydraulic fracturing might have occasionally broken through the barrier and could have added to the tensional fractures. Counteracting this process, the increase of permeability would have resulted in sudden drop of fluid pressure and swift deposition of hydrothermal minerals. This “hydrothermal sealing” mechanism (Cox et al., 2005) would have subsequently been responsible for renewed fluid pressure build-up (Jébrak, 1997). Eventually, multi-stage hydrothermal overprinting and time-integrated mineral deposition formed the steep orebodies in our study area.

6.4. Implications for mineral exploration

Our study demonstrates that the Narusongduo Pb-Zn deposit is hosted by composite structures formed by compressive deformation alongside multi-phased volcanic activity. This process might have broader implications for Pb-Zn mineralization in the Gangdese *retro*-arc.

Most of the deposits in the Gangdese *retro*-arc are located in the vicinity of the LMF (Fig. 1b-c). The compressive deformation structures were likely formed during the late Cretaceous-Paleogene Cordilleran orogeny at the Gangdese arc and superimposed by propagative crustal shortening during the continental collision of India with Eurasia (Kapp et al., 2007a). The fault and shear zones played a key role during fluid influx from deeper reservoirs to upper crustal levels. The deposited minerals are hosted mainly by the fracture networks in the fault zone and associated folds (Wang et al., 2010; Ma et al., 2017a). It is noteworthy that the more pervasive fracturing of the carbonate rocks under compaction would enhance the permeability of the fault-fold system (Billi, 2010; Vajdova et al., 2010). Therefore, we propose that the strongly folded carbonate rocks in the LMF are suitable targets for further exploration.

It has been proposed that the Sinongduo and Narusongduo deposits in the central segment of the Gangdese *retro*-arc are genetically linked to the Linzizong volcanic rocks (Tang et al., 2016; Ding, 2017). We hypothesize that the long-lived volcanism there formed steep tensional structures that were crucial in draining overpressurized fluids to shallower levels. The repeated hydraulic brecciation and hydrothermal self-sealing produced the time-integrated mineralization that was hosted in the breccia pipes and dykes. In general, the volcanic structures, especially diatremes and volcanic plugs in the LVS are potential targets for exploration.

Another interesting point is the exact timing of the mineralization, or how many stages of mineralization were involved in the formation of the ore deposits. The available age constraints on the mineralization in the western GRAZ range from ca. 65 Ma to 55 Ma (see Li et al., 2019a and references therein). This period is contemporaneous with the Linzizong volcanic activity, advocating the genetic links between them (Ding, 2017). However, our study on the structural and hydrothermal overprints in the Narusongduo deposit highlights the complexity and difficulties when tackling these mineralization ages. Indeed, the time-integrated mineralization can have been formed via various pulses of fluid injection and mineral precipitation, partially resetting and blurring the dating results (Lipman et al., 1976; Nadeau et al., 2016; Li et al., 2017, 2018, 2019b). Therefore, more attention needs to be paid to illustrating the spatial patterns of the mineralization, and detailed chronological frame works should be integrated with systematic geological observation and structural analyses.

7. Conclusions

- (1) Two stages of structural evolution could be recognized in the Narusongduo region. The first stage, represented by the regional N-S crustal shortening, took place during the late Cretaceous-early Paleocene in response to the Cordilleran orogeny (India-Eurasia collision) at the southern Lhasa terrane. The second stage is characterized by multi-phased Linzizong volcanism (ca. 66–55 Ma) and propagative N-S compressive deformation with decreasing shortening rate.
- (2) The mineralization in orebody III was controlled by the northern boundary fault of the Luobadui-Milashan fault zone and the adjacent E-W trending folds, which were forged during the first deformation stage. During the second stage, the thrust faults were repeatedly reactivated and the ore-forming fluids were drained to shallower crustal levels along the fault zone. These pulsed overpressurized fluids percolated through the fault zone and the overlying less deformed Linzizong volcanic succession, resulting in the mineralization and alteration.
- (3) The formation of orebody I in the Narusongduo deposit was related to multi-stage magmatism and associated hydrothermal activity during the second deformational stage (ca. 66–55 Ma). The ores are hosted in several breccia bodies controlled by the eruptive fractures and normal faults formed by the volcanic activity. The intersection between different sets of structural discontinuities enhanced the permeability. This multi-stage magmatism and hydrothermal activity were guided along these zones of structural weakness, resulting in progressive brecciation and mineral precipitation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We appreciate Mr. Daiwa and Mr. Jigme for their help with the fieldwork. Dr. Zhou Hongying and Dr. Tu Jiarun helped a lot with isotopic dating. We are also very grateful to journal editor Dr. Chen Huayong and two anonymous reviewers for their valuable comments on this paper. This study is sponsored by the Deep Resources Exploration and Mining, the National Key R&D Program of China (2018YFC0604105), and the research start-up Project of the Chengdu University of Technology (grant number: 10912-KYQD2019_08166). The support provided by the China Scholarship Council (CSC, 201806190214; 201908320260) is appreciated for financing the research stay of Z. He and W. Su in Belgium. This is a contribution to the “Qomolangma Science Project” of the Chengdu University of Technology.

References

- Acocella, V., 2007. Understanding caldera structure and development: An overview of analogue models compared to natural calderas. *Earth Sci. Rev.* 85 (3–4), 125–160.
- All  re, C.J., Courtillot, V., Tapponnier, P., Hirn, A., Mattauer, M., Coulon, C., Jaeger, J. J., Achache, J., Sch  rer, U., Marcoux, J., Burg, J.P., Girardeau, J., Armijo, R., Gari  py, C., G  pel, C., Tindong, L.I., Xuchang, X., Chenfa, C., Guangqin, L.I., Baoyu, L., Jiwen, T., Naiwen, W., Guoming, C., Tonglin, H., Xibin, W., Wanning, D., Huaibin, S., Yougong, C., Ji, Z., Hongrong, Q., Peisheng, B., Songchan, W., Bixiang, W., Yaoxiu, Z., Xu, R., 1984. Structure and evolution of the Himalaya-Tibet orogenic belt. *Nature* 307 (5946), 17–22.
- Andersen, T., 2002. Correction of common lead in U-Pb analyses that do not report ²⁰⁴Pb. *Chem. Geol.* 192 (1–2), 59–79.
- Arribas, A., Cunningham, C.G., Rytuba, J.J., Rye, R.O., Kelly, W.C., Podwysoc  ki, M.H., McKee, E.H., Tosdal, R.M., 1995. Geology, geochronology, fluid inclusions, and isotope geochemistry of the Rodalquilar gold alunite deposit, Spain. *Economic Geology* 90, 795–822.
- Billi, A., 2010. Microtectonics of low-P low-T carbonate fault rocks. *J. Struct. Geol.* 32 (9), 1392–1402.
- Bissig, T., Clark, A.H., Lee, J.K.W., Hodgson, C.J., 2002. Miocene Landscape Evolution and Geomorphologic Controls on Epithermal Processes in the El Indio-Pascua Au-Ag-Cu Belt, Chile and Argentina. *Econ. Geol.* 97 (5), 971–996.
- Boullier, A.-M., Robert, F., 1992. Palaeoseismic events recorded in Archaean gold-quartz vein networks, Val d’Or, Abitibi, Quebec, Canada. *J. Struct. Geol.* 14 (2), 161–179.
- Bucholz, C.E., Eddy, M.P., Jagoutz, O., Bowring, S.A., Schmidt, M.W., Sambuu, O., 2017. Constraining the time scales of magmatic differentiation with U-Pb zircon geochronology. *Geology* 45 (1), 11–14.
- C.G.S. (China Geological Survey), 2002. Report on the regional geology of the P. R. C., Xigaze sheet (1:2500000) (in Chinese).
- C.G.S. (China Geological Survey), 2019. Regional Geological Survey Report of the P.R.C. at the 1:50000 scale (Langdui, Zexu and Zhuoluo sheets) (in Chinese).
- Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. *Geology* 24 (11), 1025. [https://doi.org/10.1130/0091-7613\(1996\)024<1025:FZAAPS>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<1025:FZAAPS>2.3.CO;2).
- Cas, R., Giordano, G., Balsamo, F., Esposito, A., Mastro, S.L., 2011. Hydrothermal Breccia Textures and Processes: Lisca Bianca Islet, Panarea Volcano, Aeolian Islands, Italy. *Econ. Geol.* 106 (3), 437–450.
- Chiaradia, M., Schaltegger, U., Spikings, R., Wotzlaw, J.-F., Ovtcharova, M., 2013. How Accurately Can We Date the Duration of Magmatic-Hydrothermal Events in Porphyry Systems?—An Invited Paper. *Econ. Geol.* 108 (4), 565–584.
- Corfu, F., 2013. A century of U-Pb geochronology: The long quest towards concordance. *Geol. Soc. Am. Bull.* 125 (1–2), 33–47.

- Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of Zircon Textures. *Rev. Mineral. Geochem.* 53, 469–500.
- Cox, S.F., 1995. Faulting processes at high fluid pressures: An example of fault valve behavior from the Wattle Gully Fault, Victoria, Australia. *J. Geophys. Res. Solid Earth* 100, 12841–12859.
- Cox, S.F., 2016. Injection-Driven Swarm Seismicity and Permeability Enhancement: Implications for the Dynamics of Hydrothermal Ore Systems in High Fluid-Flux, Overpressured Faulting Regimes—An Invited Paper. *Econ. Geol.* 111 (3), 559–587.
- Cox, S.F., Knackstedt, M.A., Braun, J., 2001. Principles of structural control on permeability and fluid flow in hydrothermal systems. *Rev. Econ. Geol.* 14, 1–24.
- Cox, S.F., Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P., 2005. Coupling between Deformation, Fluid Pressures, and Fluid Flow in Ore-Producing Hydrothermal Systems at Depth in the Crust, One Hundredth Anniversary Volume. *Soc. Econ. Geol.* 39–75.
- Cunningham, C.G., Aparicio N., H., Murillo S., F., Jimenez C., N., Lizeca B., J.L., McKee, E.H., Erickson, G.E., Tavera V., F., 1994. Relationship between the Porco, Bolivia, Ag-Zn-Pb-Sn deposit and the Porco Caldera. *Economic Geology* 89, 1833–1841.
- Dewey, J., Shackleton, R., Chang, C.F., Sun, Y.Y., 1988. The Tectonic Evolution of the Tibetan Plateau. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 327, 379–413.
- Ding, L., Lai, Q., 2003. New geological evidence of crustal thickening in the Gangdese block prior to the Indo-Asian collision. *Chin. Sci. Bull.* 48 (15), 1604–1610.
- Ding, L., Xu, Q., Yue, Y., Wang, H., Cai, F., Li, S., 2014. The Andean-type Gangdese Mountains: Paleoelevation record from the Paleocene-Eocene Linzhou Basin. *Earth Planet. Sci. Lett.* 392, 250–264.
- Ding, S., 2017. The diagenesis and metallogenesis of Sinongduo epithermal Ag-Pb-Zn deposit in Gangdese belt, Tibet. Chengdu University of Technology, Chengdu, China (in Chinese with English abstract), School of Earth Sciences.
- Ding, S., Chen, Y., Tang, J., Xie, F., Hu, G., Yang, Z., Shi, S., Li, Y., Yang, H., 2017. Relationship between Linzizong volcanic rocks and mineralization: A case study of Sinongduo epithermal Ag-Pb-Zn deposit. *Mineral Deposits* 36, 1074–1092 (in Chinese with English abstract).
- Dong, G., Mo, X.X., Zhao, Z., Wang, L., Zhou, S., 2005. A new understanding of the stratigraphic successions of the Lingzizong volcanic rocks in the Lhazhu basin, northern Lhasa. Tibet. *Geological Bulletin of China* (in Chinese with English abstract) 24, 549–557.
- Elston, W.E., 1994. Siliceous volcanic centers as guides to mineral exploration; review and summary. *Economic Geology* 89, 1662–1686.
- Evans, J.P., Forster, C.B., Goddard, J.V., 1997. Permeability of fault-related rocks, and implications for hydraulic structure of fault zones. *J. Struct. Geol.* 19 (11), 1393–1404.
- Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J., Withjack, M.O., 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *J. Struct. Geol.* 32 (11), 1557–1575.
- Fu, Q., Yang, Z., Zheng, Y., Huang, K., Duan, L., 2014. Ar-Ar age of phlogopite from the Longmala copper-iron-lead-zinc deposit in Tibet and its geodynamic significance. *Acta Petrologica et Mineralogica* 33, 283–293 (in Chinese with English abstract).
- Fu, Q., Huang, K., Zheng, Y., Yang, Z., Duan, L., 2015. Ar-Ar age of muscovite from skarn orebody of the Mengya'a lead-zinc deposit in Tibet and its geodynamic significance. *Acta Geol. Sin.* 89, 569–582 (in Chinese with English abstract).
- Fu, Q., Xu, B.O., Zheng, Y., Yang, Z., Hou, Z., Huang, K., Liu, Y., Zhang, C., Zhao, L., 2017. Two episodes of mineralization in the Mengya'a deposit and implications for the evolution and intensity of Pb-Zn-(Ag) mineralization in the Lhasa terrane. Tibet. *Ore Geology Reviews* 90, 877–896.
- Gao, Y., Chen, Y., Tang, J., Li, C., Li, X., Gao, M., Cai, Z., 2011. Re-Os dating of molybdenite from the Yagula porphyry molybdenum deposit in Gongbo'gyamda area, Tibet, and its geological significance. *Geological Bulletin of China* 30, 1027–1035 (in Chinese with English abstract).
- Garden, T.O., Gravelly, D.M., Kennedy, B.M., Deering, C., Chambefort, I., 2017. Controls on hydrothermal fluid flow in caldera-hosted settings: Evidence from Lake City caldera, USA. *Geosphere* 13, 1993–2016.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., Taylor, R.Z., 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? *Gsa Today* 14 (4), 4. [https://doi.org/10.1130/1052-5173\(2004\)014<0004:APAOMO>2.0.CO;2](https://doi.org/10.1130/1052-5173(2004)014<0004:APAOMO>2.0.CO;2).
- Gong, X.J., Yang, Z.S., Zhuang, L.L., Ma, W., 2019. Petrogenesis of quartz diorites of the Narusongduo Pb-Zn deposit, Tibet: Constraints from geochemistry and Sr-Nd-Pb isotopes. *Mineral Deposits* 38 (1), 48–60 (in Chinese with English abstract).
- Guo, F., Li, Z., Deng, T., Qu, M., Zhou, W., Huang, Q., Shang, P., Zhang, C., Yan, Z., 2020a. Key factors controlling volcanic-related uranium mineralization in the Xiangshan Basin, Jiangxi Province, South China: A review. *Ore Geol. Rev.* 122, 103517. <https://doi.org/10.1016/j.oregeorev.2020.103517>.
- Guo, N.a., Guo, W., Shi, W., Huang, Y., Guo, Y., Lian, D., 2020b. Characterization of Illite Clays associated with the Sinongduo low sulfidation epithermal deposit, Central Tibet using field SWIR spectrometry. *Ore Geol. Rev.* 120, 103228. <https://doi.org/10.1016/j.oregeorev.2019.103228>.
- Guo, X., Gao, R., Zhao, J., Xu, X., Lu, Z., Klemperer, S.L., Liu, H., 2018. Deep-seated lithospheric geometry in revealing collapse of the Tibetan Plateau. *Earth Sci. Rev.* 185, 751–762.
- Haider, V.L., Dunkl, I., Eynatten, H.V., Ding, L., Frei, D., Zhang, L., 2013. Cretaceous to Cenozoic evolution of the northern Lhasa Terrane and the Early Paleogene development of peneplains at Nam Co, Tibetan Plateau. *J. Asian Earth Sci.* 70–71, 79–98.
- Harris, N.B.W., Pearce, J.A., Tindle, A.G., 1986. Geochemical characteristics of collision-zone magmatism. *Geological Society, London, Special Publications* 19 (1), 67–81.
- Hattori, K.H., Keith, J.D., 2001. Contribution of mafic melt to porphyry copper mineralization: evidence from Mount Pinatubo, Philippines, and Bingham Canyon, Utah, USA. *Miner. Deposita* 36 (8), 799–806.
- He, S., Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., 2007. Cretaceous-Tertiary geology of the Gangdese Arc in the Linzhou area, southern Tibet. *Tectonophysics* 433 (1–4), 15–37.
- Hedenquist, J.W., Matsuhisa, Y., 1987. Volcanic-related hydrothermal systems in the Circum-Pacific Basin and their potential for mineralisation. *Mining Geology* 37, 347–364 (in Japanese with English abstract).
- Hou, Z., Song, Y., Li, Z., Wang, Z., Yang, Z., Yang, Z., Liu, Y., Tian, S., He, L., Chen, K., Wang, F., Zhao, C., Xue, W., Lu, H., 2008. Thrust-controlled, sediments-hosted Pb-Zn-Ag-Cu deposits in eastern and northern margins of Tibetan orogenic belt: Geological features and tectonic model. *Mineral Deposits* 27, 123–144 (in Chinese with English abstract).
- Hou, Z., Zhang, H., 2015. Geodynamics and metallogeny of the eastern Tethyan metallogenic domain. *Ore Geol. Rev.* 70, 346–384.
- Hou, Z., Duan, L., Lu, Y., Zheng, Y., Zhu, D., Yang, Z., Yang, Z., Wang, B., Pei, Y., Zhao, Z., McCuaig, T.C., 2015a. Lithospheric Architecture of the Lhasa Terrane and Its Control on Ore Deposits in the Himalayan-Tibetan Orogen. *Econ. Geol.* 110 (6), 1541–1575.
- Hou, Z.Q., Yang, Z.M., Lu, Y.J., Kemp, A., Zheng, Y.C., Li, Q.Y., Tang, J.X., Yang, Z.S., Duan, L.F., 2015. A genetic linkage between subduction- and collision-related porphyry Cu deposits in continental collision zones. *Geology* 43, 247–250.
- Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. *Chem. Geol.* 211 (1–2), 47–69.
- Jébrak, M., 1997. Hydrothermal breccias in vein-type ore deposits: A review of mechanisms, morphology and size distribution. *Ore Geol. Rev.* 12 (3), 111–134.
- Ji, X., 2013. Study on geology, geochemistry and genesis of Narusongduo lead-zinc deposit, Tibet, China University of Geosciences (Beijing). Beijing 1–119 (in Chinese with English abstract).
- Ji, X., Yang, Z., Yu, Y., Shen, J., Tian, S., Meng, X., Li, Z., Liu, Y., 2012. Formation mechanism of magmatic rocks in Narusongduo lead-zinc deposit of Tibet: Evidence from magmatic zircon. *Mineral Deposits* 31, 758–774 (in Chinese with English abstract).
- Ji, X., Meng, X., Yang, Z., Zhang, Q., Tian, S., Li, Z., Liu, Y., Yu, Y., 2014. The Ar-Ar geochronology of sericite from the cryptexplosive breccia type Pb-Zn deposit in Narusongduo, Tibet and its geological significance. *Geology and Exploration* 50, 281–290 (in Chinese with English abstract).
- Kapp, P., Murphy, M.A., Yin, A.n., Harrison, T.M., Ding, L., Guo, J., 2003. Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet. *Tectonics* 22 (4), n/a–n/a.
- Kapp, P., Yin, A.n., Harrison, T.M., Ding, L., 2005. Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet. *Geol. Soc. Am. Bull.* 117 (7), 865. <https://doi.org/10.1130/B25595.110.1130/2005099>.
- Kapp, P., DeCelles, P.G., Leier, A.L., Fabijanic, J.M., He, S., Pullen, A., Gehrels, G.E., Ding, L., 2007a. The Gangdese retroarc thrust belt revealed. *GSA Today* 17 (7), 4. <https://doi.org/10.1130/GSAT01707A.110.1130/2007173>.
- Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., Ding, L., 2007b. Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area of central Tibet. *Geol. Soc. Am. Bull.* 119 (7–8), 917–933.
- Kapp, P., DeCelles, P.G., 2019. Mesozoic-Cenozoic geological evolution of the Himalayan-Tibetan orogen and working tectonic hypotheses. *Am. J. Sci.* 319 (3), 159–254.
- Karakas, O., Degruyter, W., Bachmann, O., Dufek, J., 2017. Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism. *Nat. Geosci.* 10 (6), 446–450.
- Ke, X., Long, W., Zhou, D., Wang, J., Zhong, S., 2017. Metallogenesis of the main collisional period in mid-western Gangdise: Zircon U-Pb geochronology of the granite porphyry in Dexin deposit. Tibet. *Geological Bulletin of China* 36, 772–779 (in Chinese with English abstract).
- Kenworthy, S., Hagemann, S.G., 2007. Fault and vein relationships in a reverse fault system at the Centenary orebody (Darlot gold deposit), Western Australia: Implications for gold mineralisation. *J. Struct. Geol.* 29 (4), 712–735.
- Klemm, L.M., Pettker, T., Heinrich, C.A., 2008. Fluid and source magma evolution of the Questa porphyry Mo deposit, New Mexico, USA. *Miner. Deposita* 43 (5), 533–552.
- Komuro, H., 1987. Experiments on cauldron formation: A polygonal cauldron and ring fractures. *J. Volcanol. Geoth. Res.* 31 (1–2), 139–149.
- Lang, X., Wang, X., Deng, Y., Tang, J., Xie, F., Yang, Z., Yin, Q., Jiang, K., 2019. Hydrothermal evolution and ore precipitation of the No. 2 porphyry Cu-Au deposit in the Xiongcu district, Tibet: Evidence from cathodoluminescence, fluid inclusions, and isotopes. *Ore Geol. Rev.* 114, 103141. <https://doi.org/10.1016/j.oregeorev.2019.103141>.
- Lee, H.-Y., Chung, S.-L., Lo, C.-H., Ji, J., Lee, T.-Y., Qian, Q., Zhang, Q.i., 2009. Eocene Neotethyan slab breakoff in southern Tibet inferred from the Linzizong volcanic record. *Tectonophysics* 477 (1–2), 20–35.
- Lee, H.-Y., Chung, S.-L., Ji, J., Qian, Q., Gallet, S., Lo, C.-H., Lee, T.-Y., Zhang, Q.i., 2012. Geochemical and Sr-Nd isotopic constraints on the genesis of the Cenozoic Linzizong volcanic successions, southern Tibet. *J. Asian Earth Sci.* 53, 96–114.
- Li, H., Tang, J., Hu, G., Ding, S., Li, Z., Xie, F., Teng, L., Cui, S., 2019a. Fluid inclusions, isotopic characteristics and geochronology of the Sinongduo epithermal Ag-Pb-Zn deposit, Tibet, China. *Ore Geol. Rev.* 107, 692–706.
- Li, Y., Wang, C., Dai, J., Xu, G., Hou, Y., Li, X., 2015. Propagation of the deformation and growth of the Tibetan-Himalayan orogen: A review. *Earth Sci. Rev.* 143, 36–61.
- Li, Y., Li, X.-H., Selby, D., Li, J.-W., 2018. Pulsed magmatic fluid release for the formation of porphyry deposits: Tracing fluid evolution in absolute time from the Tibetan Qulong Cu-Mo deposit. *Geology* 46, 7–10.

- Li, Y., Selby, D., Condon, D., Tapster, S., 2017. Cyclic Magmatic-Hydrothermal Evolution in Porphyry Systems: High-Precision U-Pb and Re-Os Geochronology Constraints on the Tibetan Qulong Porphyry Cu-Mo Deposit. *Economic Geology* 112.
- Li, Y., McCoy-West, A.J., Zhang, S., Selby, D., Burton, K.W., Horan, K., 2019b. Controlling Mechanisms for Molybdenum Isotope Fractionation in Porphyry Deposits: The Qulong Example. *Economic Geology* 114, 981–992.
- Liang, Y., Zhu, J., Ci, Q., He, W., Zhang, K., 2010. Zircon U-Pb Ages and Geochemistry of Volcanic Rock from Linzizong Group in Zhunuo Area in Middle Gangdise Belt, Tibet Plateau. *Earth Sci.* 35, 211–223 (in Chinese with English abstract).
- Lipman, P.W., Fisher, F.S., Mehnert, H.H., Naeser, C.W., Luedke, R.G., Steven, T.A., 1976. Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado. *Economic Geology* 71, 571–588.
- Lipman, P.W., Zimmerer, M.J., McIntosh, W.C., 2015. An ignimbrite caldera from the bottom up: Exhumed floor and fill of the resurgent Bonanza caldera, Southern Rocky Mountain volcanic field, Colorado. *Geosphere* 11 (6), 1902–1947.
- Liu, A., Wang, Q., Zhu, D.-C., Zhao, Z., Liu, S.-A., Wang, R., Dai, J., Zheng, Y., Zhang, L.-L., 2018. Origin of the ca. 50 Ma Linzizong shoshonitic volcanic rocks in the eastern Gangdese arc, southern Tibet. *Lithos* 304, 374–387.
- Liu, H.F., 1993. Division of Linzizong volcanic series and its geochronology in Lhasa area. *Tibet Geology* 2, 59–69 (in Chinese with English abstract).
- Liu, Y., Hou, Z., Yang, Z., Tian, S., Yang, T., Song, Y., Zhang, H., Carranza, E.J.M., 2011. Formation of the Dongmohazhua Pb–Zn Deposit in the Thrust-Fold Setting of the Tibetan Plateau, China: Evidence from Fluid Inclusion and Stable Isotope Data. *Resource Geology* 61, 384–406.
- Liu, Y., Hu, Z., Li, M., Gao, S., 2013. Applications of LA-ICP-MS in the elemental analyses of geological samples. *Chin. Sci. Bull.* 58 (32), 3863–3878.
- Liu, Z., Zhong, K., Zeng, Q., Xiluolangjie, Gou, J., Lu, Y., Zhang, Y., Zhang, C., Lei, B., Fan, Z., Ma, H., Zhang, Q., Yang, G., Huang, X., Bao, C., Yuan, H., Jia, F., Wei, J., Wang, C., Zhou, Z., Chen, L., Liu, X., Pang, J., 2019. Guide book of 1:1000000 geological map of the Tibet autonomous region. Geological publishing house, Beijing (in Chinese).
- Ludwig, K.W., 2008. User's manual for Isoplot 3.70: A geochronological toolkit for Microsoft Excel, Berkeley Geochronology Center Special Publication Number 4, Berkeley.
- Ma, L., Wang, Q., Wyman, D.A., Jiang, Z.Q., Wu, F.Y., Li, X.H., Yang, J.H., Gou, G.N., Guo, H.F., 2015. Late Cretaceous back-arc extension and arc system evolution in the Gangdese area, southern Tibet: Geochronological, petrological, and Sr–Nd–Hf–O isotopic evidence from Dazge diabbases. *J. Geophys. Res. Solid Earth* 120, 6159–6181.
- Ma, W., Liu, Y., Yang, Z., Li, Z., Zhao, X., Fei, F., 2017a. Alteration, mineralization, and genesis of the Lietinggang-Leqingla Pb–Zn–Fe–Cu–Mo skarn deposit, Tibet, China. *Ore Geol. Rev.* 90, 897–912.
- Ma, X., Xu, Z., Chen, X., Meert, J.G., He, Z., Liang, F., Meng, Y., Ma, S., 2017b. The origin and tectonic significance of the volcanic rocks of the Yeba Formation in the Gangdese magmatic belt, South Tibet. *J. Earth Sci.* 28 (2), 265–282.
- Ma, X., Meert, J.G., Xu, Z., Zhao, Z., 2017c. Evidence of magma mixing identified in the Early Eocene Caina pluton from the Gangdese Batholith, southern Tibet. *Lithos* 278–281, 126–139.
- MARTI, J., ABLAY, G.J., REDSHAW, L.T., SPARKS, R.S.J., 1994. Experimental studies of collapse calderas. *Journal of the Geological Society* 151 (6), 919–929.
- Maughan, D., Keith, J., Christiansen, E., Pulsipher, T., Hattori, K., Evans, N., 2002. Contributions from mafic alkaline magmas to the Bingham porphyry Cu–Au–Mo deposit, Utah, USA. *Miner. Deposita* 37 (1), 14–37.
- McCuaig, T.C., Kerrich, R., 1998. P–T–t–deformation–fluid characteristics of lode gold deposits: evidence from alteration systematics. *Ore Geol. Rev.* 12, 381–453.
- Milési, J.P., Marcoux, E., Sitorus, T., Simandjuntak, M., Leroy, J., Bailly, L., 1999. Pongkor (west Java, Indonesia): a Pliocene supergene-enriched epithermal Au–Ag–(Mn) deposit. *Miner. Deposita* 34 (2), 131–149.
- Mo, X., Dong, G., Zhao, Z., Guo, T., Wang, L., Chen, T., 2005. Timing of Magma Mixing in the Gangdise Magmatic Belt during the India-Asia Collision: Zircon SHRIMP U-Pb Dating. *Acta Geologica Sinica - English Edition* 79, 66–76.
- Mo, X., Niu, Y., Dong, G., Zhao, Z., Hou, Z., Zhou, S., Ke, S., 2008. Contribution of syn-collisional felsic magmatism to continental crust growth: A case study of the Paleogene Linzizong volcanic Succession in southern Tibet. *Chem. Geol.* 250 (1–4), 49–67.
- Murphy, M., Yin, A., Harrison, T., Dürr, S., Chen, Z., Ryerson, F., Kidd, W., X. W., X. Z., 1997. Did the Indo-Asian collision alone create the Tibetan Plateau? *Geology* 25, 719–722.
- Nadeau, O., Stix, J., Williams-Jones, A.E., 2016. Links between arc volcanoes and porphyry-epithermal ore deposits. *Geology* 44 (1), 11–14.
- Nguyen, P.T., Harris, L.B., Powell, C.McA., Cox, S.F., 1998. Fault-valve behaviour in optimally oriented shear zones: an example at the Revenge gold mine, Kambalda, Western Australia. *J. Struct. Geol.* 20 (12), 1625–1640.
- Pan, G., Wang, L., Li, R., Yuan, S., Ji, W., Yin, F., Zhang, W., Wang, B., 2012. Tectonic evolution of the Qinghai-Tibet Plateau. *J. Asian Earth Sci.* 53, 3–14.
- Pullen, A., Kapp, P., Gehrels, G.E., DeCelles, P.G., Brown, E.H., Fabijanic, J.M., Ding, L., 2008. Gangdese retroarc thrust belt and foreland basin deposits in the Damxung area, southern Tibet. *J. Asian Earth Sci.* 33 (5–6), 323–336.
- REDWOOD, STEWART.D., 1987. The Soledad Caldera, Bolivia: A Miocene caldera with associated epithermal Au–Ag–Cu–Pb–Zn mineralization. *GSA Bulletin* 99 (3), 395. [https://doi.org/10.1130/0016-7606\(1987\)99<395:TSCBAM>2.0.CO;2](https://doi.org/10.1130/0016-7606(1987)99<395:TSCBAM>2.0.CO;2).
- Reiners, P.W., Brandon, M.T., 2006. Using Thermochronology to understand orogenic erosion. *Annu. Rev. Earth Planet. Sci.* 34 (1), 419–466.
- Richards, J.P., 2009. Postsubduction porphyry Cu–Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere. *Geology* 37, 247–250.
- Richards, J.P., 2011. Magmatic to hydrothermal metal fluxes in convergent and collided margins. *Ore Geol. Rev.* 40 (1), 1–26.
- Richards, J.P., 2013. Giant ore deposits formed by optimal alignments and combinations of geological processes. *Nat. Geosci.* 6 (11), 911–916.
- Richards, J.P., 2015. Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: From subduction to collision. *Ore Geol. Rev.* 70, 323–345.
- Rowland, J.V., Simmons, S.F., 2012. Hydrologic, Magmatic, and Tectonic Controls on Hydrothermal Flow, Taupo Volcanic Zone, New Zealand: Implications for the Formation of Epithermal Vein Deposits. *Economic Geology* 107, 427–457.
- Rytuba, J.J., Arribas, A., Cunningham, C.G., McKee, E.H., Podwysocki, M.H., Smith, J.G., Kelly, W.C., Arribas, A., 1990. Mineralized and unmineralized calderas in Spain; Part II, evolution of the Rodalquilar caldera complex and associated gold-alunite deposits. *Miner. Deposita* 25 (S1), S29–S35.
- Rytuba, J.J., 1994. Evolution of volcanic and tectonic features in caldera settings and their importance in localization of ore deposits. *Economic Geology* 89, 1687–1696.
- Schoene, B., Schaltegger, U., Brack, P., Latkoczy, C., Stracke, A., Günther, D., 2012. Rates of magma differentiation and emplacement in a ballooning pluton recorded by U–Pb TIMS-TEA, Adamello batholith, Italy. *Earth Planet. Sci. Lett.* 355–356, 162–173.
- Shi, D., Gong, Y., Xiao, H., Yang, Z., Deng, T., Lu, Z., Tang, W., Jiang, X., 2016. Report on the resource reserve of the Narusongduo Lead-Zinc ore deposit in the Xietongmen county, Tibet autonomous region. Chongqing Institute of Geology and Mineral Resources 1–241 (in Chinese).
- Sibson, R., Robert, F., Poulsen, K., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposit. *Geology* 16, 551–555.
- Sibson, R.H., 1996. Structural permeability of fluid-driven fault-fracture meshes. *J. Struct. Geol.* 18 (8), 1031–1042.
- Sidorov, A.A., Volkov, A.V., Savva, N.E., 2015. Volcanism and epithermal deposits. *J. Volcanol. Seismolog.* 9 (6), 349–357.
- Sillitoe, R.H., 1985. Ore-related breccias in volcanoplutonic arcs. *Economic Geology* 80, 1467–1514.
- Stix, J., Kennedy, B., Hannington, M., Gibson, H., Fiske, R., Mueller, W., Franklin, J., 2003. Caldera-forming processes and the origin of submarine volcanogenic massive sulfide deposits. *Geology* 31 (4), 375. [https://doi.org/10.1130/0091-7613\(2003\)031<0375:CFPATO>2.0.CO;2](https://doi.org/10.1130/0091-7613(2003)031<0375:CFPATO>2.0.CO;2).
- Sun, Z., Pei, J., Li, H., Xu, W., Jiang, W., Zhu, Z., Wang, X., Yang, Z., 2012. Palaeomagnetism of late Cretaceous sediments from southern Tibet: Evidence for the consistent palaeolatitudes of the southern margin of Eurasia prior to the collision with India. *Gondwana Res.* 21 (1), 53–63.
- Tang, J., Wang, D., Wang, X., Zhong, K., Ying, L., Zheng, W., Li, F., Guo, N., Qin, Z., Yao, X., Li, L., Wang, Y., Tang, X., 2010. Geological features and metallogenic model of the Jiama copper-polymetallic deposit in Tibet. *Acta Geoscientia Sinica* 31, 495–506 (in Chinese with English abstract).
- Tang, J., Wang, L., Zheng, W., Zhong, K., 2014. Ore Deposits Metallogenic Regularity and Prospecting in the Eastern Section of the Gangdese Metallogenic Belt. *Acta Geol. Sin.* 88, 2545–2555 (in Chinese with English abstract).
- Tang, J., Ding, S., Meng, Z., Hu, G., Gao, Y., Xie, F., Li, Z., Yuan, M., Yang, Z., Chen, G., Li, Y., Yang, H., Fu, Y., 2016. The first discovery of the low sulfidation epithermal deposit in Linzizong volcanics, Tibet: A case study of the Sinogduo Ag Polymetallic deposit. *Acta Geoscientia Sinica* 37, 461–470 (in Chinese with English abstract).
- Taylor, R., 2009. Infill Textures. In: Taylor, R. (Ed.), *Ore Textures: Recognition and Interpretation*. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 1–31.
- Tramparulo, F.D.A., Vitale, S., Isaia, R., Tadini, A., Bisson, M., Prinzi, E.P., 2018. Relation between alternating open/closed-conduit conditions and deformation patterns: An example from the Somma-Vesuvius volcano (southern Italy). *J. Struct. Geol.* 112, 138–153.
- Vajdova, V., Baud, P., Wong, T.-F., 2004. Compaction, dilatancy, and failure in porous carbonate rocks. *J. Geophys. Res. Solid Earth* 109, 1–16.
- Vajdova, V., Zhu, W., Natalie Chen, T.-M., Wong, T.-fong., 2010. Micromechanics of brittle faulting and cataclastic flow in Tavel limestone. *J. Struct. Geol.* 32 (8), 1158–1169.
- Volkmer, J.E., Kapp, P., Horton, B.K., Gehrels, G.E., Minervini, J.M., Ding, L., 2014. Northern Lhasa thrust belt of central Tibet: Evidence of Cretaceous–early Cenozoic shortening within a passive roof thrust system? In: Nie, J., Horton, B.K., Hoke, G.D. (Eds.), *Toward an Improved Understanding of Uplift Mechanisms and the Elevation History of the Tibetan Plateau*. Geological Society of America.
- Wang, L., Gu, X., Cheng, W., Tang, J., Zhong, K., Liu, X., 2010. Sulfur and Lead isotope composition and tracing for the sources of ore-forming materials in the Mengya'a Pb–Zn deposit. *Tibet. Geoscience* 24, 52–58 (in Chinese with English abstract).
- Wang, L., Tang, J., Deng, J., Kang, H., Lin, X., Cheng, W., Li, Z., Zhang, Z., 2015. The Longmala and Mengya'a skarn Pb–Zn deposits, Gangdese region, Tibet: evidence from U–Pb and Re–Os geochronology for formation during early India-Asia collision. *Int. Geol. Rev.* 57 (14), 1825–1842.
- Wang, X., Lang, X., Tang, J., Deng, Y., He, Q., Xie, F., Li, L., Yin, Q., Li, Z., Li, Z., Yang, Z., Dong, S., Ding, F., Wang, Z., Huang, Y., 2020. Early Carboniferous back-arc rifting-related magmatism in southern Tibet: Implications for the history of the Lhasa terrane separation from Gondwana. *Tectonics* 39, e2020TC006237.
- White, N.C., Hedenquist, J.W., 1990. Epithermal environments and styles of mineralization: Variations and their causes, and guidelines for exploration. *J. Geochem. Explor.* 36 (1–3), 445–474.
- Williams-Jones, A.E., Heinrich, C.A., 2005. 100th Anniversary Special Paper: Vapor Transport of Metals and the Formation of Magmatic-Hydrothermal Ore Deposits. *Econ. Geol.* 100 (7), 1287–1312.
- Woodcock, N.H., Mort, K., 2008. Classification of fault breccias and related fault rocks. *Geological Magazine* 145, 435–440.
- Yang, Y., Ji, D., Liu, H., Zhang, J., Wang, L., Zhang, Z., Hu, Z., 2014. Re-Os dating of molybdenite from the Lietinggang iron polymetallic deposit of Tibet and its

- geological significance. *Geology in China* 41, 1554–1564 (in Chinese with English abstract).
- Yang, Z., Lu, Y.-j., Hou, Z., Chang, Z., 2015a. High-Mg Diorite from Qulong in Southern Tibet: Implications for the Genesis of Adakite-like Intrusions and Associated Porphyry Cu Deposits in Collisional Orogens. *Journal of Petrology* 56, 227–254.
- Yang, Z., Meng, X., Yao, S., Liu, Y., Ma, H., Zhao, M., Zhao, X., Liu, W., Tan, H., Yang, Z., Zhang, X., Zhou, J., Su, X., 2015b. Supplementary survey report on the Pb-Zn ore deposit in the Naursongduo mining district. Xietongmen county, Xizang autonomous region 1–198 (in Chinese).
- Yang, Z., Hou, Z., Chang, Z., Li, Q., Liu, Y., Qu, H., Sun, M., Xu, B., 2016. Cospacial Eocene and Miocene granitoids from the Jiru Cu deposit in Tibet: Petrogenesis and implications for the formation of collisional and postcollisional porphyry Cu systems in continental collision zones. *Lithos* 245, 243–257.
- Yang, Z., Tang, J., Zhao, X., Wang, Y., Santosh, M., Ran, F., Zhang, P., 2021. Direct dating of the Sinongduo thrust system in southern Tibet: immediate response to India-Asia collision. *Int. Geol. Rev.* 1–11.
- Yin, A., Harrison, T.M., 2000. Geologic Evolution of the Himalayan-Tibetan Orogen. *Annu. Rev. Earth Planet. Sci.* 28 (1), 211–280.
- Zhang, H., Yang, T., Hou, Z., Song, Y., Liu, Y., Yang, Z., Tian, S., 2017. Structural controls on carbonate-hosted Pb–Zn mineralization in the Dongmohazhua deposit, central Tibet. *Ore Geol. Rev.* 90, 863–876.
- Zheng, X., Jiao, W., Zhang, C., Wang, L., 2010. Short-Period Rayleigh-Wave Group Velocity Tomography through Ambient Noise Cross-Correlation in Xinjiang, Northwest China. *Bull. Seismol. Soc. Am.* 100 (3), 1350–1355.
- Zheng, Y., Sun, X., Gao, S., Zhao, Z., Zhang, G., Wu, S., You, Z., Li, J., 2014. Multiple mineralization events at the Jiru porphyry copper deposit, southern Tibet: Implications for Eocene and Miocene magma sources and resource potential. *J. Asian Earth Sci.* 79, 842–857.
- Zheng, Y., Sun, X., Gao, S., Wu, S., Xu, J., Jiang, J., Chen, X., Zhao, Z., Liu, Y., 2015. Metallogensis and the minerogenetic series in the Gangdese polymetallic copper belt. *J. Asian Earth Sci.* 103, 23–39.
- Zhong, K., Li, L., Zhou, H., Bai, J., Li, W., Zhong, W., Zhang, Y., Lin, J., Zheng, F., Huang, X., Lu, B., Lei, B., 2012. Features of Jiama (Gyama)-Kajunguo thrust-gliding nappe tectonic system in Tibet. *Acta Geoscientia Sinica* 33, 411–423 (in Chinese with English abstract).
- Zhong, K., Yao, D., Dorji, Zheng, F., Xu, C., Huang, X., Lu, B., Lei, B., Lin, J., Bao, C., Yan, G., 2013. Structural Features of Yeba Tectonite Group in Jiama (Gyama)-Qulong Area of Tibet. *Acta Geoscientia Sinica* 34, 75–86 (in Chinese with English abstract).
- Zhou, J., Yang, Z., Hou, Z., Liu, Y., Zhao, X., Zhang, X., Zhao, M., Ma, W., 2017. The geochemical evolution of syncollisional magmatism and the implications for significant magmatic-hydrothermal lead–zinc mineralization (Gangdese, Tibet). *Lithos* 288–289, 143–155.
- Zhou, J., Yang, Z., Wang, Q., Zheng, Y., Hou, Z., Wyman, D., 2020. Extraction of high-silica granites from an upper crustal magma reservoir: Insights from the Narusongduo magmatic system, Gangdese arc. *Am. Mineral.* 105, 1572–1584.
- Zhu, D.-C., Mo, X.-X., Niu, Y., Zhao, Z.-D., Wang, L.-Q., Pan, G.-T., Wu, F.-Y., 2009. Zircon U-Pb dating and in-situ Hf isotopic analysis of Permian peraluminous granite in the Lhasa terrane, southern Tibet: Implications for Permian collisional orogeny and paleogeography. *Tectonophysics* 469 (1–4), 48–60.
- Zhu, D.-C., Zhao, Z.-D., Niu, Y., Mo, X.-X., Chung, S.-L., Hou, Z.-Q., Wang, L.-Q., Wu, F.-Y., 2011. The Lhasa Terrane: Record of a microcontinent and its histories of drift and growth. *Earth Planet. Sci. Lett.* 301 (1–2), 241–255.
- Zhu, D.-C., Zhao, Z.-D., Niu, Y., Dilek, Y., Hou, Z.-Q., Mo, X.-X., 2013. The origin and pre-Cenozoic evolution of the Tibetan Plateau. *Gondwana Res.* 23 (4), 1429–1454.
- Zhu, D.-C., Wang, Q., Zhao, Z.-D., Chung, S.-L., Cawood, P.A., Niu, Y., Liu, S.-A., Wu, F.-Y., Mo, X.-X., 2015. Magmatic record of India-Asia collision. *Sci. Rep.* 5, 14289.
- Zhu, D.-C., Li, S.-M., Cawood, P.A., Wang, Q., Zhao, Z.-D., Liu, S.-A., Wang, L.-Q., 2016. Assembly of the Lhasa and Qiangtang terranes in central Tibet by divergent double subduction. *Lithos* 245, 7–17.
- Zhu, D., Wang, Q., Zhao, Z., 2017. Constraining quantitatively the timing and process of continent-continent collision using magmatic record: Method and examples. *Science China Earth Sciences* 60 (6), 1040–1056.
- Zhu, D.-C., Wang, Q., Chung, S.-L., Cawood, P.A., Zhao, Z.-D., 2019. Gangdese magmatism in southern Tibet and India-Asia convergence since 120 Ma. *Geological Society, London, Special Publications* 483 (1), 583–604.
- Zhang, Z., Zhao, G., Santosh, M., Wang, J., Dong, X., Shen, K., 2010. Late Cretaceous charnockite with adakitic affinities from the Gangdese batholith, southeastern Tibet: Evidence for Neo-Tethyan mid-ocean ridge subduction? *Gondwana Res.* 17 (4), 615–631.