Underfilled peripheral foreland development in response to the Proto-Tethys Ocean closure in the North Qilian, NE Tibet Plateau

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Abstract

The North Qilian Ocean (NQO) was the northernmost branch of the Proto-Tethys separating the Central Qilian Terrane (CQT) from the North China Block (NCB) since the Neoproterozoic Rodinia breakup. An enhanced knowledge on its evolutionary history would greatly improve our understanding on the tectonics of the Proto-Tethys and the assembly of the East Asia. However, the timing of the NQO closure onset remains unsolved with assumptions ranging from the end-Ordovician to the Devonian. To address this issue, integrated studies of stratigraphy, petrology and geochronology were conducted on the Ordovician strata in the SWNCB and the eastern North Qilian Accretionary Belt (ENQAB). Stratigraphic and paleontologic syntheses demonstrate that the pre-Katian strata in the SWNCB are shallow-marine deposits containing abundant benthonic faunas, while the Katian successions atop an unconformity are dominated by deep-water calcareous debrites and siliciclastic turbidites with the dominance of planktonic graptolites. Provenance analysis reveals an evolving source from the NCB basement to the CQT orogen since the Katian. The pre-Katian quartz arenites in the SWNCB contain zircons of ca. 1600–2800 Ma significantly older than their depositional timing, in contrast, the Katian turbidites in the SWNCB and the ENQAB display similar age patterns dominated by ca. 450–900 Ma ages. These clues imply a noteworthy basin-filling shift from passive margin to underfilled peripheral foreland separated by a forebulge unconformity at the Sandbian/Katian boundary. The first arrival of CQT-originated detritus onto the SWNCB at ca. 453 Ma is the oldest stratigraphic constraint for the initial elimination of the northern Proto-Tethys.

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Running Title: Late Ordovician underfilled peripheral foreland in the North Qilian

Key Points:

1. An underfilled peripheral foreland was formed in the western North China Block at ca. 453 Ma.
2. The initial closure of the eastern North Qilian Ocean was synchronous along-strike at ca. 453 Ma.
3. The accretion of the Central Qilian arc terrane onto the western North China Block began at ca. 453 Ma.

Abstract

The North Qilian Ocean (NQO) was the northernmost branch of the Proto-Tethys separating the Central Qilian Terrane (CQT) from the North China Block (NCB) since the Neoproterozoic Rodinia breakup. An enhanced knowledge on its evolutionary history would greatly improve our understanding on the tectonics of the Proto-Tethys and the assembly of the East Asia. However, the timing of the NQO closure onset remains unsolved with assumptions ranging from the end-Ordovician to the Devonian. To address this issue, integrated studies of stratigraphy, petrology and geochronology were conducted on the Ordovician strata in the SWNCB and the eastern North Qilian Accretionary Belt (ENQAB). Stratigraphic and paleontologic syntheses demonstrate that the pre-Katian strata in the SWNCB are shallow-marine deposits containing abundant benthonic faunas, while the Katian successions atop an unconformity are dominated by deep-water calcareous debrites and siliciclastic turbidites with the dominance of planktonic graptolites. Provenance analysis reveals an evolving source from the NCB basement to the CQT orogen since the Katian. The pre-Katian quartz arenites in the SWNCB contain zircons of ca. 1600–2800 Ma significantly older than their depositional timing, in contrast, the Katian turbidites in the SWNCB and the ENQAB display similar age patterns dominated by ca. 450–900 Ma ages. These clues imply a noteworthy basin-filling shift from passive margin to underfilled peripheral foreland separated by a forebulge unconformity at the Sandbian/Katian boundary. The first arrival of CQT-originated detritus onto the SWNCB at ca. 453 Ma is the oldest stratigraphic constraint for the initial elimination of the northern Proto-Tethys.

Key Words: Ocean closure; Peripheral foreland; Katian; North Qilian Ocean; North China Block.

1. Introduction

The Central China Orogenic System is a giant orogenic collage suturing the northern and southern China blocks (Figure 01a). It has been established to represent the relic of the northern Proto-Tethys and Paleo-Tethys (Metcalfe, 2013, 2021; Liu et al., 2005, 2015; Huang et al., 2018), making it crucial to understand geologic processes from the Rodinia break-up, via Gondwana assemblage, to Pangea assembly, which finally resulted in the amalgamation of the East Asian continent (Zuza & Yin, 2017; Domeier, 2018; Zhao et al., 2018; Metcalfe, 2021).

The Qilian Orogen at the central portion of the Central China Orogenic System occupies a key position as the northernmost tectonic collage of the Proto-Tethyan realm (Xiao *et al.*, 1978, 1986, 2009; Chang *et al.*, 1986; Bian *et al.*, 2001; Pan *et al.*, 2004, 2012; Xu *et al.*, 2013a; Zhang *et al.*, 2015a, 2019b; Li et al., 2017, 2018a; Dong et al., 2018a, b). It has become the focus of extensive research for decades. Multidisciplinary approaches have contributed to a better understanding on its tectonic architecture, complicated accretionary-collisional processes and subsequent intracontinental orogenesis (Xiao *et al.*, 1978, 2009; Yin & Harrison 2000; Gehrels *et al.*, 2003a, b; Xia *et al.*, 2003, 2016; Song *et al.*, 2006, 2007, 2013, 2017; Zhang et al., 2007, 2018; Yin et al., 2008). Nonetheless, there is still no consensus on the timing of the North Qilian Ocean (NQO) closure onset, e.g., the oceanic subduction termination, with diverse presumptions varying in age from the end-Ordovician to the Devonian (Yin & Harrison, 2000; Xiao et al., 2009; Xu *et al.*, 2010a, b, 2013b; Yan *et al.*, 2010; Gehrels *et al.*, 2011; Song *et al.*, 2013; Yuan & Yang, 2015; Zuza *et al.*, 2018). This unsolved tectonic issue has greatly hampered our knowledge on the convergent processes of the NQO and the geologic evolution of the Proto-Tethys Ocean.

Sedimentary-related records are sensitive to paleotectonic and paleogeographic interrelationships, playing an increasingly important role to test alternate paleogeographic and paleotectonic reconstructions in addition to known magmatic and metamorphic approaches (Dickinson & Suczek., 1979; Du *et al.*, 2003, 2009; Cawood *et al.*, 2012; Sun & Dong, 2020a). At the initial stage of arc-continent collision, closure of the intervening ocean may bring the edge of passive margin to collide with the arc terrane, generating an underfilled foreland along the suture zone (Sinclair et al., 1997; Aitchison et al., 2000; DeCelles *et al.*, 2014). Rock masses transported from the obducting orogenic highland to foreland at the low relief on the subducting plate preserve valuable clues to limit the time when the two blocks commenced to be juxtaposed (Dickinson, 1985; Hu et al., 2012, 2015, 2016; An et al., 2021). In the light of this simple principle, identifying the oldest siliciclastic sedimentary rocks upon the western end of the SWNCB that contain detritus derived from the CQT arc will yield a straightforward and robust constraint on the timing of the ENQO closure onset, and by reference the resulted accretion of the CQT onto the SWNCB.

In the eastern North Qilian Accretionary Belt (ENQAB) and the SWNCB, relatively continuous and biostratigraphically well-constrained Ordovician successions are preserved around the North Qilian Suture. These pivotal stratigraphic imprints provide a unique window to constrain tectonic processes of the shrinking and closure of the ENQO. In this study, we integrate stratigraphy and paleontology with detrital zircon geochronology to demonstrate a Katian tectonic transition into underfilled foreland, witnessed by shift of paleogeography and source-to-sink relation in the ENQAB and the SWNCB. These new insights in basin-filling conversion allow us to propose a direct constraint on the timing of the collision onset between the CQT and the SWNCB, which will further shed light on subsequent studies concerning the Qilian Orogen.

2. Tectonic outline of the Qilian Orogen and the SWNCB

The Central China Orogenic System, striking in a NWW-SEE trend, stretches across the central China from the Kunlun-Qaidam-Qilian orogenic collage in the west to the Qinling-Dabie-Sulu orogen in the east (Figure 01a; Xiao et al., 2002a, b, 2005; Huang et al., 2018; Zhao et al., 2018; Sun et al., 2019, 2020; Zhao et al., 2020). The Early Paleozoic Qilian Orogen at the northern margin of the Tibetan Plateau occupies a conjunction among the SWNCB to the east, the Tarim Block to the west, and the Olongbuluke Terrane to the south (Figure 01b). It is truncated and sinistrally offset for ~400 km by the Altyn Tagh Fault that delineates its western border with the Tarim Block (Zhang et al., 2007, 2018; Song et al., 2013, 2019a; Qian et al., 2021). On the other side, it is continuous eastward to the North Qinling Orogen (Dong et al., 2011, 2021; Yan et al., 2006, 2014, 2019a; Zuza & Yin, 2017; Sun & Dong, 2020b).

The northern border fault of the Qilian Orogen dips southwards (Figure 01c) and extends eastwards from Longshoushan, Chahan, via Qintongxia, to Guyuan, namely the Longshoushan Fault (Figure 01b; Dong et al., 2021). Lying to its north is the SWNCB that incorporates the Alxa Terrane in the west and the Ordos Basin (Block) in the east (Figure 01b; Zhang & Gong, 2018; Sun & Dong, 2019 a, b). Much of the SWNCB is floored by an Archean to Paleoproterozoic basement that was finally crystallized at ca. 1.8 Ga

(Zhao et al., 2002, 2005, 2012; Zhao & Cawood, 2012; Zhang et al., 2013, 2015b; Wu et al., 2021a) prior to the accumulation of non-metamorphosed sedimentary cover from the Mesoproterozoic to present (Figure 01d; Chen, 2011; Sun & Dong, 2019c). Some Meso- and Neoproterozoic terranes in the western Alxa Terrane, which were accreted to the SWNCB in the Paleozoic (Sun & Dong, 2020a), complicate its tectonic composition and geologic history.

The Qilian Orogen is a wide orogenic collage that can be further divided into three sub-parallel units with distinct litho-tectonic fluctuation and resulted tectono-lithostratigraphy, including, from north to south, the NQAB, the CQT, and the South Qilian Accretionary Belt (Xiao et al., 2009; Li et al., 2017; Song et al., 2017; Sun et al., 2019, 2020; Dong et al., 2021).

In contrast to the SWNCB, the NQAB was active from the Neoproterozoic to the Paleozoic (Figure 01d), characterized by the occurrence of the end-Neoproterozoic to the Early Paleozoic accretionary mélange-ophiolite complexes (Song, 1997; Qian et al., 1998, 2001; Zhang et al., 2001, 2007; Xia & Song, 2010; Fu et al., 2019a, 2020a, 2021a), subduction-collision induced volcanic and plutonic rocks (Song et al., 2013), high-pressure metamorphic rocks (Zhang et al., 2001, 2007; Song et al., 2006, 2007; Fu et al., 2020b), as well as the Ordovician to the Devonian flysch and molasse formations (Yan et al., 2007, 2010; Yang et al., 2009; Xu et al., 2010a, 2013a). The NQAB has been interpreted to be a typical oceanic suture zone as a product of the end-Neoproterozoic to the mid-Paleozoic opening, spreading, south-dipping subduction, and ultimate termination of the NQO (Sobel & Arnaud, 1999; Geherels et al., 2003a, b). This ocean could be traceable eastwards with the Erlangping Ocean between the North Qinling Arc Terrane and the NCB (Dong et al., 2011, 2015, 2018b; Yan et al., 2016; Song et al., 2017).

The CQT is an early Paleozoic arc terrane underlain by an imbricated thrust belt of Precambrian crust that is composed mostly of 850–1000 Ma garnet-bearing granitic gneiss (Gehrels et al., 2003b; Tseng et al., 2006, 2009; Tung et al., 2007a, 2013) and paragneiss with detrital zircon ages older than 880 Ma (Tung et al. 2007b). Minor amounts of Paleoproterozoic migmatitic granites dated at ca. 1800 Ma and ca. 2500 Ma (Wang & Chen, 1987; Gehrels et al., 2003a) as well as the Meso- to Neoproterozoic cratonal and/or passive marginal strata also exist (Gehrels et al., 2003a; Wu et al., 2016; Zuza et al., 2018). The crystalline basement of the CQT has been intensively reworked by ca. 440–520 Ma arc magmatic activity and ca. 400–435 Ma collisional to post-orogenic magmatism (Gehrels et al., 2003b; Song et al., 2013, 2019a; Tung et al., 2016; Fu et al., 2019b, c) as a consequence of closure of oceanic basins to its southern and northern sides. The CQT has been hypothetically proposed to be comparable with the North Qinling Arc Terrane, given the similarity of the Precambrian basement and two episodes of orogeny during the Grenville and Caledonian age (Li et al., 2017; Zhao et al., 2020).

The South Qilian Ophiolite-Accretionary Belt is a belt of subduction–accretion complexes (Pan et al., 2012; Yan et al., 2015, 2019b; Song et al., 2017; Fu et al., 2018; Yang et al., 2019). It is characterized by the exposure of the end-Neoproterozoic to the Early Paleozoic subduction-related volcano-sedimentary rocks with several accreted terranes preserved in the east (Yan et al., 2015; Song et al., 2017). Dismembered ophiolites with formation ages of the end-Neoproterozoic to the Ordovician discontinuously outcrop along and in fault contact with the southern rim of the CQT, including, from west to east, the Dadaoerji, Muli, Gangcha, and Lajishan ophiolites generated mostly in the supra subduction zone location above a north-dipping oceanic crust (Fu et al., 2018; Yan et al., 2019a, b; Yang et al., 2019). Lying to the south of these arc–ophiolite complexes is a widespread belt of, tightly folded, cleaved, siliciclastic and volcaniclastic turbidites (Xiao et al., 2009), intruded by the pervasive mid-Paleozoic plutons (Dong et al., 2021). These deep-water sediments have been mapped as the Ordovician to the Silurian strata, while several weighted mean ages of ~720–740 Ma have been obtained from volcanic rocks (Yan et al., 2021), hinting at a much earlier depositional onset and a likely longer accretionary history. This belt is traceable further east to the Shangdan Suture in the east Qinling Orogen (Yan et al., 2015; Dong & Santosh, 2016; Song et al., 2017; Li et al., 2018b; Zhao et al., 2020).

In this study, we mainly focus on an area at the conjunction of the southwestern Ordos Basin, ENQAB and CQT, stretching across the tectonic limit between the SWNCB and the eastern Qilian Orogen (e.g., the eastern segment of the Longshoushan Fault: Figure 01b).

3. Ordovician stratigraphy and sedimentology of the SWNCB

3.1 Stratigraphic units and depositional timing

Nine stratigraphic columns of outcrops and drill cores, distributed along-strike to the eastern side of the LSF (Figure 01b), were synthesized to show Ordovician stratigraphy and sedimentology of the southernmost NCB (Figures 02&03). Chronostratigraphic estimates of each stratigraphic unit and lateral correlation among different columns employ an updated chronostratigraphic proposal (Figure 02) on basis of high-precision conodont and radiolarian biostratigraphy and zircon U-Pb dating (Jing *et al.*, 2015, 2020; Zhen et al., 2016; Fan et al., 2020; Zhang et al., 2019a; Perera & Aitchison, 2021). Numerical ages noted in

Figure 02 are according to the timescale of Cohen et al., (2013). Five stratigraphic units with distinct lithological assemblages were termed to as the Sandaokan, Zhuozishan, Kelimoli, Wulalke and Lashizhong formations, in ascending order (Figure 02). The Ordovician stratigraphy in the SWNCB is shaped by two stratigraphic breaks, an earlier one separating the Middle Ordovician successions from the underlying Cambrian strata and a younger one at the Sandbian-Katian boundary. This work focuses on the upper Zhuozishan, Kelimoli, Wulalike, and Lashizhong formations deposited in the Late Ordovician (Figure 03).

Stratigraphic age of the Kelimoli Formation has been deduced to be the end-Darriwilian on account of conodont biostratigraphy (Jing et al., 2015). However, Wang et al. (2013, 2016a) argued that these conodont assemblages belong instead to the Sandbian or Katian, which is in excellent agreement with proposals of Perera and Aitchison (2021) that assigned a late Sandbian age for radiolarian faunas obtained from the lower section. Seven robust weighted mean ages (2σ) of 454.9±3.4 Ma to 449.9±1.7 Ma (Figure 02) have been obtained for tuff layers in the Kelimoli and Wulalke formations, identical within error to late Sandbian to Katian age indicated by biostratigraphy. These insights constrain deposition onset to the earliest Katian (ca. 453 Ma). The highest level of the Katian strata in the SWNCB have been suggested to be ca. 448 Ma (Chen et al., 2013). Thus, the Kelimoli, Wulalike, and Lashizhong formations can be reinterpreted to be the Katian with a short period of ca. 453–448 Ma. Meanwhile, deposition of the underlying Zhuozishan Formation may sustain to the Sandbian from the late Darriwilian (Zhen et al., 2016; Zhang et al., 2019a).

3.2 Pre-Katian shallow carbonate shelf facies (Sandaokan and Zhuozishan formations)

Stratigraphic contact below the Darriwilian Sandaokan Formation is a craton-wide unconformity overlying layers of diverse ages from the Cambrian to the Early Ordovician (Myrow et al., 2015; Zhen et al., 2016). A set of terrestrial sediments composed of gravel-bearing quartz arenites and carbonate clasts constitute the base of the Sandaokan Formation in the Zhuozishan, grading southward to thick dolostone with a small amount of sand-sized quartz grains in the Qinlongshan (Yang et al., 2011). The Sandaokan Formation consists of thick beds of dolostone interbedded with limestone and quartz sandstone (Li et al., 2021). Carbonate beds are mostly bioturbated and contain abundant benthic gastropods, brachiopods, and cephalopods (Fei et al., 2004). This mixed carbonate-siliciclastic sequence represents neritic deposition in a relatively shoreward inner shelf portion (Mount, 1984; Fei et al., 2004; Varejão et al., 2021). Limestone, mostly massive bedded bioclastic grainstone and packstone (Figures 04a, b), dominates the lithology of the

Zhuozishan Formation (Li et al., 2012; 2020) that conformably overlies the Sandaokan Formation. Patch reefs and mounds (Figure 04c) also present (Zhao et al., 2014). This lithofacies association and the enrichment of benthic faunas (Jing et al., 2015) imply deposition in a seaward shallow shelf far away from the terrigenous influx. Collectively, the Darriwilian to Sandbian sequence represents a nearly uninterrupted sedimentation in shallow-water carbonate shelf environments and records an overall transgression from shoreline and nearshore settings to more offshore environments (Feng et al., 1998; Myrow et al., 2015; Sun & Dong, 2020a).

3.3 Katian deep-water assemblages (Kelimoli, Wulalike and Lashizhong formations)

The Zhuozishan Formation is capped by a disconformity (Guo et al., 2012), where the major lithology changes abruptly from thick stack of bioclastic limestone to rhythmic thin- to medium-bedded lime mudstone (Figure 04d) with thin interbeds of shale and calciturbidite, and then grade upwards into multi-episodic slumps (Chen, 2011; Ma et al., 2013) slides and debrites (Figure 04e). Surfaces of limestone beds are planar to nodular with sets of beds mappable over wide areas (Figure 04f). The uneven fabric and the occurrence of subaqueous mass-transport deposits indicate deep-water gravitational settling of calcareous oozes (Wang et al., 2021a) that were winnowed from adjacent shallow platforms to an unstable slope (Sun & Dong, 2020b). This insight is supported by paleontological observations (Jing et al., 2015) that noted the dominance of radiolarian faunas and planktonic graptolites (Fu et al., 1993). Volcanic interbeds are common in outcrops and have been identified in core drillings (e.g., Yutan 1; Kang, 2021). Lateral stratigraphic relation shows that the bathyal carbonate slope varied eastwards into shallow platform as exemplified by thick deposition of bioclastic limestone and dolomite around wells Lucan 1 (Figure 03) and Gutan 1 (Ma et al., 2013; Wu et al., 2018). The inferred westwards deepening topography is coherent with WNW-dipping palaeoslope based on measurements of slumped folds, imbricated thrust beds, imbricated breccia, and strike of channels (Li et al., 2021).

The Wulalike Formation underlying the Lashizhong Formation (Figure 05a) is dominated by pelagic black graptolite-bearing shale (Figure 05b; Li et al., 2012; Chen et al., 2020), thin beds of radiolarian chert and lime mudstone with interlayers of gravity flow deposits (Figure 05c). Breccias are mostly irregular and chaotic limestone gravels, the lithologies of which are consistent with rocks of the underlying Kelimoli Formation, although in a few cases mixed lithologies exists (Figure 05d). Beds of breccias generally show lenticular morphology with erosional bases and substantial variation in lateral thickness (Ma et al., 2013).

Faunas obtained from this unit comprise mixed shallow-water and in situ deep-water forms (Jing et al., 2015). The Wulalike Formation represents deposition in a slope-basin transition, where in-situ pelagic basin plain shales were deposited and were continually disturbed by the redeposition of carbonates that constructed submarine fans around the slope apron (Gao et al., 1995; Li et al., 2012).

The Lashizhong Formation is typical siliciclastic turbidites (Sun & Dong, 2020a) composed of alternating greenish-gray shale, sandstone and thin bedded argillaceous limestone (Figure 05e), from which *Nereites* ichnofacies representing deep-marine environment have been found (Fei, 2001). Mass movement deposits, such as slides and slumps (Figure 05f), are common. Coeval successions in the ENQAB, e.g., the Miboshan Group, are also siliciclastic turbidites (Figure 05g) reworked by gravity-induced mass transportation (Figure 05h). These siliciclastic flysches indicate accumulation in a politic abyssal plain punctuated by turbidity currents in front of subaqueous fans relatively far from the continental rise (Sun & Dong, 2020a).

4. Provenance data: sandstone petrology and detrital zircon U-Pb geochronology

Analytical methods of sandstone petrology and detrital zircon U-Pb geochronology, as well as reprehensive mircophotos for sandstone and cathodoluminescence (CL) images of analyzed zircons are listed in the **Appendix**.

3.1. Petrographic composition

The Cambrian Sample SYSX01 is quartz arenite; its petrology is similar with other Cambrian to Middle Ordovician samples obtained from the SWNCB. Principal grain types are dominated by monocrystalline quartz grains, with a few amounts of polycrystalline quartz grains. Framework grains are well rounded and moderately sorted, indicating high textural and compositional maturity.

In contrast, the Upper Ordovician samples from the SWNCB (e.g., the Lashizhong Formation) and the ENQAB (e.g., the Miboshan Formation) are generally subangular and poorly sorted, characteristic of low textural maturity. According to the petrologic classification proposed by Pettijohn (1975), these sandstones are mostly sublitharenite or subfeldspathic arenite (Figure 06a) with moderate compositional maturity. These sublitharenitic and subfeldspathic arenites are characterized by a variably ranging percentage of monocrystalline quartz (27.1–76.1 %), feldspar (1.5–29.9 %) and lithic fragments (6.6–68.0 %). Except for the Shibangou section, samples from which comprise a large amount of limestone lithic fragments (12.7–55.3 %), samples from other sections are dominated by 44.8–76.1 % of monocrystalline quartz grains, and relatively lack lithic grains (2.6–18.9 %). Averaged modal composition values of Qt/F/L and Qm/F/Lt are 70.8/8.7/16.4 and 62.6/8.7/24.6, respectively, which both fall within the range of "continental block provenances" (Figure 06b) and "recycled orogeny provenances" (Figure 06c) on the tectonic discrimination diagrams of Dickinson (1985). In comparison, those for the Cambrian to Middle Ordovician all plot in the field of "craton interior sediments". This inference is coherent with result of the Qp/Lv/Ls diagram that depicts a mixed orogen source (Figure 06d).

3.2. LA-ICP–MS zircon U–Pb dating

Eight representative medium- to coarse-grained sandstone samples and one tuff sample were selected for zircon U–Pb dating by Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Of these eight sandstone samples, one (Sample SYSX01) is from the Cambrian Xuzhuang Formation in the SWNCB, five samples are from the Upper Ordovician Lashizhong Formation in the SWNCB and two samples are from Upper Ordovician Miboshan Formation in the ENQAB. Approximate geologic locations and stratigraphic levels of these samples from this and published studies were shown on Figures 01b & 03, respectively. Detailed information on location and petrology of each sample is listed in the Appendix Part 2.

3.2.1. Cambrian quartz arenite

Zircons from the Cambrian Sample SYSX01 are well rounded and sorted with clear margin of abrasion. Diameters of unbroken grains range from 80 μm to 100 μm. On the CL image, majority of zircons show clear oscillatory zoning and nebulous internal structures, with a few grains being sector-zoned or structureless.

A total of 100 analyses on 100 grains produced 88 data with sufficient precision for geochronological interpretation (Figure 07a). The concordant ages are all Paleoproterozoic, falling in the span of ca. 1584 Ma to ca. 2826 Ma, and are grouped into two major clusters (Figure 07b). The early Paleoproterozoic cluster contains 37 ages and constitutes a narrow peak at ca. 2446 Ma. The late Paleoproterozoic population is composed of 32 data that define a wide peak at ca. 1801 Ma. A small number of ages occur at ca. 1970 Ma to ca. 2187 Ma with two poorly defined peaks at ca. 2010 Ma.

3.2.2. Upper Ordovician turbidite

Zircons from the Upper Ordovician sandstones are mostly prismatic euhedral fragments, with some sub-rounded to rounded grains displaying abrasive shapes (Figures 07b, c, d, e, f, g & h). The lengths of unbroken grains vary variably from 60 μm to 180 μm with aspect ratios of 1:1 to 2:1. Most grains exhibit oscillatory zoning and nebulous internal structures in CL images, and a few grains show core-rim and plate structures. Most of them have Th/U values greater than 0.1, indicating an igneous origin (Belousova et al., 2002; Corfu, 2003). Minor amounts of grains display homogeneous or structureless structures with low Th/U ratios, likely suggesting a metamorphic origin.

Analyses on the Lashizhong Formation sandstone SMN01 from the Xishan section yielded 115 concordant results ranging in age from 489±10 Ma to 3215±35 Ma, and display age peaks at ca. 490 Ma, ca. 565 Ma, ca. 776 Ma, ca. 959 Ma, ca. 2463 Ma and ca. 2664 Ma (Figures 07c & d). Two major age populations display peaks at 959 Ma composed of 28 ages of 900–1018 Ma and 2463 Ma composed of 18 ages of 2433 Ma–2798 Ma. Six ages of 1603–1717 Ma define a subordinate peak at 1633 Ma.

A total of 113 concordant ages obtained from the Lashizhong Formation sandstone SXG03 from the Xianggen section span from 514±10 Ma to 3500±31 Ma (Figures 07e & f). Three oldest zircons have ages of 3046±35 Ma, 3412±31 Ma and 3500±31 Ma. The largest age clusters include 27 ages between 961 Ma and 1053 Ma with a single peak at 1024 Ma. Secondary clusters peaking at 1748 Ma and 2462 Ma also present.

A total of 120 analyses on zircons of the Lashizhong Formation sandstone SGK03 generated 109 concordant data. Its age spectrum spans from 451±11 Ma to 3542±32 Ma (Figures 07g & h). This sample is characterized by the early Paleozoic results, which comprise 56 data of 451±11–470±11 Ma and define a prominent peak at ca. 466 Ma. A few ages make up subsidiary peaks at 956 Ma (13 ages between 888 Ma and 976 Ma) and 2440 Ma (5 ages between 2363 Ma and 2485 Ma).

Up to 120 datings on the Lashizhong Formation sandstone SHX04 collected from the Shibangou section yielded 108 reliable ages (Figures 07i & j). The notable age cluster occurs at ca. 995 Ma, with secondary ages peaking at ca. 1607 Ma and ca. 2482 Ma.

A total of 120 analyses on the Lashizhong Formation sandstone SHX06 from the Shibangou section generated 110 ages with less than 10% discordance (Figures 08a & b). These ages fall in the range from

533 Ma to 3532 Ma. Nineteen ages of 2360–2563 Ma, twenty-two ages of ca. 900–1022 Ma and thirteen ages of ca. 1522–1675 Ma define 3 peaks at 2497 Ma, 969 Ma and 1603 Ma.

A total of 100 analyses on 100 zircons from the Miboshan Formation sandstone SJSP01 yielded 99 isotopic data of acceptable discordance and precision, ranging in ages from 448±9 Ma to 3483±31 Ma (Figures 08c & d). One youngest zircon yields a Late Ordovician age of 448±9 Ma. Major age groups occur at 656 Ma to 2728 Ma and define a single age cluster of 900–1100 Ma with a highest age peak at 964 Ma. Secondary age populations define some subdominant peaks at ca. 1580 Ma, ca. 1834 Ma, and ca. 2440 Ma. Two scatted late Neoproterozoic ages are 622±11 Ma and 624±6 Ma.

Of the up to 100 analyses on the Miboshan Formation sandstone SWRO01, 98 analyses plot on or near the concordia and yield ages with less than 10% discordance (Figures 08e & f). The concordant ages vary from 447±9 Ma to 2565±36 Ma. Thirteen Early Paleozoic ages were detected; the youngest 8 ages are clustered in the range of 447±9 Ma to 461±9 Ma and yield a weighted average age of 453±3 Ma (Figure 08e). The majority of ages fall in the span of ca. 1300–1700 Ma, with three unobvious peaks at ca. 1418, ca. 1600 and ca. 1736 Ma. Some Neoproterozoic ages define two secondary peaks at ca. 777 Ma and ca. 901 Ma.

3.2.3. Upper Ordovician tuff

A total of 48 analyses on the volcanic sample SJT-05 from a tuffaceous layer of the lower Lashizhong Formation at the Pingliang section generated 41 concordant ages between 444±10 Ma and 456±10 Ma, which define a weighted average age of 452±3 Ma with mean squared weighted deviation (MSWD) = 0.071 (Figures 08g & h).

5. Discussion

5.1. The NCB-Qilian provenance reversal at the Katian

Paleogeographic reconstructions reveal a reverse of sediment supply in the SWNCB from northeast to southwest (present coordinate) at the Katian. Paleocurrent directions, obtained from orientated fossils in the end-Darriwilian Sandaokan Formation, indicate the Middle Ordovician sediment transport from the northeast (Fei et al., 2004), consistent with stratigraphic correlation that shows southward-decreasing terrestrial influx from tens of meters thick quartz sandstone to pure carbonate (Sun & Dong, 2020a). In contrast, paleocurrent directions, measured from the Katian Lashizhong Formation, direct northeastwards to eastwards (Figure 03; Gao et al., 1995), inferring northeastward sediment dispersal. Facies distribution also displays decreasing siliciclastic influx towards the northeast, until termination in the well Lucan 1 where turbidites are absolutely absent (Figure 03). Triangular diagrams also highlight a sharp compositional change from the end-Darriwilian pure quartz arenites derived from cratonic interiors to the Katian subfeldspathic/sublithic arenites sourced from mixed orogen sources (Figure 06).

This evolving provenance is also supported by the changing detrital zircon U-Pb age spectra. Age patterns of the Middle Ordovician quartz arenites of the SWNCB compare well with those of the underlying Mesoproterozoic to Cambrian samples (Figure 09a), which comprise zircons without ages younger than Paleoproterozoic. However, age relations for turbidites from the Late Ordovician Lashizhong Formation (Figure 09b) are very similar to those of time-equivalent Miboshan Formation in the ENQAB (Figure 09c), comprising mostly post-Mesoproterozoic ages with a strong peak at ca. 950 Ma or ca. 460 Ma, notably close to their depositional timing.

Cratonization of the NCB was terminated by the amalgamation of the Yinshan (Alxa) and Ordos Blocks along the Khondalite Belt at ca. 1.92 Ga (Zhao et al., 2005; Zhao et al., 2012; Wan et al., 2013; Zuza & Yin, 2017). Its Archean and Paleoproterozoic crystalline basement (with predominately ca. 2.5 and 1.95–1.80 Ga ages; Sun & Dong, 2019c, Liu et al., 2021) was subsequently stable and capped by shallow marine deposits accumulated in rift to passive margin settings from the Mesoproterozoic to the Paleozoic age (Gehrels et al., 2011; Zhao & Cawood, 2012; Dong & Santosh, 2016). The post-Paleoproterozoic magmatic activities occur rarely and are even absent in the Paleozoic, except for a few ca. 900 Ma-aged mafic dikes (Peng et al., 2011; Peng, 2015). In contrast, crustal evolution of the CQT was constructed by two major episodes of pervasive granitic pluton emplacements at the Neoproterozoic and the Paleozoic (Gehrels et al., 2003b; Yong et al., 2008; Xia et al., 2012; Song et al., 2013; Yu et al., 2013, 2021). Thus, the presence and/or absence of ubiquitous magmatic flare-ups of ca. 900 Ma and ca. 460 Ma makes us easily distinguishing sources from each unit.

All NCB-originated sandstones yield two age peaks at ca. 1850 and ca. 2450 Ma (Figure 09a), characteristic of those identified from the NCB basement (Figure 10a; Darby & Gehrels, 2006; Sun & Dong, 2019c). Therefore, we attribute the provenance of the Pre-Katian strata to the erosion of the SWNCB basement to the northeast and possible recycling of older covers sourced from it (Sun & Dong, 2020a). In the northeastern Ordos Basin, a topographic high termed as the Yimeng highland (Figure 01b) existed in the Ordovician (Li et al., 2012, 2020), where ca. 2500 Ma supracrustal rocks and ca. 2000–2200 Ma granitic rocks as the basement of the Yinshan and Ordos Blocks were exposed then (Zhao et al., 2005, 2012; Jian et al., 2012; Dong et al., 2013; Liu et al., 2018a, b, 2020, 2021). In addition, ca. 1850–1950 Ma khondalite series that recorded continent–continent collision between the Yinshan and Ordos Blocks were exposed in the Khondalite Belt (Zhao et al., 2002, 2012; Yin et al., 2009, 2011; Li et al., 2011).

As discussed above, the Neoproterozoic to the Paleozoic tectonic activities are not substantial in the SWNCB, whereas age distributions of the Late Ordovician turbidites from the SWNCB and the ENQAB are all characterized by the dominance of age populations of both stages (Figures 09b & c). The strong similarity of age patterns between the CQT with the Late Ordovician Miboshan and Lashizhong formations (Figures 10b & c) allows us to invoke the CQT as a more likely source. The basement of the CQT is mostly composed of orthogenesis with ages of ca. 800–1000 Ma (Guo et al., 1999; Tung et al., 2007a; Yan et al., 2015; Wu et al., 2017b), responsible for the largest ca. 900 Ma cluster in most samples. The dominance of ca. 450–520 Ma grains in few samples (e.g., samples SGK03 and LSY) are attributed to penecontemporaneous magmatic activities in the CQT (Song et al., 2013; Li et al., 2017; Fu et al., 2021b). In addition, some scholars preferred to regard the presence of ca. 1800 and ca. 2500 Ma detritus as a signal of sedimentary supply from the NCB (Xu et al., 2013a). However, in this period, carbonate sedimentation existed throughout the Ordos Basin; the absence of carbonate lithic fragments excludes the possibility of sediment input from the NCB. Meanwhile, recent studies have demonstrated tectonothermal events of such episodes in the CQT and the Olongbuluke Terrane (Sun et al., 2019) to its south (see its location in Figure 01c). Older basement paragneiss in the CQT also contains detrital zircons with ages between ca. 1800 and ca. 2500 Ma (Gehrels et al., 2003b; Tung et al., 2007a; Yan et al., 2015; Liu et al., 2018b). Therefore, the appearance of zircons with ages of ca. 1800 and ca. 2500 Ma are not age-specific, making it unnecessary to require a contribution from the NCB. Moreover, our data do not rule out the possibility of a more proximal source from the older forearc successions in the ENQAB based upon the presence of low-grade metasedimentary fragments and the similarity of age profiles.

5.2. Subduction polarity and ca. 453 Ma synchronous closure of the North Qilian Ocean

5.2.1. ca. 453 Ma initial closure of the ENQO and the CQT-WNCB collision onset

One unresolved primary issue regarding the North Qilian Orogen is the timing of the initial elimination of the NQO and resultant accretion of the CQT onto the SWNCB (Fu et al., 2018; Zuza et al., 2018), with hypotheses of the Ordovician/Silurian boundary (Yin & Harrison, 2000; Xia et al., 2003; Song et al., 2013), the middle Silurian (Sobel & Arnaud, 1999; Gehrels et al., 2003a, b; Fu et al., 2018, 2021a), and the Devonian (Xiao et al., 2009; Yuan & Yang, 2015). The timing of collision onset is most aptly defined as the moment when the distal edge of the passive margin came into physical contact with and subducted beneath the arc system (DeCelles et al., 2014; Hu et al., 2015, 2016; An et al., 2021). Instantly, detrital aprons from the opposite landmasses will comingle at abyssal depths on shelf or slope of the former passive continental margin (DeCelles et al., 2014). Hence, dating siliciclastic sedimentary rocks that contain detritus derived from the CQT and rested stratigraphically upon the westernmost NCB will provide a most direct and robust constraint (Garzanti et al., 1987) on the timing of the initial ENQO closure.

The Mesoproterozoic to the Middle Ordovician deposition with sources from the SWNCB basement requires the study area to be a coherent part of the SWNCB throughout that period, and indicates that the Lashizhong turbidites were in-situ deposited upon the SWNCB continental lithosphere. The overall age spectrum of the Katian Lashizhong turbidites is very similar with a strong degree of overlap to those of time-equivalent successions in the ENQAB (Figures 09b, c), suggesting that they shared a common provenance and their depositional sites were linked. Therefore, we can confirm that no matter how many branches once existed in the ENQO, all these oceanic basins should have been terminated to allow the SWNCB receiving the CQT-derived detritus at no younger than ca. 448 Ma. Given that the study area situates at the westernmost flank of the NCB, rather proximal to the suture zone (Figure 01b), this time estimate may be the oldest archive of the CQT-WNCB collision onset. It is clear that a lag time for the progressive progradation of turbidite to the SWNCB exists, and the time when passive continental lithosphere started to subside intensively is closer to the initial timing of arc-continent collision (DeCelles et al., 2014). Thus, another consideration is the unconformity directly capped by carbonate slope successions of the Kelimoli Formation, given that this stratigraphic break can be inferred to represent the forebulge uplift during the flexural passage over the SWNCB (see discussion below), which occurred slightly older at ca. 453 Ma.

Such an age bracket is fully compatible in error with several lines of evidences of collision induced clues retrieved from the Qilian Orogen, including (1) the age of the youngest Laohushan ophiolite (448±5 Ma; Song et al., 2013), (2) the latest arc-related volcanism (446±3 Ma; Wang et al., 2005) followed by syn-collision granitic plutonism of ca. 445 Ma (Li et al., 2017; Dong et al., 2021; Wu et al., 2021a), (3) the youngest major pulse of plutonism of ca. 445 Ma (Wu et al., 2016), (4) the youngest matrix monazite ages (ca. 450–420 Ma; Zuza et al., 2018), (5) the cessation of ductile shearing by ca. 445 Ma (Zuza et al., 2018), (6) the ca. 454–442 Ma $^{39}Ar/^{40}Ar$ mica cooling ages (Liu et al., 2006), (7) the high-grade blueschist metamorphism of 446–454 Ma (Liou et al. 1989; Liu et al. 2006), and (8) the Silurian foreland basin deposition (Dong et al., 2021). Collectively, we argue for a CQT-WNCB collision onset at the Katian (ca. 453 Ma), slightly predating all known amalgamation timing derived independently from metamorphic and igneous dataset, because of the consequent lag time of the crustal response in the arc zone.

5.2.2. Subduction polarity of the NQO: south-dipping or north-dipping

Another tectonic controversy is whether the subduction polarity of the NQO was north- or south-dipping (Zuza et al., 2018). The northward subduction scenario would predict a south facing magmatic arc constructed north of the main suture within the SWNCB during the Cambrian-Ordovician. The Early Paleozoic magmatic plutons in the southern Alxa have been invoked as indicators for northward subduction polarity (Fu et al., 2020a). While in more views, this phase of plutonism is preferred to infer the southward subduction of the Paleo-Asian Ocean beneath the Alxa continental arc (Liu et al., 2016), raising an ambiguous debete. In the SWNCB, there is no sign of corresponding magmatism having been found. Furthermore, source interpretation shows that the CQT has obducted eastwards above the SWNCB. Otherwise, the southward thrusting of the SWNCB will require sources of the Lashizhong turbidites to contain a considerable amount of zircons from the uplifted SWNCB above a north-dipping suture zone and the foreland should be created in the CQT instead of the SWNCB.

Accordingly, our stratigraphic investigation approves for a southward subduction polarity for the NQO (Sobel & Arnaud, 1999; Gehrels et al., 2003a; Xiao et al., 2009; Dong et al., 2021). But, we do not mean to conclusively preclude the possibility of northward subduction of some oceans in the NQO as there may be multiple subduction systems between the SWNCB and the CQT.

5.2.3. Synchronous closure of the NQO at least in the east

The third tectonic uncertain can be addressed here is the process of the NQO closure. Almost all models on the NQO prefer a diachronous suturing mode (Xu et al., 2013a; Wu et al., 2016; Li et al., 2017; Zuza et al., 2018; Fu et al., 2021a). A sequence of basin-filling events triggered by the NQO closure occurred in the SWNCB, including forebulge flexural uplift (e.g., unconformity below the Kelimoli Formation), followed by rapid shallow shelf drowning to abyssal plain setting (e.g., the Kelimoli and

Wulalike formations), until the arrival and superimposition of turbidites from the west (e.g., the Lashizhong Formation). Evolution of these geologic activities of each stage was broadly synchronous over time in all sections (Figure 03), hinting at along-strike synchronicity of orogenic activities over a distance of ~800 km. Therefore, we here propose a strikingly distinct model that argues, at least in the east, the NQO was closed synchronously. Or, the closure of the NQO should be clockwise as its easternmost portion has an older closure age.

5.3. Ordovician tectono-sedimentary evolution of peripheral foreland in the SWNCB

The pre-Katian strata are characteristic of records of passive margin deposition, capped by a regionally traceable, nearly uninterrupted, carbonate shelf (Chen, 2011; Li et al. 2012; Wang et al., 2016b), which was fed by a small amount of quartzose influx from the craton interior to the northeast (Sun & Dong 2020a). The stable setting was punctuated by the initial CQT-NCB collision that spurred intense peripheral upwarp and basin reverse in the SWNCB, recorded by a stratigraphic break on top of the Zhuozishan Formation. This unconformity and correlative conformable contact separate passive margin sediments from overlying underfilled foreland fills with a distinctive type of megasequence formed in a more unstable tectonic setting (Figure 09d). The basin-filling process of peripheral foreland can be categorized into three distinct stages as expressed by three diverse lithological facies in ascending order.

Stage 1 (The Kelimoli Formation). Ongoing eastward outgrowth of CQT orogen wedge caused the SWNCB lithosphere to flex by depressing leading edge of the plate beneath it (Crampton & Allen, 1995) and created a zone of foredeep (e.g., the Qingliang Foredeep) in the study area triggered by flexural subsidence nearby. The tectonic load led to rapid drowning of the forebulge unconformity, recorded by basin deepening into a west-dipping carbonate slope at the distal foredeep (Figure 11). Given the flexural rigidity of the lithosphere, the eastern portion should have been uplifted as the forebulge where shallow carbonate platform sustained in the east (e.g., well Lucan 1; Figure 03).

Stage 2 (The Wulalke Formation). Forward passage of the flexural wave enhanced deepening of the distal foredeep and led to the cratonward migrating of carbonate slope-platform to the well Lucan 1 (Figure 03). The study area underwent a stage of starved sedimentation accompanied by fallout of volcanic ash cloud, with the abyssal accumulation of hemipelagic black shale that contains thin beds of laminated chert. Ongoing forebulge uplift finally led to large-scale erosion and destruction of the carbonate platform margin further to the east, as evidenced by the carbonate debrites. These carbonate breccias were resedimented from underlying carbonate slope-platform sediments, and were transported downslope by gravitational processes to deposition in the base-of-slope apron at the easternmost basin plain.

Stage 3 (The Lashizhong Formation). The turbidites in the Xishan area are over 3000 meters thick, reflecting the rather rapid topographic growth and erosion of the CQT, possibly due to intense crustal thickening of the Qilian Orogen. Tectonic activities pushed terrigenous turdidity currents eastwards from the high-elevation thrust wedge over the east-dipping slope until sitting depositionally on the abyssal plain. Two respective detrital aprons from opposite landmasses comingled at abyssal depths on top of the abyssal plain shales. It is interestingly to note that the Early Paleozoic zircons are infrequent in most of the Lashizhong turbidites (besides the samples LSY and SGK03; Figure 09b), incompatible with the present proportion of widely exposed Early Paleozoic plutons in the CQT. This inference hints at that much of those intrusions have not been evlavetd to the surface to serve as sources during the initial collision. Yet, at least in part, those rocks were rapidly uplifted to the crustal surface as local sources shedding sediments to some drainage systems (e.g., SGK03 & LSY; Figure 09).

Collectively, during the very first suturing stage of the CQT-WNCB at ca. 453 Ma, an eastward-expanding foredeep was constructed in the SWNCB when the orogenic wedge in the Qilian Orogen expanded eastwards. Considerable subsidence was filled by the eastward progradation of westerly turbiditic influxes superposing atop of the eastward-backsteeping carbonate platform-slope system (Figure 12).

5.4. Implication for the early Paleozoic tectonic evolution of the ENQO

The CQT along with other terranes that make up the present northern Tibet participated in the global Rodinia assemblage, occupying a position at the northern Indo-Australian margin (Song et al., 2013; Fu et al., 2019a) witnessed by the widespread ca. 950 Ma plutonism across the northern Tibet (Song et al., 2012; Gehrels et al., 2003b; Wu et al., 2016, 2017b; Peng et al., 2019; Yu et al., 2021) and coeval deformation (Zuza et al., 2018).

This spatial linkage probably sustained until the dispersal of the Rodinia at the late Neoproterozoic (Song et al., 2010, 2013) before a sequence of break-up rifting events that ultimately isolated the northern Tibetan terranes from the Indo-Australian margin at ca. 750 Ma. The rifting was recorded by ca. 830–600 Ma bimodal magmatism observed throughout the northern Tibet (Xu et al., 2015; Song et al., 2019b; Wu et al., 2021a), leading to the opening of the Proto-Tethys Ocean that separated the Tarim, NCB, and northern

Tibetan terranes from the northern peripheral of the Gondwana (Huang et al., 2018; Zhao et al., 2018; Metcalfe, 2021).

In this period, these East Asian terranes, including the Tarim, NCB, as well as various micro-blocks that constitute the Central China Orogenic System, were located relatively adjacent to the Gondwana, and far away from the Siberia-Baltica-Laurasia landmass separated by the vast Paleo-Asian Ocean (Figure 13a; Xiao et al., 2003, 2015; Huang et al., 2018; Zhao et al., 2018). During the northward drift of these continental slivers, multiple Tethyan ocean basins formed, making the northern Proto-Tethys to be an archipelagic ocean (Figures 13a, b). Of these branches, the Shangdan-Kunlun Ocean is conventionally considered as the major branch separating the eastern Asian blocks from the Gondwana (Zhao et al., 2018; Dong et al., 2021). In the North Qilian Orogen, the oldest recognized Yushigou ophiolitic mélange yield high precise formation ages of ca.530–560 Ma (Qian *et al.*, 1998, 2001; Xia *et al.*, 2003; Smith & Yang, 2006; Xia & Song, 2010; Song *et al.*, 2013; Li *et al.*, 2017), and a west-dipping passive continental margin evolved in the SWNCB.

The proximity of the northern Tibetan terranes with the NCB is endorsed by comparisons of trilobite fossils (McKenzie et al., 2011; Myrow et al., 2015), litho-stratigraphy (Sun et al., 2014, 2019) and shelly faunas (Rong et al., 2003; Huang et al., 2018), making it more likely that the NQO was a relatively small ocean between the CQT and SWNCB as argued by Zuza et al. (2018). The shrinking of these oceans began at ca. 520 Ma, and the northern Tibetan terranes were bounded by a north-facing Qilian arc in the north and a south-facing Kunlun arc in the south, dispersed along the southern margin (present coordinate) of the NCB (Figures 12a&13c). Convergence between the CQT and the NCB was accomplished by a single south-dipping (present-day coordinate) convergent system (Sobel & Arnaud, 1999; Gehrels *et al.*, 2003a, 2003b; Xiao *et al.*, 2009; Wu *et al.*, 2016; Zuza *et al.*, 2018), as the SWNCB lacks plutonic rocks of this age with the formation of a passive continental margin that faced the NQO until Middle Ordovician (Sun & Dong, 2020a). Arc related plutonic rocks of ca.477–512 Ma (Wu *et al.*, 2004, 2006, 2010) and boninite massif of ca. 517 Ma imply that the southward subduction of the NQO should initiate at ca. 520 Ma (Song *et al.*, 2013; Fu et al., 2021a), leading to the conversion of an Atlantic-type passive margin into an Andean-type active margin in the CQT (Song et al., 2013).

Microslices in the northern Tibet were later accreted to and remained juxtaposed to a position at the southern flank of the NCB–Tarim (Yin & Harrison, 2000; Song et al., 2007, 2014, 2019a; Zhao et al., 2018; Yan et al., 2021; Fu et al., 2021a) by the closure of the NQO at ca. 453 Ma. The ribbon-like “Asiatic Hunic superterrane" (Metcalfe, 2013, 2021; Stampfli et al., 2013) that comprises an assemblage of continental blocks and intra-oceanic arcs including the NCB-Tarim and all terranes in the Central China Orogenic System was amalgamated then (Figures 13d). The closure of these various branches of the Tethyan oceans, including the Erlangping back-arc Ocean, N-Qilian Ocean, S-Qilian Ocean, N-Qaidam Ocean, and Qimantage Ocean was nearly synchronous at ca. 450–445 Ma (Sun et al., 2021). This finding infers the nearly coeval accretion of the North Qinling, CQT, Olongbuluke, Qaidam, and Central Kunlun at ca. 450–445 Ma onto the NCB-Tarim, rather than sequential accretion from north to south, which would predict progressively southward younging closure timing. The synchronous collision of the North Qinling and CQT with the NCB is at odds with clockwise or counterclockwise rotation of the Qilian-Qaidam-Kunlun terrane during the ocean closure, indicating presumably that the extent of these oceanic branches is relatively narrow. Therefore, we favor a model that places the northern Tibetan terranes in the marginal sea setting behind the Kunlun Arc.

6. Conclusions

Our new data allow the following four major conclusions:

1) The Pre-Katian quartz arenite in the SWNCB were sourced from NCB basement to the east, and were deposited in a passive margin setting in response to the spreading of the ENQO.
2) The Katian turbidites in both the SWNCB and the ENQAB have a common provenance from the CQT, and show features of deposition in a collision-induced underfilled foreland basin.
3) The first arrival of the CQT-originated detritus above passive continental margin in the westernmost NCB yields a solid constraint on the initial ENQO closure that the resulted the CQT-SWNCB collision onset at ca. 453 Ma.
4) An eastward-expanding foredeep was constructed in the SWNCB during the eastward expansion of the Qilian orogenic wedge. This foredeep was filled by the eastward progradation of turbiditic influxes superposing on the eastward-backsteeping carbonate platform-slope.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability Statement

All data related to this manuscript, including sandstone modal composition, sampling location and detrital zircon U-Pb dating, have been fully submitted to and are available from the editorial board.

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Table Caption

Supplementary Table 01. Laser ablation-inductively coupled plasma-mass spectrometry data of detrital zircons from the Cambrian and Ordovician sandstones from eastern Qilian Orogen and western North China Block.

Figure Caption

Figure 01. (a) Tectonic outline of the mainland China showing the location of the Central China Orogenic System (modified after Zhao & Cawood, 2012); (b) Geologic sketch of the North Qilian Orogen and western NCB illustrating tectonic division, major boundaries and geologic components (modified after Zhao et al., 2019); (c) Geophysical section of the Qilian Shan highlighting the deep relationships between the individual tectonic units (Xiao et al., 2009); (d) Litho-stratigraphy of the ENQAB and the WNCB.

Figure 02. Stratigraphic log of the Ordovician sequence in the WNCB. The distribution of conodonts and radiolarian nannofossils that constrains the age of individual stratigraphic units is quoted from Jing et al. (2021) and Perera & Atitchison (2021), respectively.

Figure 03. Stratigraphic profile of the lithological assemblages and interpreted sedimentary facies of the Ordovician sections/boreholes in the SWNCB (see their locations in Figure 01b).

Figure 04. Representative photographs showing stratigraphy and sedimentology of the Ordovician strata in the WNCB. Section locations are labeled in Figure 01b. Scales used in Figures 04–05 include pen (~8 cm long), geologic hammers (~35 cm long), geologists (~170 cm tall), and card (~2 cm wide). (a) Thick bedded wackestone, packstone, and grainstone of the Zhuozishan Formation at the Qinglongshan Section, with the insert photomicrograph (cross-polarized light) showing oolitic limestone from the Shibangou Section. (b) Bioclastic bearing packstone of the Zhuozishan Formation at the Qinglongshan Section with a close-up insert of Gastropoda. (c) Patch reef within thick wackestone of the Zhuozishan Formation at the Qinglongshan Section. (d) An unconformity separates the Sandbian Zhuozishan Formation and Katian Kelimoli Formation at the Qinglongshan Section. (e) Carbonate breccias within the Kelimoli Formatin at the Shibangou Section. (f) Thin bedded lime mudstone with thin tuff interlayers of the Kelimoli Formation at the Pingliang Section.

Figure 05. Representative photographs showing stratigraphy and sedimentology of the Ordovician strata in the WNCB and the ENQAB. Section locations are labeled in Figure 01b. (a) Distant view of the massive siliciclastic turbidites of the Lashizhong Formation depositionally sitting above the black shale dominated Wulalike Formation at the Xishan Section. (b) Thin bedded pelagic black graptolite-bearing shale of the Wulalike Formation at the Xishan Section. (c) Intraclastic limestone of the Wulalike Formation at the well Gutan 1. (d) Mixed carbonate and siliciclastic breccias of basal Lashizhong Formation at the Sanguan Section. (e) Siliciclastic turbidites alternating with graptolite-bearing shale of the Lashizhong Formation at the Shibangou Section. (f) Soft-sediment deformation indicating sandstone slump of the Lashizhong Formation at the Xianggen Section. (g) Massive siliciclastic turbidites of the Miboshan Formation at the Niuhoushan Section. (h) Gravity-induced mass transport deposit within sandstone turbidite of the Miboshan Formation at the Niuhoushan Section.

Figure 06. Ternary plots for the Cambrian and Ordovician sandstone modal composition data from the ENQAB and the SWNCB are shown. (A) Petrologic classification is according to Pettijohn (1975). (B–D) Provenance fields are from Dickinson & Suczek (1979). Fm.—formation; Qt—total quartz; Qm—monocrystalline quartz; Qp—polycrystalline quartz; K— K-feldspar; Pl—plagioclase;

L—lithic fragment; Qt—Qm + Qp; F—K + Pl; Lt—L + Qp. Samples of the Majiagou Formation are quoted from Sun & Dong, (2020).

Figure 07. Concordia diagrams show the results of single-grain zircon U–Pb analyses and frequency (bars) and relative probability density distribution (curves) of ages of samples from the Lashizhong Formation. Ellipses show individual analyses. Error ellipses represent 2σ uncertainties. See Supplementary Table 01 for detailed data.

Figure 08. Concordia diagrams show the results of single-grain zircon U–Pb analyses and frequency (bars) and relative probability density distribution (curves) of ages of samples from the Lashizhong and Miboshan Formations. Ellipses show individual analyses. Error ellipses represent 2σ uncertainties. See Supplementary Table 01 for detailed data.

Figure 09. Normalized relative probability density distributions (spectra) show detrital zircon U–Pb ages of the Mesoproterozoic to Middle Ordovician (a) and the Late Ordovician (b) siliciclastic rocks from the WNCB, and (c) the Late Ordovician samples from the ENQAB. (e) Cumulative probability curves of measured crystallization ages for detrital zircon grains relative to the depositional ages of samples. The base figure is modified from Cawood et al. (2012). DA, depositional age. CA, crystallization age of the youngest 5% of detrital zircons. Convergent basin (A, pink), collisional basin (B, light blue) and extensional basin (C, light green).

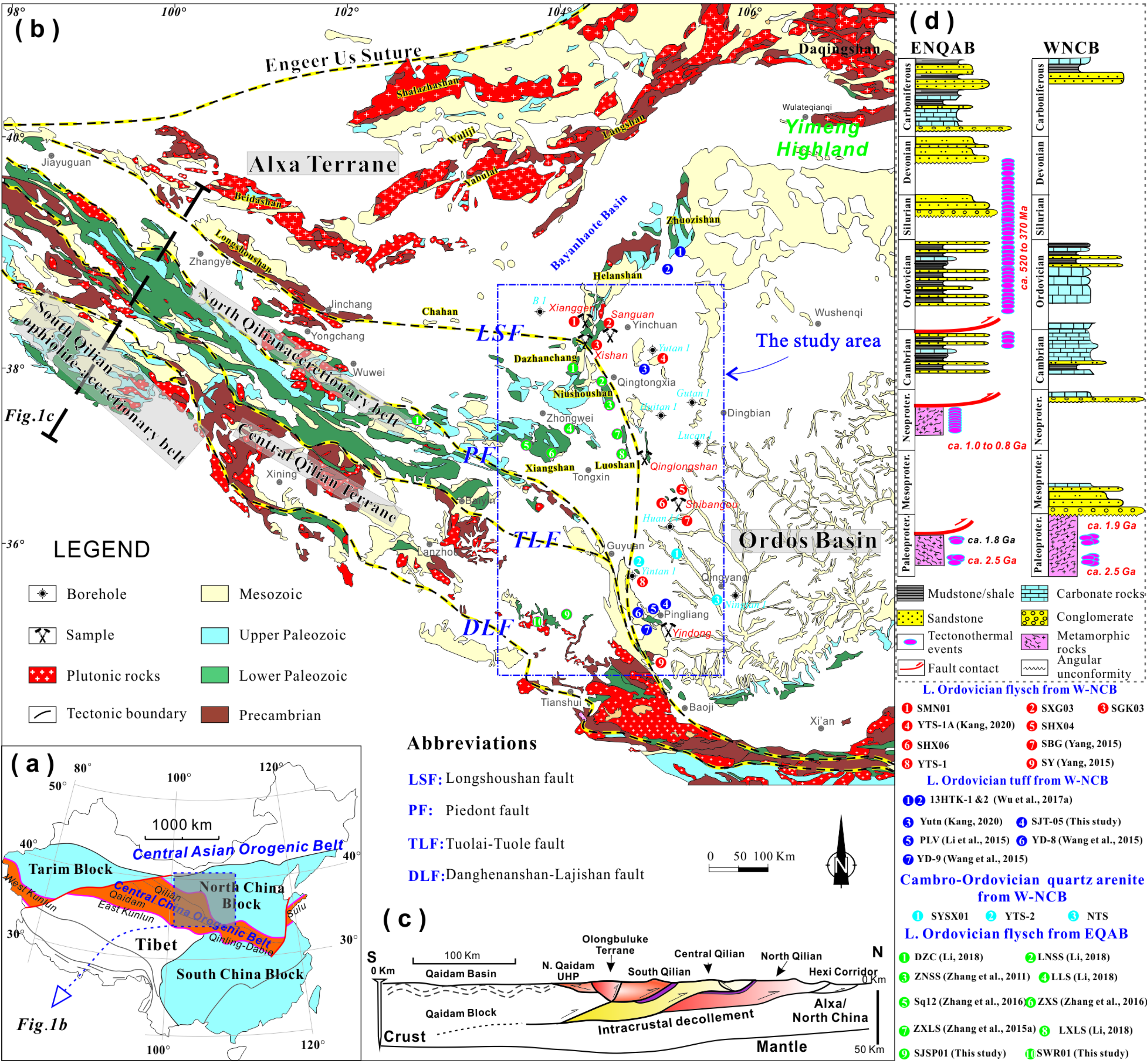
Figure 10. Probability density distribution (curves) of ages for: (a) Mesoproterozoic to Cambrian sandstones from the WNCB (Sun & Dong, 2020a) and Middle Ordovician Sandaokan Formation (Sun & Dong, 2020a); (b) Upper Ordovician (the Katian Lashizhong Formation) turbidites from the WNCB (this study); (c) Upper Ordovician Miboshan Formation (Zhang et al., 2016, 2017). The age spectra for the CQT basement and the NCB basement are quoted from Zhang et al. (2019c) and Wu et al. (2021b), respectively. n—number of concordant zircon U–Pb ages for each sample.

Figure 11. Schematic model showing the Late Ordovician deep-water basin-filling of the SWNCB and the Qilian Orogen (Modified from Charlotte et al., 2020). See the main text for details.

Figure 12. Theoretical block models showing the tectonic evolution of the WNCB and indicating multiple stages of evolution in paleogeography and provenance from the Early to the Late Ordovician (Modified from Xiao et al., 2017). See the main text for details.

Figure 13. Tectonic reconstructions of East Asian blocks showing closure of the Proto-Tethys Ocean (Modified from Dong et al., 2021).

Figure 01.



(b)
98°
100°
102°
104°
106°
40°
38°
36°
Engeer Us Suture
Daqingshan
Shalazhashan
Wuliji
Langshan
Yabulai
Wulateqianqi
Yimeng Highland
Alxa Terrane
Jiayuguan
Beidashan
Longshoushan
Zhangye
Bayanhaote Basin
Zhuozishan
Helanshan
Jinchang
Chahan
B 1
Xianggen
Sanguan
Yinchuan
Yutan 1
Wushenqi
The study area
LSF
Xishan
Dazhanchang
Qingtongxia
Yongchang
Wuwei
North Qilian accretionary belt
South Qilian ophiolite-accretionary belt
Fig.1c
Niushoushan
Gutan 1
Huitan 1
Dingbian
Zhongwei
Lucan 1
PF
Xiangshan
Luoshan
Qinglongshan
Tongxin
Xining
Central Qilian Terrane
Shibangou
Baiyin
Huan 14
TLF
Guyuan
Ordos Basin
Lanzhou
Yintan 1
Qingyang
Ningtan 1
Pingliang
Yindong
DLF
Tianshui
Baoji
Xi'an
LEGEND
Borehole
Mesozoic
Sample
Upper Paleozoic
Plutonic rocks
Lower Paleozoic
Tectonic boundary
Precambrian
Abbreviations
LSF: Longshoushan fault
PF: Piedont fault
TLF: Tuolai-Tuole fault
DLF: Danghenanshan-Lajishan fault
0 50 100 Km
N
(a)
80°
100°
120°
50°
40°
30°
1000 km
Central Asian Orogenic Belt
Tarim Block
North China Block
Central China Orogenic Belt
West Kunlun
Qilian
Qaidam
East Kunlun
Qinling-Dabie
Sulu
Tibet
South China Block
Fig.1b
(c)
S
N
0 Km
100 Km
Olongbuluke Terrane
N. Qaidam UHP
Central Qilian
North Qilian
Qaidam Basin
South Qilian
Hexi Corridor
Qaidam Block
Intracrustal decollement
Alxa/ North China
Crust
Mantle
50 Km
(d)
ENQAB
WNCB
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Neoproter.
Mesoproter.
Paleoproter.
ca. 520 to 370 Ma
ca. 1.0 to 0.8 Ga
ca. 1.8 Ga
ca. 2.5 Ga
ca. 1.9 Ga
ca. 2.5 Ga
Mudstone/shale
Carbonate rocks
Sandstone
Conglomerate
Tectonothermal events
Metamorphic rocks
Fault contact
Angular unconformity
L. Ordovician flysch from W-NCB
1 SMN01
2 SXG03
3 SGK03
4 YTS-1A (Kang, 2020)
5 SHX04
6 SHX06
7 SBG (Yang, 2015)
8 YTS-1
9 SY (Yang, 2015)
L. Ordovician tuff from W-NCB
1 2 13HTK-1 &2 (Wu et al., 2017a)
3 Yutn (Kang, 2020)
4 SJT-05 (This study)
5 PLV (Li et al., 2015)
6 YD-8 (Wang et al., 2015)
7 YD-9 (Wang et al., 2015)
Cambro-Ordovician quartz arenite from W-NCB
1 SYSX01
2 YTS-2
3 NTS
L. Ordovician flysch from EQAB
1 DZC (Li, 2018)
2 LNSS (Li, 2018)
3 ZNSS (Zhang et al., 2011)
4 LLS (Li, 2018)
5 Sq12 (Zhang et al., 2016)
6 ZXS (Zhang et al., 2016)
7 ZXLS (Zhang et al., 2015a)
8 LXLS (Li, 2018)
9 SJSP01 (This study)
10 SWR01 (This study)

Figure 02.

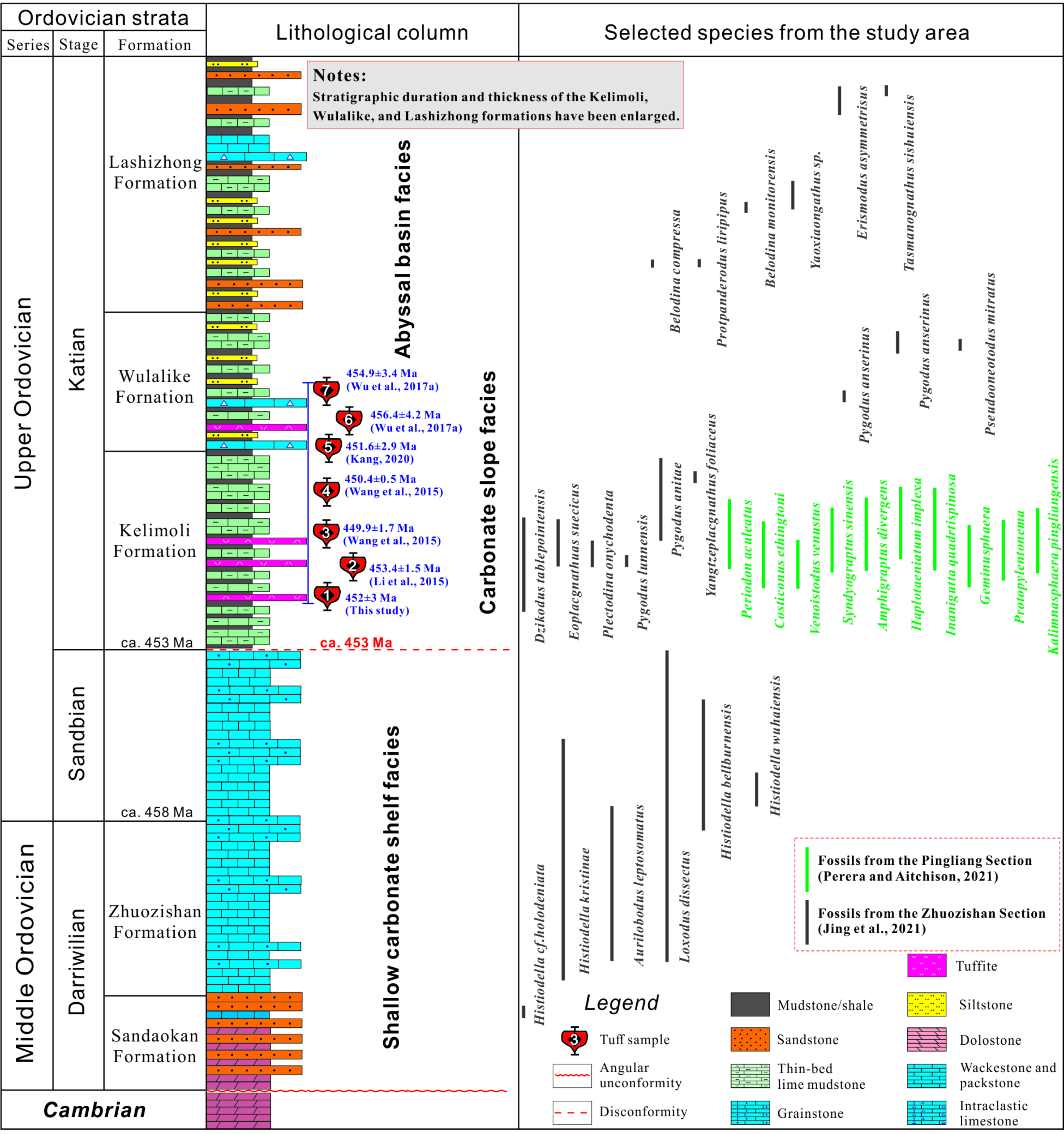
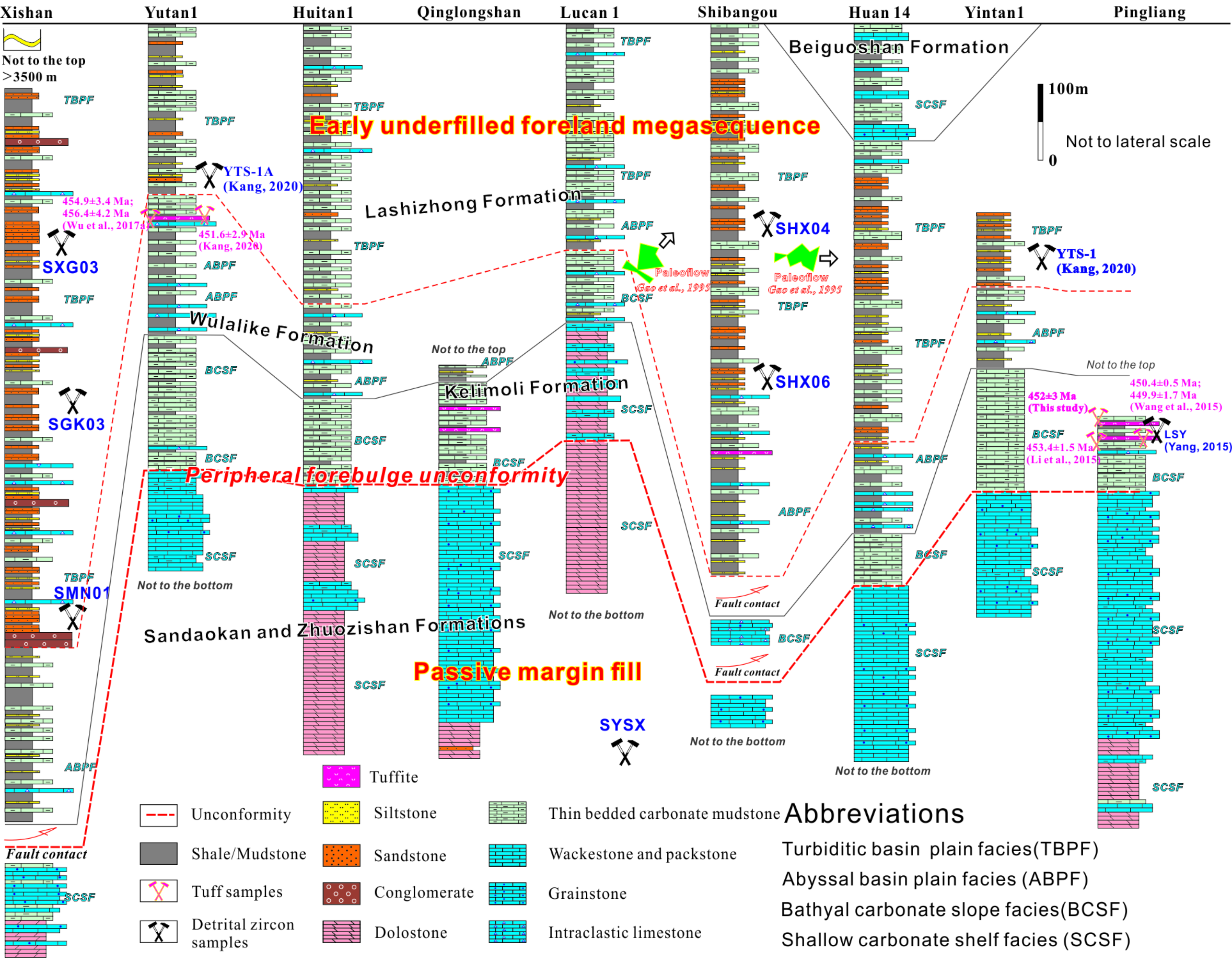

Ordovician strata
Series
Stage
Formation
Lithological column
Selected species from the study area
Notes:
Stratigraphic duration and thickness of the Kelimoli, Wulalike, and Lashizhong formations have been enlarged.
Upper Ordovician
Middle Ordovician
Cambrian
Katian
Sandbian
Darriwilian
Lashizhong Formation
Wulalike Fornation
Kelimoli Formation
Zhuozishan Formation
Sandaokan Formation
ca. 453 Ma
ca. 458 Ma
ca. 453 Ma
Abyssal basin facies
Carbonate slope facies
Shallow carbonate shelf facies
454.9±3.4 Ma (Wu et al., 2017a)
456.4±4.2 Ma (Wu et al., 2017a)
451.6±2.9 Ma (Kang, 2020)
450.4±0.5 Ma (Wang et al., 2015)
449.9±1.7 Ma (Wang et al., 2015)
453.4±1.5 Ma (Li et al., 2015)
452±3 Ma (This study)
Belodina compressa
Protpanderodus liripipus
Belodina monitorensis
Yaoxiaongathus sp.
Erismodus asymmetrisus
Tasmanognathus sishuiensis
Pygodus anserinus
Pygodus anserinus
Pseudooneotodus mitratus
Dzikodus tablepointensis
Eoplacgnathuas suecicus
Plectodina onychodenta
Pygodus lunnensis
Pygodus anitae
Yangtzeplacgnathus foliaceus
Periodon aculeatus
Costiconus ethingtoni
Venoistodus venustus
Syndyograptus sinensis
Amphigraptus divergens
Haplotaeniatum implexa
Inanigutta quadrtispinosa
Geminusphaera
Protopylentonema
Kalimnasphaera pingliangensis
Histiodella cf.holodeniata
Histiodella kristinae
Aurilobodus leptosomatus
Loxodus dissectus
Histiodella bellburnensis
Histiodella wuhaiensis
Fossils from the Pingliang Section (Perera and Aitchison, 2021)
Fossils from the Zhuozishan Section (Jing et al., 2021)
Legend
Tuff sample
Angular unconformity
Disconformity
Mudstone/shale
Sandstone
Thin-bed lime mudstone
Grainstone
Tuffite
Siltstone
Dolostone
Wackestone and packstone
Intraclastic limestone

Figure 03.



Xishan
Yutan1
Huitan1
Qinglongshan
Lucan 1
Shibangou
Huan 14
Yintan1
Pingliang
Not to the top
>3500 m
Beiguoshan Formation
100m
0
Not to lateral scale
Early underfilled foreland megasequence
Lashizhong Formation
Wulalike Formation
Kelimoli Formation
Peripheral forebulge unconformity
Sandaokan and Zhuozishan Formations
Passive margin fill
YTS-1A (Kang, 2020)
454.9±3.4 Ma; 456.4±4.2 Ma (Wu et al., 2017a)
451.6±2.9 Ma (Kang, 2020)
SXG03
SGK03
SMN01
SHX04
SHX06
YTS-1 (Kang, 2020)
452±3 Ma (This study)
450.4±0.5 Ma; 449.9±1.7 Ma (Wang et al., 2015)
453.4±1.5 Ma (Li et al., 2015)
LSY (Yang, 2015)
SYSX
Paleoflow
Gao et al., 1995
Not to the top
Not to the bottom
Fault contact
TBPF
ABPF
BCSF
SCSF
Tuffite
Unconformity
Siltstone
Thin bedded carbonate mudstone
Shale/Mudstone
Sandstone
Wackestone and packstone
Tuff samples
Conglomerate
Grainstone
Detrital zircon samples
Dolostone
Intraclastic limestone
Abbreviations
Turbiditic basin plain facies(TBPF)
Abyssal basin plain facies (ABPF)
Bathyal carbonate slope facies(BCSF)
Shallow carbonate shelf facies (SCSF)

Figure 04.

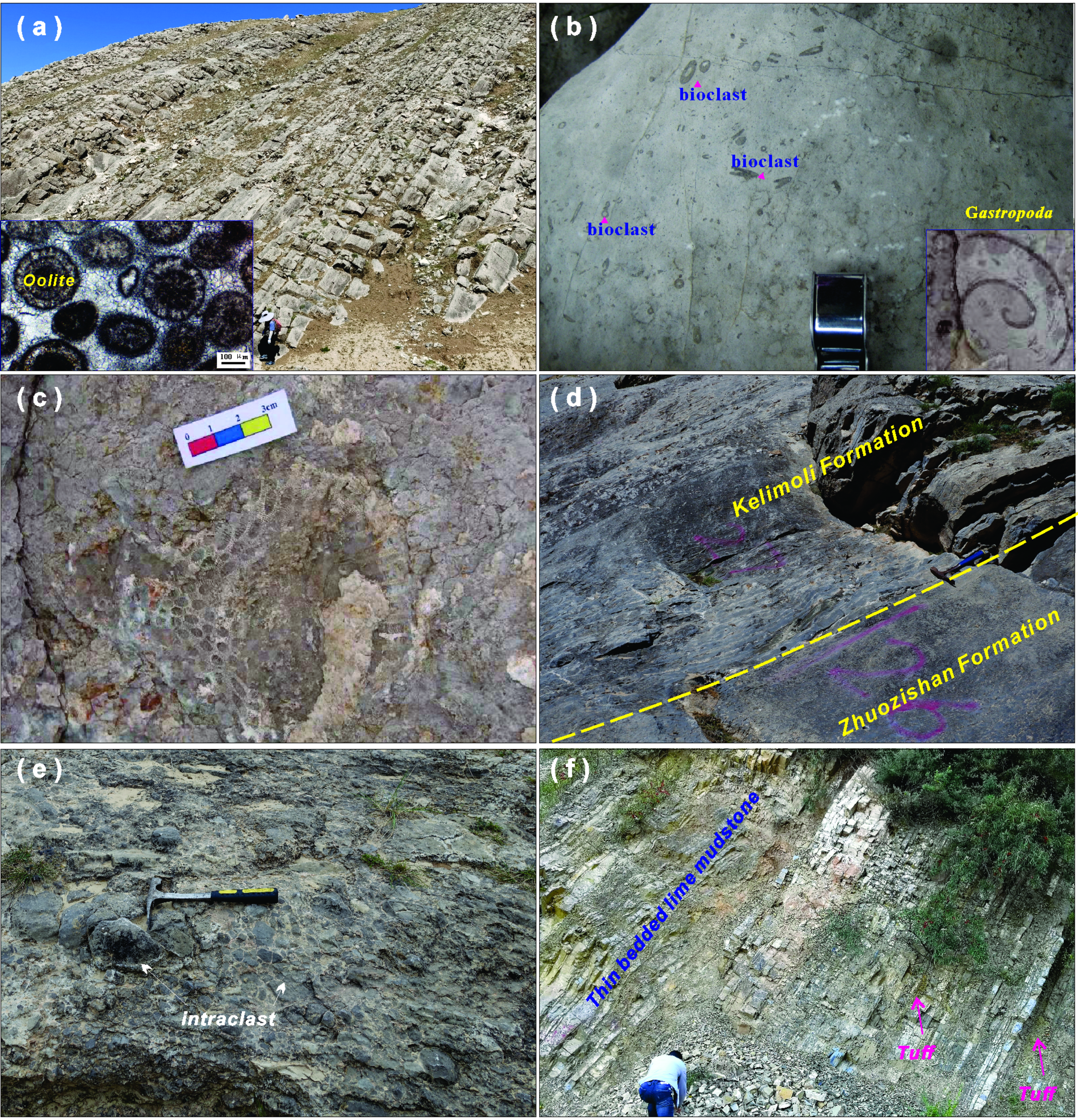
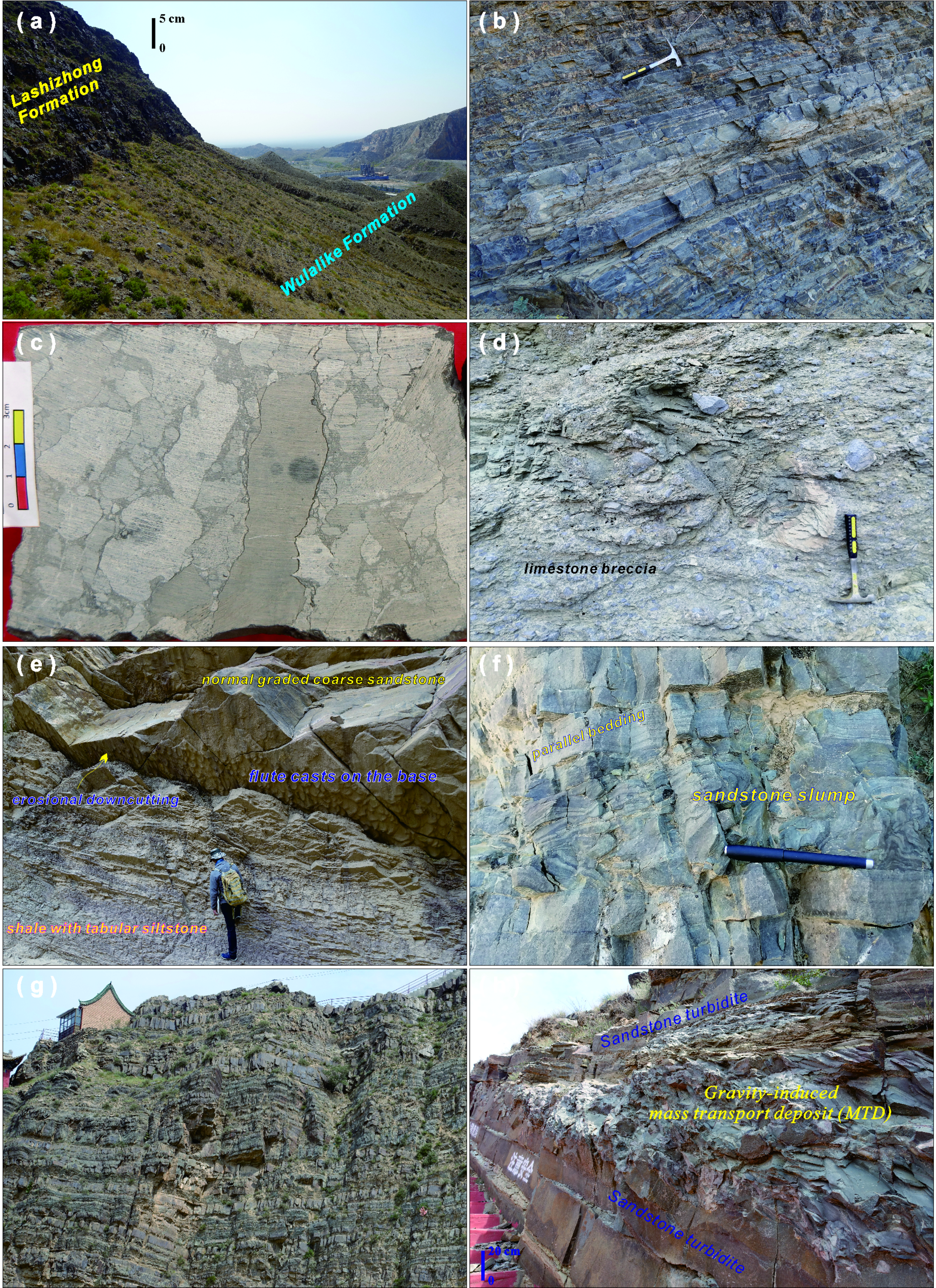

(a)
Oolite
100 μm
(b)
bioclast
bioclast
bioclast
Gastropoda
(c)
0 1 2 3cm
(d)
Kelimoli Formation
Zhuozishan Formation
(e)
intraclast
(f)
Thin bedded lime mudstone
Tuff
Tuff

Figure 05.



(a)
5 cm
0
Lashizhong Formation
Wulalike Formation
(b)
(c)
3cm
2
1
0
(d)
limestone breccia
(e)
normal graded coarse sandstone
erosional downcutting
flute casts on the base
shale with tabular siltstone
(f)
parallel bedding
sandstone slump
(g)
Sandstone turbidite
Gravity-induced
mass transport deposit (MTD)
Sandstone turbidite
20 cm
0

Figure 06.

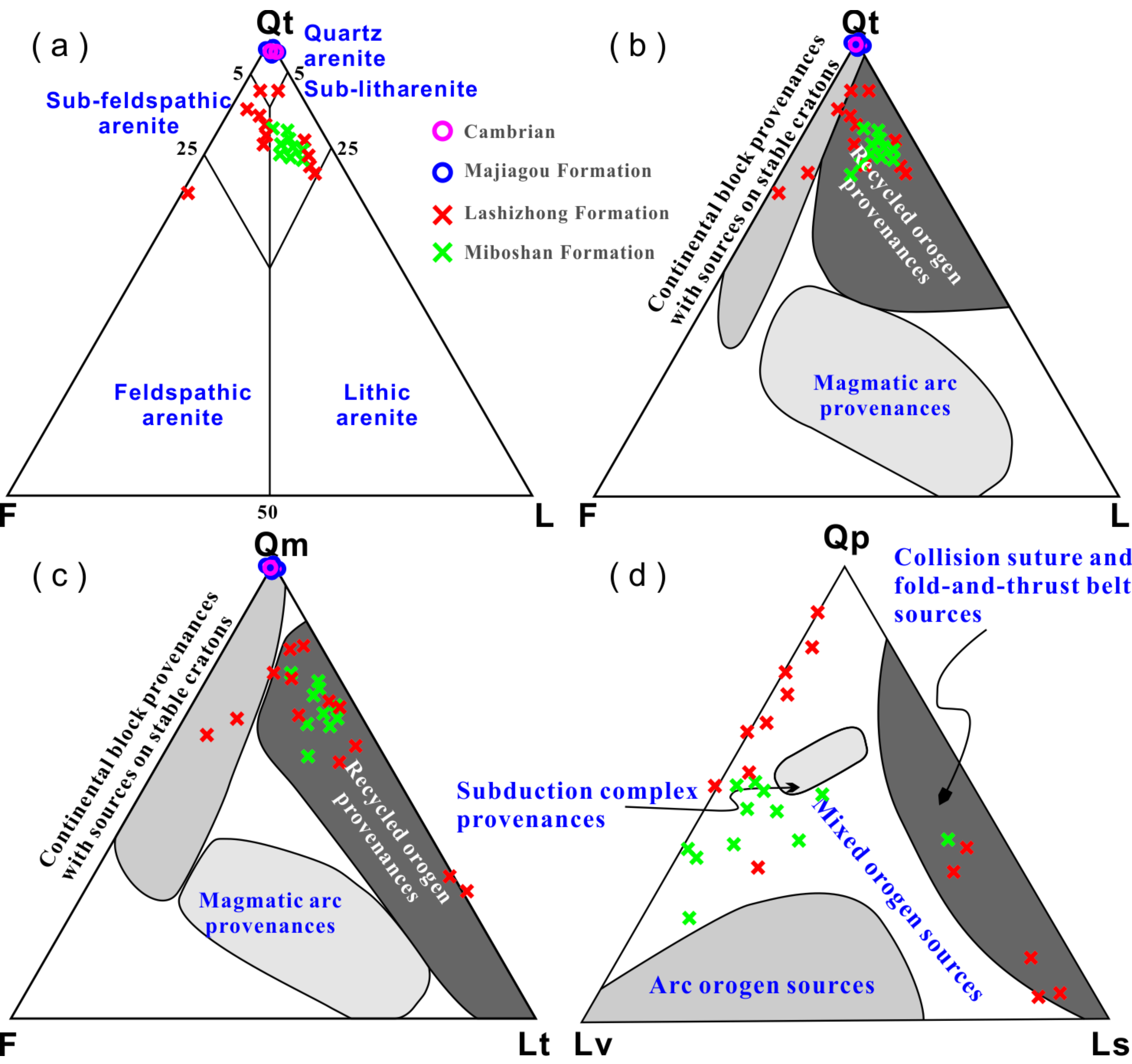
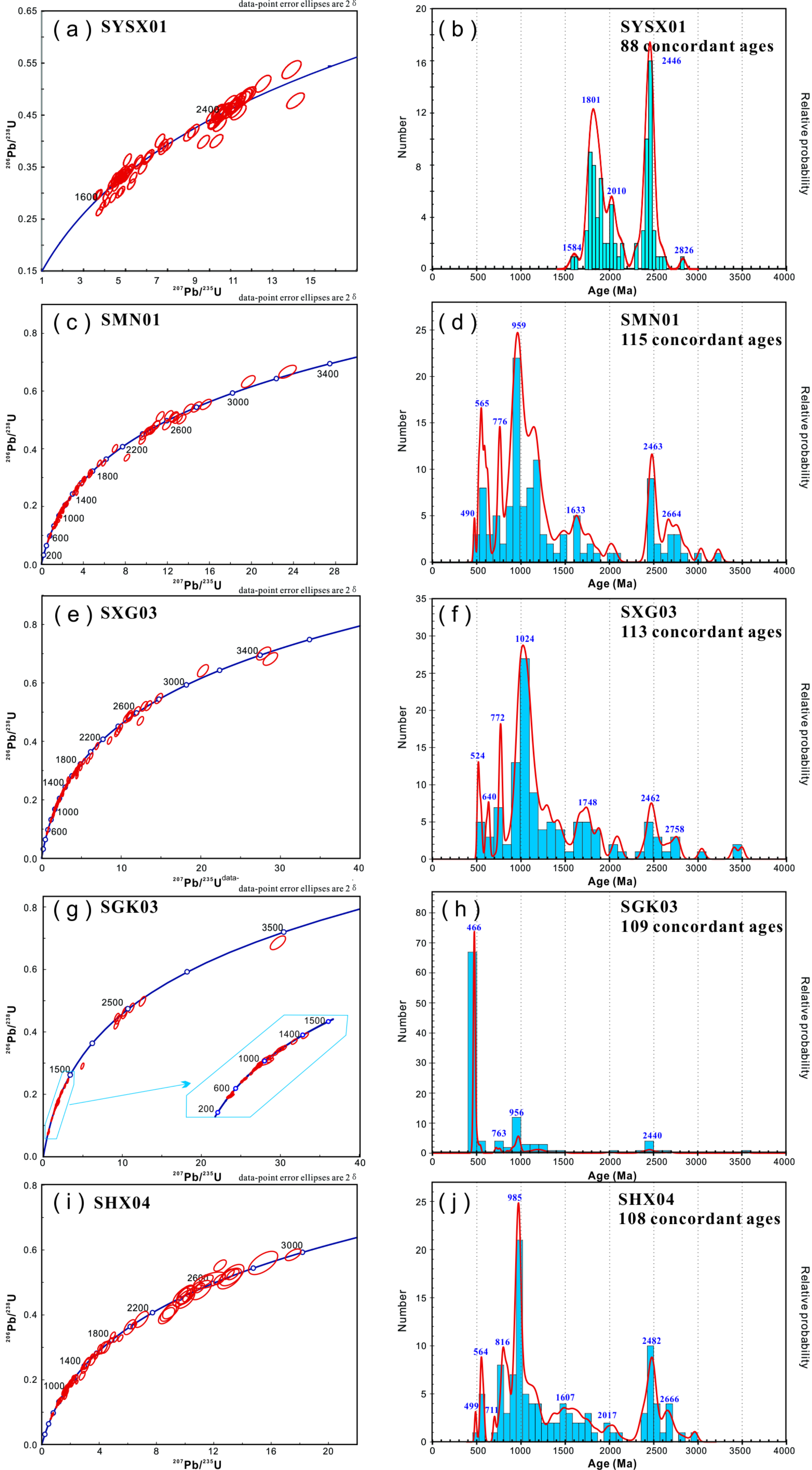

(a)
Qt
Quartz arenite
Sub-litharenite
Sub-feldspathic arenite
5
5
25
25
Cambrian
Majiagou Formation
Lashizhong Formation
Miboshan Formation
Feldspathic arenite
Lithic arenite
F
50
L
(b)
Qt
Continental block provenances with sources on stable cratons
Recycled orogen provenances
Magmatic arc provenances
F
L
(c)
Qm
Continental block provenances with sources on stable cratons
Recycled orogen provenances
Magmatic arc provenances
F
Lt
(d)
Qp
Collision suture and fold-and-thrust belt sources
Subduction complex provenances
Mixed orogen sources
Arc orogen sources
Lv
Ls

Figure 07.



(a) SYSX01
(b) SYSX01
88 concordant ages
(c) SMN01
(d) SMN01
115 concordant ages
(e) SXG03
(f) SXG03
113 concordant ages
(g) SGK03
(h) SGK03
109 concordant ages
(i) SHX04
(j) SHX04
108 concordant ages
data-point error ellipses are 2 δ
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
Number
Relative probability
Age (Ma)

Figure 08.

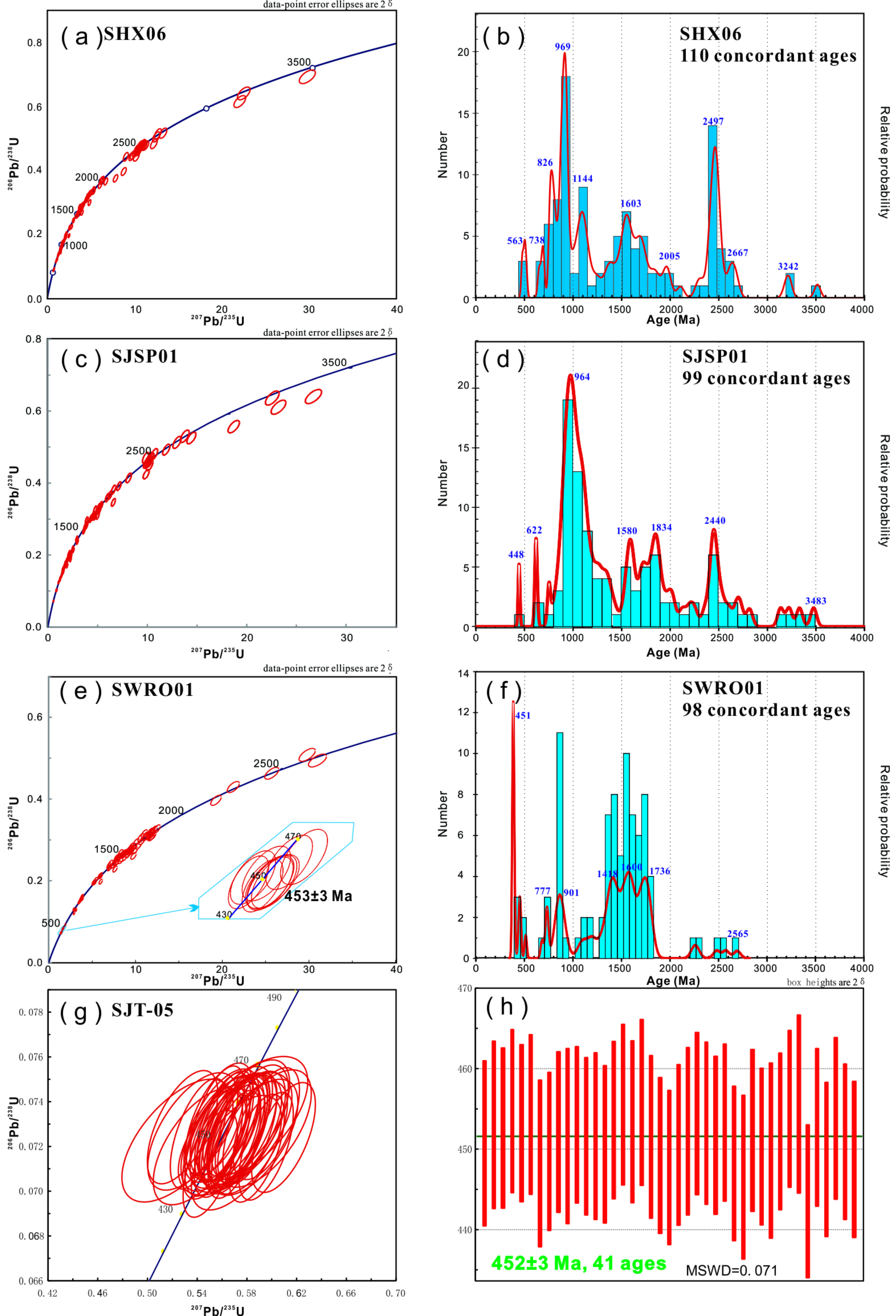
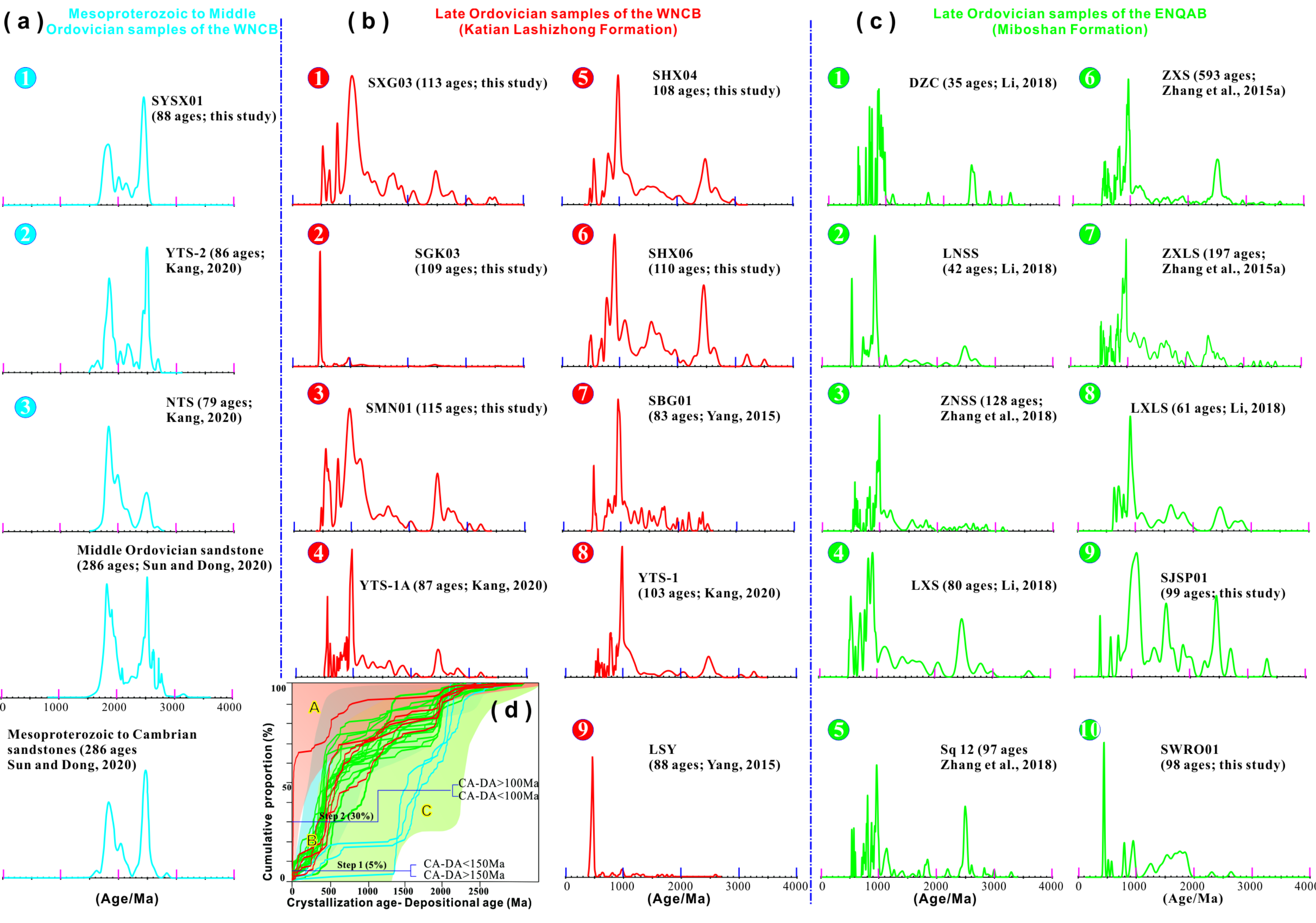
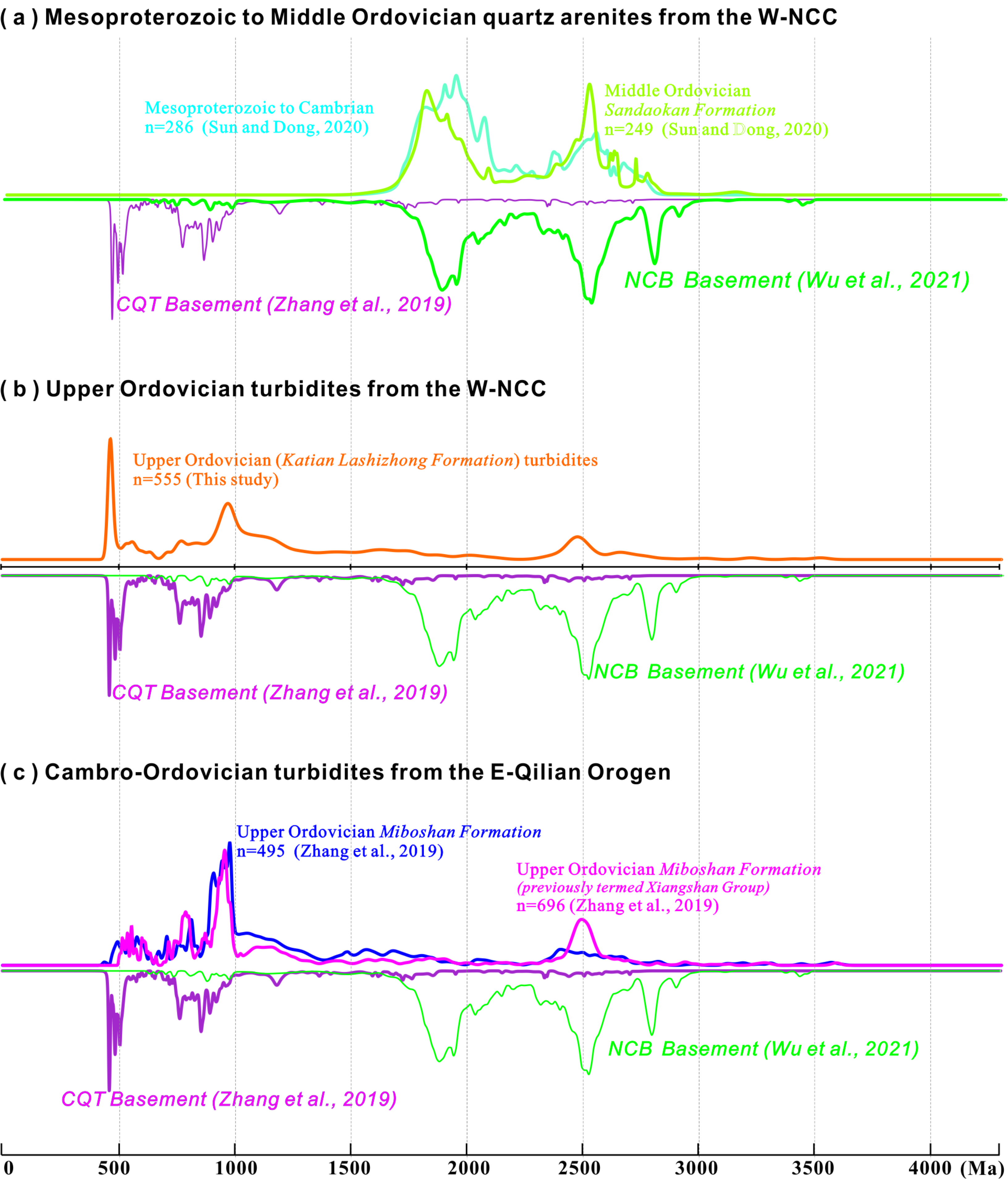

data-point error ellipses are 2 δ
(a) SHX06
3500
2500
2000
1500
1000
206Pb/238U
207Pb/235U
(b) SHX06
110 concordant ages
969
826
1144
1603
563
738
2005
2497
2667
3242
Number
Relative probability
Age (Ma)
data-point error ellipses are 2 δ
(c) SJSP01
3500
2500
1500
206Pb/238U
207Pb/235U
(d) SJSP01
99 concordant ages
964
448
622
1580
1834
2440
3483
Number
Relative probability
Age (Ma)
data-point error ellipses are 2 δ
(e) SWRO01
2500
2000
1500
500
470
450
430
453±3 Ma
206Pb/238U
207Pb/235U
(f) SWRO01
98 concordant ages
451
777
901
1418
1600
1736
2565
Number
Relative probability
Age (Ma)
(g) SJT-05
490
470
450
430
206Pb/238U
207Pb/235U
box heights are 2 δ
(h)
452±3 Ma, 41 ages
MSWD=0. 071

Figure 09.



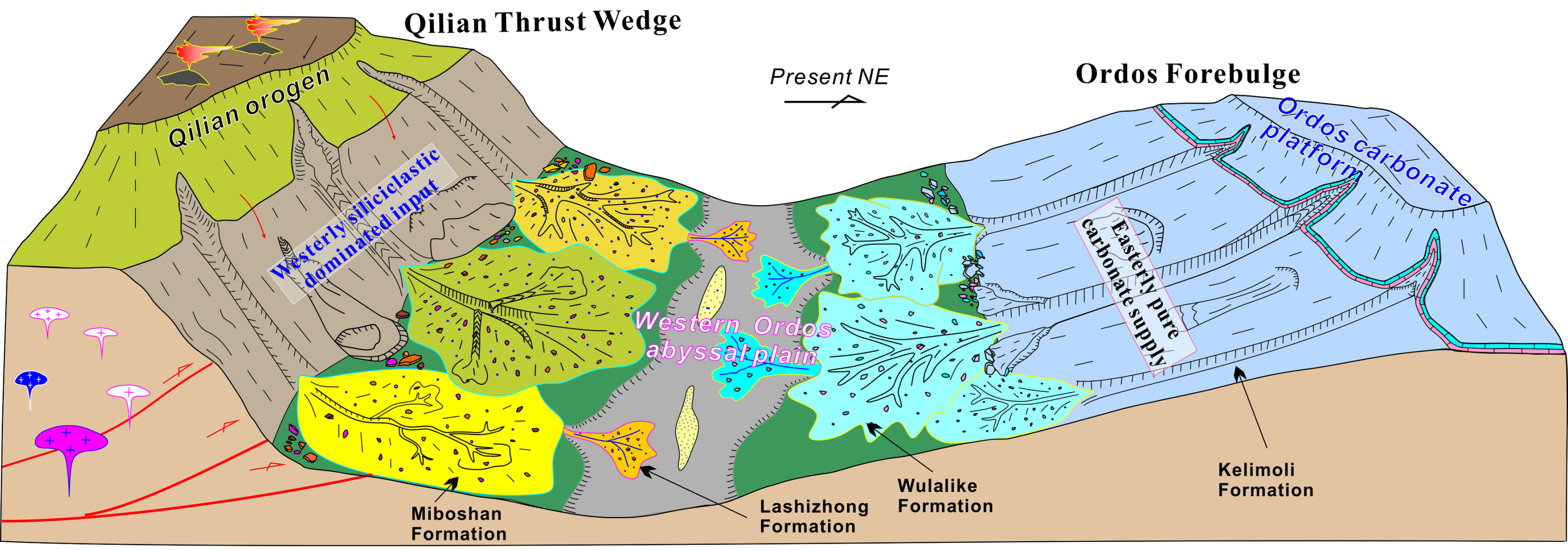
(a)
Mesoproterozoic to Middle Ordovician samples of the WNCB
(b)
Late Ordovician samples of the WNCB (Katian Lashizhong Formation)
(c)
Late Ordovician samples of the ENQAB (Miboshan Formation)
SYSX01 (88 ages; this study)
YTS-2 (86 ages; Kang, 2020)
NTS (79 ages; Kang, 2020)
Middle Ordovician sandstone (286 ages; Sun and Dong, 2020)
Mesoproterozoic to Cambrian sandstones (286 ages Sun and Dong, 2020)
SXG03 (113 ages; this study)
SGK03 (109 ages; this study)
SMN01 (115 ages; this study)
YTS-1A (87 ages; Kang, 2020)
SHX04 108 ages; this study)
SHX06 (110 ages; this study)
SBG01 (83 ages; Yang, 2015)
YTS-1 (103 ages; Kang, 2020)
LSY (88 ages; Yang, 2015)
DZC (35 ages; Li, 2018)
LNSS (42 ages; Li, 2018)
ZNSS (128 ages; Zhang et al., 2018)
LXS (80 ages; Li, 2018)
Sq 12 (97 ages Zhang et al., 2018)
ZXS (593 ages; Zhang et al., 2015a)
ZXLS (197 ages; Zhang et al., 2015a)
LXLS (61 ages; Li, 2018)
SJSP01 (99 ages; this study)
SWRO01 (98 ages; this study)
(d)
Cumulative proportion (%)
Crystallization age- Depositional age (Ma)
Step 2 (30%)
Step 1 (5%)
CA-DA>100Ma
CA-DA<100Ma
CA-DA<150Ma
CA-DA>150Ma
A
B
C
(Age/Ma)

Figure 10.



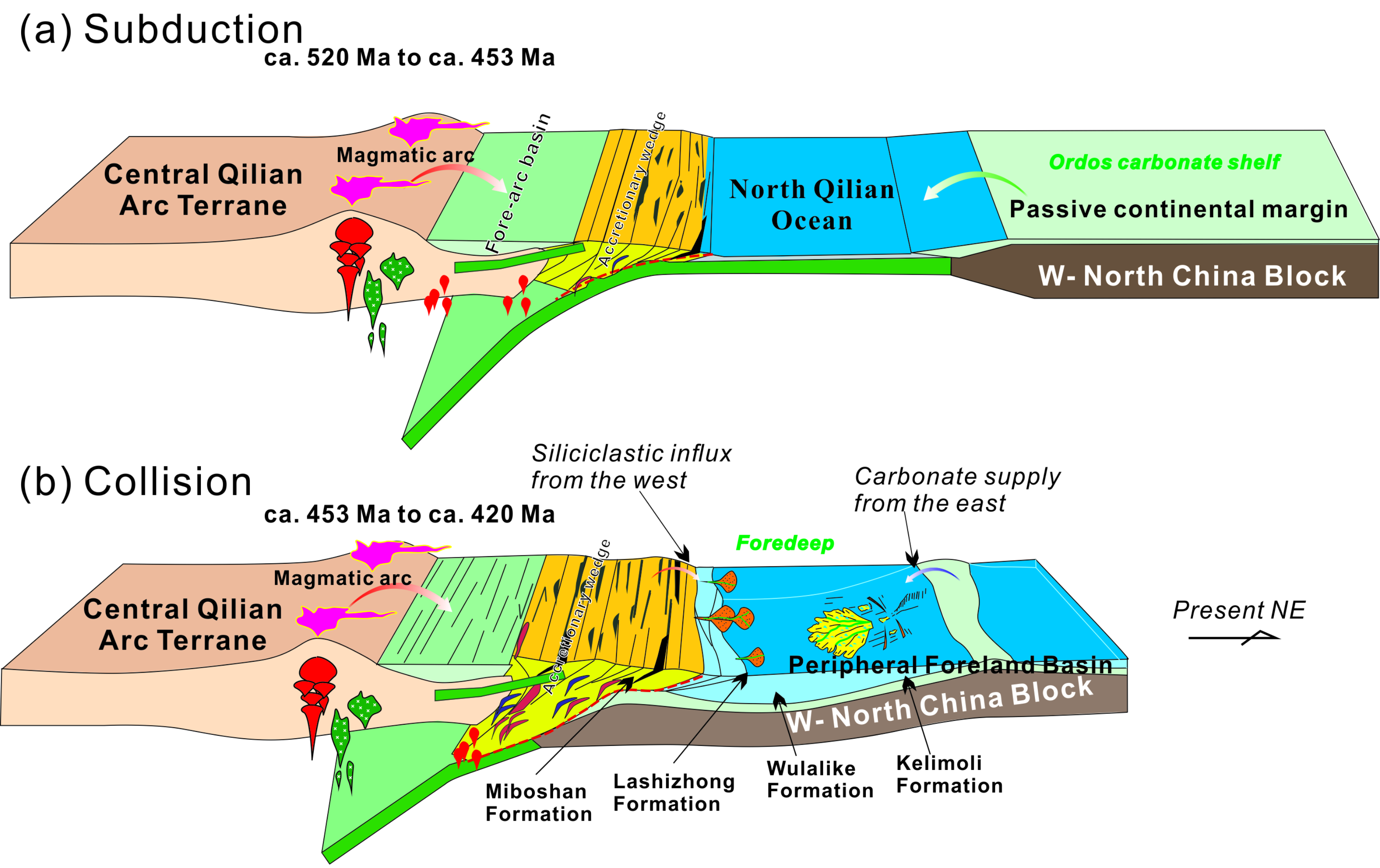
(a) Mesoproterozoic to Middle Ordovician quartz arenites from the W-NCC
Mesoproterozoic to Cambrian
n=286 (Sun and Dong, 2020)
Middle Ordovician
Sandaokan Formation
n=249 (Sun and Dong, 2020)
CQT Basement (Zhang et al., 2019)
NCB Basement (Wu et al., 2021)
(b) Upper Ordovician turbidites from the W-NCC
Upper Ordovician (Katian Lashizhong Formation) turbidites
n=555 (This study)
CQT Basement (Zhang et al., 2019)
NCB Basement (Wu et al., 2021)
(c) Cambro-Ordovician turbidites from the E-Qilian Orogen
Upper Ordovician Miboshan Formation
n=495 (Zhang et al., 2019)
Upper Ordovician Miboshan Formation
(previously termed Xiangshan Group)
n=696 (Zhang et al., 2019)
NCB Basement (Wu et al., 2021)
CQT Basement (Zhang et al., 2019)
0
500
1000
1500
2000
2500
3000
3500
4000
(Ma)

Figure 11.



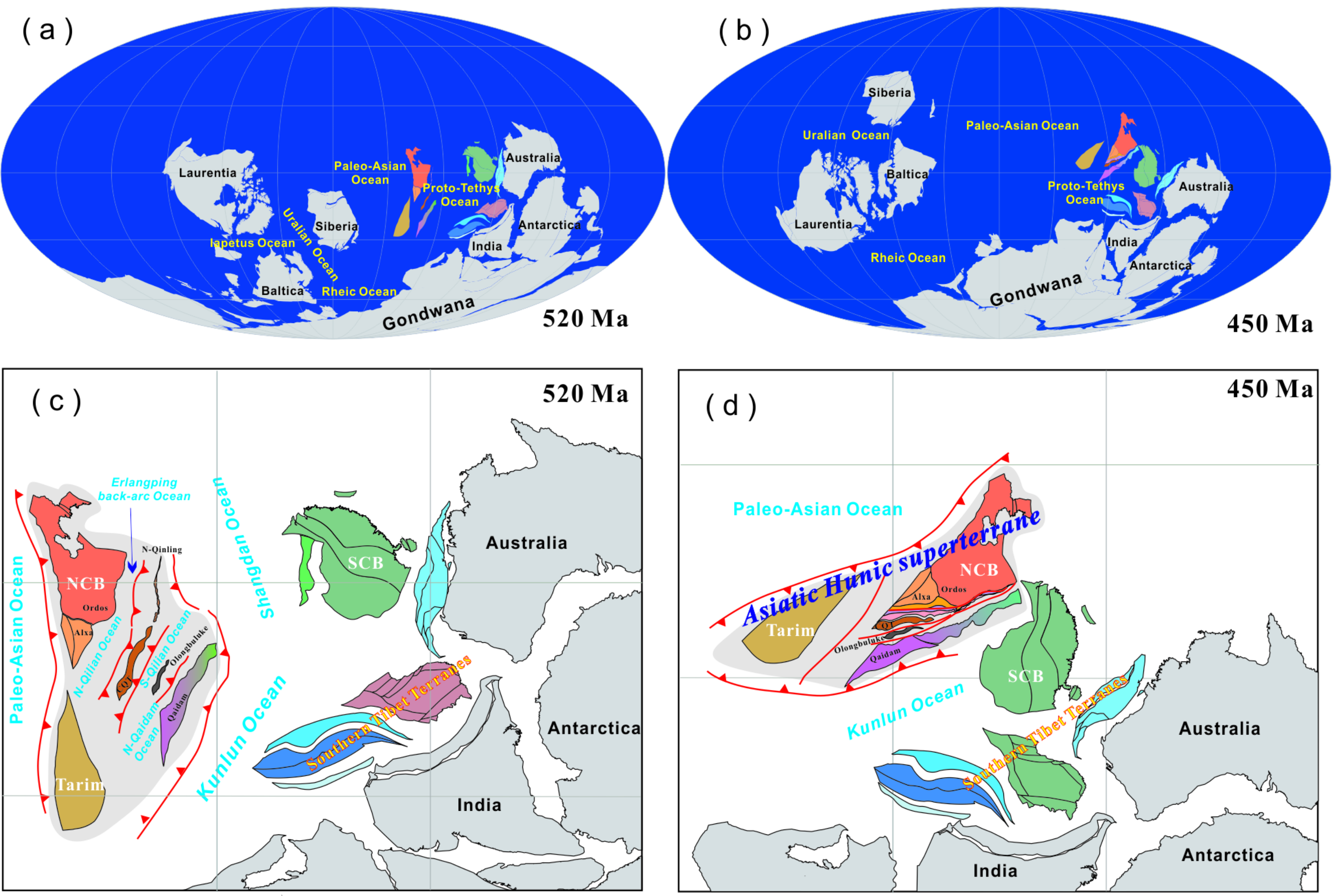
Qilian Thrust Wedge
Qilian orogen
Westerly siliciclastic dominated input
Present NE
Ordos Forebulge
Ordos carbonate platform
Easterly pure carbonate supply
Western Ordos abyssal plain
Miboshan Formation
Lashizhong Formation
Wulalike Formation
Kelimoli Formation

Figure 12.



(a) Subduction
ca. 520 Ma to ca. 453 Ma
Central Qilian
Arc Terrane
Magmatic arc
Fore-arc basin
Accretionary wedge
North Qilian
Ocean
Ordos carbonate shelf
Passive continental margin
W- North China Block
(b) Collision
ca. 453 Ma to ca. 420 Ma
Siliciclastic influx
from the west
Carbonate supply
from the east
Foredeep
Magmatic arc
Central Qilian
Arc Terrane
Accretionary wedge
Peripheral Foreland Basin
W- North China Block
Present NE
Miboshan
Formation
Lashizhong
Formation
Wulalike
Formation
Kelimoli
Formation

Figure 13.



(a)
Laurentia
Iapetus Ocean
Uralian Ocean
Siberia
Baltica
Rheic Ocean
Paleo-Asian Ocean
Proto-Tethys Ocean
Australia
Antarctica
India
Gondwana
520 Ma
(b)
Siberia
Uralian Ocean
Paleo-Asian Ocean
Baltica
Laurentia
Proto-Tethys Ocean
Australia
India
Antarctica
Rheic Ocean
Gondwana
450 Ma
(c)
520 Ma
Erlangping back-arc Ocean
N-Qinling
Shangdan Ocean
Paleo-Asian Ocean
NCB
Ordos
Alxa
N-Qilian Ocean
QT
S-Qilian Ocean
Olongbuluke
N-Qaidam Ocean
Qaidam
Tarim
Kunlun Ocean
SCB
Australia
Southern Tibet Terranes
Antarctica
India
(d)
450 Ma
Paleo-Asian Ocean
Asiatic Hunic superterrane
NCB
Alxa
Ordos
Tarim
QT
Olongbuluke
Qaidam
SCB
Kunlun Ocean
Southern Tibet Terranes
Australia
India
Antarctica