Tectonic evolution of the Proto-Qiangtang Ocean and its relationship with the Palaeo-Tethys and Rheic oceans

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Abstract: An evaluation of the potential geodynamic connections between the evolution of Paleozoic oceans in NW Gondwana and NE Gondwana is challenging. Until recently, most syntheses emphasized only two Paleozoic oceans (the Proto-Tethys and the Palaeo-Tethys) in the east Tethys realm. However, the discovery of early Paleozoic ophiolites along Palaeo-Tethys sutures located south of Proto-Tethys sutures challenges these traditional views. After a comprehensive review of relevant early Paleozoic tectonomagmatic events, we herein recognize and propose a model for the tectonic evolution of a hitherto unrecognized early Paleozoic ocean, which we call the Proto-Qiangtang Ocean. This ocean was short lived; it opened in the late Cambrian, began to subduct in the Middle Ordovician, and closed diachronously westwards between the Late Ordovician and the middle Silurian. Its closure by middle Silurian time indicates that was a spatially and temporally distinct ocean from the Palaeo-Tethys Ocean. The early tectonic evolution of the Proto-Qiangtang Ocean shares many characteristics with that of the Rheic Ocean. Both opened in the late Cambrian in the back-arc region of the Iapetus–Proto-Tethys Ocean, and the Proto-Qiangtang Ocean is considered to represent the eastern extension of the Rheic Ocean. This correlation has important implications for the Paleozoic tectonic evolution and palaeogeography of northern Gondwana.

Supplementary material: Compiled tectono-magmatic ages relevant to the evolution of the Proto-Qiangtang Ocean are available at https://doi.org/10.6084/m9.figshare.c.6263311

Several successive oceans were generated in the late Neoproterozoic and Paleozoic outboard of the northern Gondwanan margin, and their evolution profoundly influences Paleozoic palaeogeographical reconstructions. The vestiges of the Iapetus and Rheic oceans in NW Gondwana, and the Proto-Tethys and Palaeo-Tethys oceans in NE Gondwana are the most widely documented. The Iapetus and Proto-Tethys oceans opened in the late Neoproterozoic and closed in the Silurian (van Staal *et al.* 1998, 2009; Murphy *et al.* 2010; Li *et al.* 2018). The Rheic Ocean opened in the late Cambrian–Early Ordovician and closed in the Devonian and Carboniferous (van Staal *et al.* 2009, 2012; Murphy *et al.* 2010; Nance *et al.* 2010; Kroner and Romer 2013; Wu *et al.* 2021). The Palaeo-Tethys Ocean opened in the Silurian–Devonian and closed in the Triassic (Metcalfe 2013; X.Z. Zhang *et al.* 2016; Dan *et al.* 2018*a*; W. Xu *et al.* 2020). There have been many attempts to compare the geodynamic evolution of these oceanic tracts and to deduce their palaeogeography in the Paleozoic. There is a broad consensus that the Iapetus and Proto-Tethys oceans represent a continuous oceanic tract (Stampfli and Borel 2002; Torsvik and Cocks 2017; Li *et al.* 2018); however, the identity of the eastern extension of the Rheic Ocean and its potential relationship with the Palaeo-Tethys Ocean is hotly debated (e.g. Stampfli and Borel 2002; Metcalfe 2013; Stampfli *et al.* 2013; Torsvik and Cocks 2017). The main reason for this controversy is that the complex evolution of these oceans has been overprinted by events associated with the evolution of the younger Neo-Tethys Ocean and other marginal seas.

In recent years, a few early Paleozoic ophiolites have been discovered in the east Tethys realm

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along the Palaeo-Tethys sutures that lie to the south of sutures associated with the closure of the Proto-Tethys Ocean (B.D. Wang *et al.* 2013; Zhai *et al.* 2016; Nguyen *et al.* 2019). Two different models have been proposed to account for these early Paleozoic ophiolites. Some researchers consider these ophiolites to reflect the opening of the Palaeo-Tethys Ocean in the late Cambrian (B.D. Wang *et al.* 2013; Zhai *et al.* 2016). Alternatively, others have proposed the existence of an early Paleozoic ocean, located south of the Proto-Tethys Ocean in the east Tethys realm, that closed during the Silurian (H.T. Tran *et al.* 2014; X.Z. Zhang *et al.* 2014; Faure *et al.* 2018; T.V. Tran *et al.* 2020; W. Xu *et al.* 2020). In this paper, we review the Paleozoic tectonic framework in east Tethys and the tectonomagmatic events thought to be related to this early Paleozoic ocean, here called the Proto-Qiangtang Ocean, and briefly compare its geodynamic evolution with those of the Palaeo-Tethys and Rheic oceans.

Geological framework in eastern Asia

Multiple suture zones, including those that reflect the closure of the Proto-, Palaeo- and Neo-Tethys oceans, divide eastern Asia into many small terranes or blocks. These suture zones are uniformly younger from north to south: that is, the Silurian Proto-Tethys sutures in the Qinling–Qilian–Kunlun Orogen, the Triassic Palaeo-Tethys sutures in northern Tibet and adjacent regions; and the Cretaceous–Paleogene Neo-Tethys sutures in southern Tibet and adjacent regions (Fig. 1) (Metcalfe 2013). The terranes south of the Palaeo-Tethys sutures are collectively called Cimmerian microcontinents (Şengör 1979), and include the Karakorum, Southern Qiangtang, Amdo, Lhasa, Baoshan, Tengchong and Sibumasu terranes in eastern Asia, which probably remained attached to northeastern Gondwana until the opening of the Neo-Tethys Ocean in the Early Permian (Dan *et al.* 2021). Other terranes located between the Cimmerian microcontinents and the Tarim–Alxa–North China blocks are related to the evolution of the Proto- and Palaeo-Tethys oceans. However, another recently documented Cambrian ocean (the Proto-Qiangtang Ocean), which was located between the Northern Qiangtang–South China Block and Gondwana, complicates reconstructions of the Paleozoic evolution of eastern Asia.

The Proto-Tethys Ocean is commonly viewed as an Ediacaran–early Paleozoic ocean that was initiated by rifting of the Qilian–Qaidam Block at *c.* 600–580 Ma from NE Gondwana (X. Xu *et al.* 2015). Its vestiges are ophiolite complexes with crystallization ages ranging from 540 to 460 Ma, composed of serpentinite, gabbro, diabase and basalt with compositions similar to normal mid-ocean ridge basalt (N-MORB) or enriched mid-ocean ridge basalt (E-MORB). These ophiolites occur in parallel suture zones within the Qinling–Qilian–Kunlun Orogen (sutures 1–6 in Fig. 1) between the Tarim–North China and Tibetan Plateau–South China continental blocks (e.g. Dong and Santosh 2016; Dong *et al.*

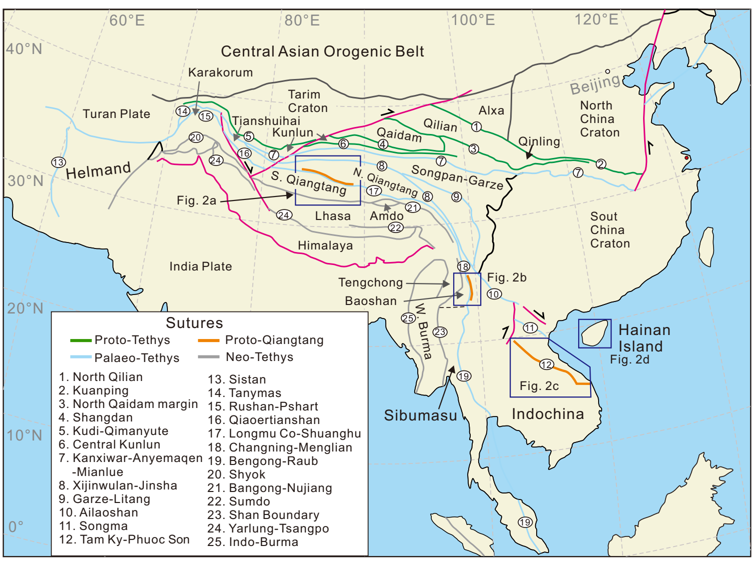

Fig. 1. Tectonic framework of East Asia and adjacent areas, highlighting the locations of Tethys sutures. The numbers represent sutures given in the legend and the terrane names are labelled in the figure.

2018), and are thought to represent vestiges of several branches of the same ocean (Dong *et al.* 2018; Song *et al.* 2018). Arc magmatism in the Kunlun–Qilian segment of the orogen began at *c.* 530–520 Ma and terminated at *c.* 450–440 Ma (C.L. Zhang *et al.* 2019). These events, together with 440–430 Ma regional metamorphism, suggest that ocean closure had occurred by the early Silurian (e.g. Song *et al.* 2013, 2018). Although previously thought to have been closed by north-directed subduction (present orientation), restoration of Mesozoic–Cenozoic deformation suggests that the ocean closed by southward subduction beneath the NE Gondwanan margin (Li *et al.* 2018). The latter interpretation is supported by the documentation of *c.* 530–450 Ma arc magmatism in the Tianshuihai Terrane of the West Kunlun segment, which is located to the south of the Proto-Tethys Suture Zone (suture 5 in Fig. 1) (C.L. Zhang *et al.* 2018).

Multiple Triassic sutures (sutures 7–19 in Fig. 1) are related to the evolution of the Palaeo-Tethys Ocean and relevant oceanic basins. The Longmu Co–Shuanghu, Changning–Menglian and Bengong–Raub sutures are generally considered to be relicts of the main Palaeo-Tethys Ocean (Li 1987; Metcalfe 2013; X.Z. Zhang *et al.* 2017; Dan *et al.* 2018*a*). This ocean probably opened between the late Silurian and the Middle Devonian (Metcalfe 2013; X.Z. Zhang *et al.* 2014, 2016), although some researchers argue for an older opening based on a few Cambrian–Ordovician ophiolites discovered in the main sutures (B.D. Wang *et al.* 2013; Zhai *et al.* 2016). The tectonic evolution of the main Palaeo-Tethys Ocean is recorded by Early Carboniferous and Early Permian ophiolites (Jian *et al.* 2009; Zhai *et al.* 2013; X.Z. Zhang *et al.* 2016), Late Devonian–Middle Triassic arc igneous rocks (Dan *et al.* 2018*b*, 2019), and Late Triassic blueschists and eclogites (K.J. Zhang *et al.* 2006; Dan *et al.* 2018*a*; H.N. Wang *et al.* 2020*b*). The penecontemporaneous subsidiary sutures north of, and associated with, the main Palaeo-Tethys sutures are generally thought to be relicts of back-arc basins (Y.J. Wang *et al.* 2018), that closed in the Late Triassic (Y.J. Wang *et al.* 2018; Tang *et al.* 2021), coeval with the closure of the main Palaeo-Tethys Ocean.

Abundant early Paleozoic igneous rocks are exposed south of the main Palaeo-Tethys sutures. They are composed predominantly of S-type granites and minor mafic rocks, and were mostly intruded between 510 and 460 Ma (Gao *et al.* 2019; Dan *et al.* 2020). Varied geodynamic settings, including subduction, lithospheric delamination and back-arc extension (Cawood *et al.* 2007, 2021; Y.M. Liu *et al.* 2019; W. Xu *et al.* 2020), have been proposed to explain these igneous rocks. Their composition, as well as their temporal and spatial characteristics, are typical of a silicic large igneous province (known as Pinghe SLIP) generated above a mantle plume (Dan *et al.* in press). Emplacement of plumes along the periphery of Gondwana may have been common in the late Neoproterozoic–early Paleozoic (Murphy *et al.* 2021), consistent with geodynamic models that predict plumes preferentially nucleating along the edges of large low-shear-wave-velocity provinces (LLSVPs) (e.g. Tan *et al.* 2002; Steinberger and Torsvik 2012), which may have underlain Gondwana at that time (Doucet *et al.* 2020).

Tectonomagmatic events relevant to the Proto-Qiangtang Ocean

Over the past two decades, application of precise U–Pb (zircon) dating techniques has constrained the crystallization ages of early Paleozoic tectonic–magmatic events from central Qiangtang, across Sanjiang, Indochina to Hainan Island. As zircon is rarely crystallized from mafic magmas and is often recrystallized during high-grade metamorphic events, we employed several criteria to evaluate whether or not the zircon dates represent the crystallization age of their host rock. First, cathodoluminescence (CL) images of zircon grains crystallized from felsic magmas typically exhibit oscillatory zoning but only weak internal oscillatory or broad-banded zoning if crystallized from mafic magmas (Corfu *et al.* 2003; Dan *et al.* 2021). Second, if the zircon crystallized from the same magma as its host rock, its Hf isotopic values should be compatible with whole-rock Nd isotopic values. Third, zircon grains that have experienced the same high-grade metamorphism as their host are typically recrystallized, producing oval shapes that are highly luminescent in CL images and have Th/U ratios of >0.1 (Chen *et al.* 2010; Dan *et al.* 2012*b*). After checking the original data, some dating results have been reinterpreted as the ages of xenocrystic zircon grains in mafic rocks or metamorphic ages in metamorphic rocks (see Supplementary Table S1).

In the central Qiangtang region, a *c.* 500 km-long belt of early Paleozoic ophiolites has been discovered in the Taoxinghu, Guoganjialianshan and Shuanghu areas (Figs 2a & 3a), spatially associated with the Longmu Co–Shuanghu Palaeo-Tethys Suture Zone. This belt is typically exposed in isolated blocks or mélanges and is in faulted contact with late Paleozoic sedimentary rocks. The ophiolites are composed of serpentinites, gabbros, basalts and plagiogranites (Fig. 4a), and metamorphosed mafic rocks, some of which are now amphibolites. No sheeted dykes have been found. Whole-rock geochemical data show that the mafic rocks are akin to MORBs but are depleted in high-field strength elements (HFSEs), including Nb and Ti (Fig. 4b, c)

(Zhai *et al.* 2016). Zircon U–Pb dating of gabbros/amphibolites and plagiogranites constrain the formation of oceanic crust to between *c.* 500 and 440 Ma (Hu *et al.* 2014; Zhai *et al.* 2016). Dating of amphibolites and high-pressure granulites indicate that the oceanic lithosphere underwent *c.* 430–420 Ma peak metamorphism (X.Z. Zhang *et al.* 2014), an event accompanied by the intrusion of a few *c.* 430 Ma diorites and granites (H. Liu *et al.* 2021). These high-pressure granulites exhibit clockwise pressure–temperature–time (*P–T–t*) paths, indicating that the early Paleozoic ocean between the Southern and

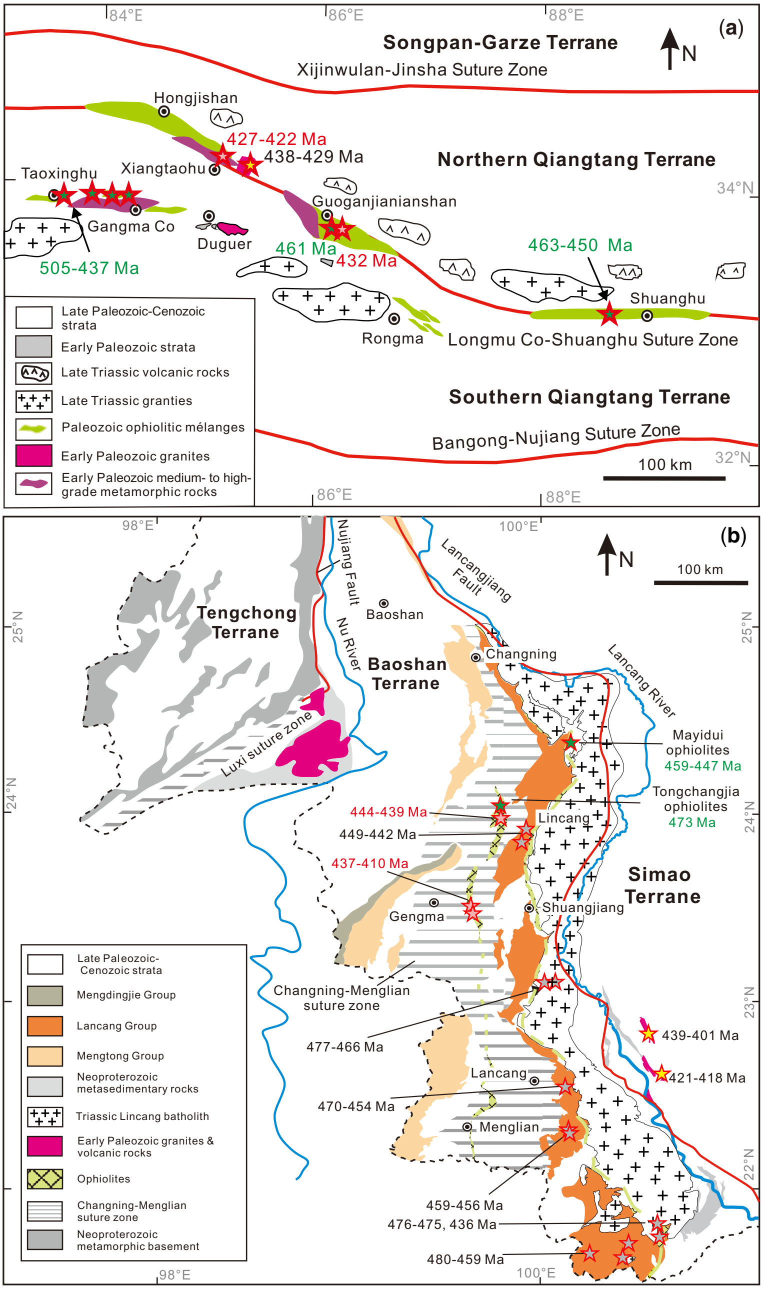

Fig. 2. Simplified regional geological maps for the study areas: (**a**) Qiangtang, (**b**) Sanjiang (only shown in China).

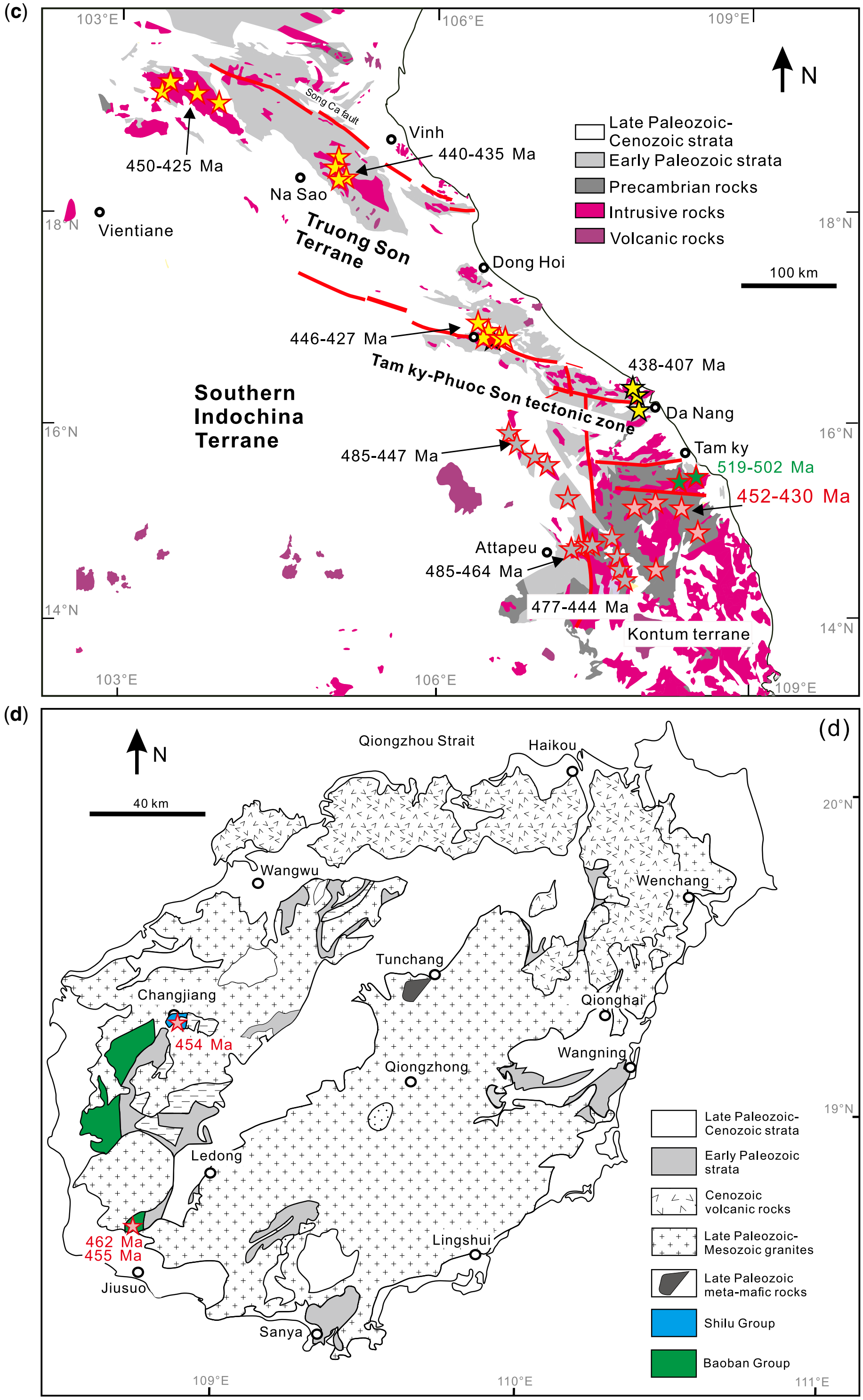

Fig. 2. *Continued* (**c**) Indochina and (**d**) Hainan Island. Age data are based on Supplementary Table S1.

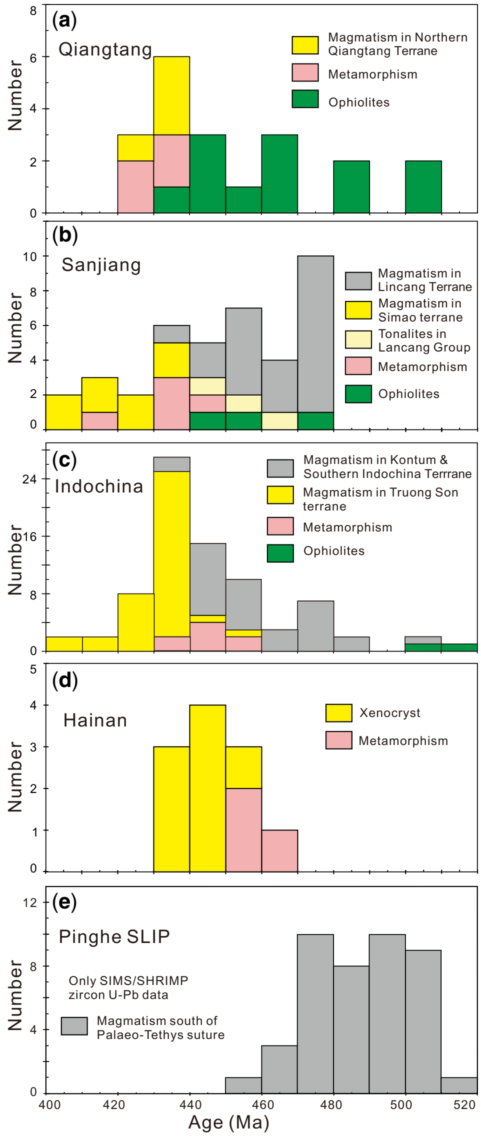

Fig. 3. A compilation of tectonomagmatic ages relevant to the Proto-Qiangtang Ocean. (**a**)–(**d**) Zircon U–Pb age or monazite U–Pb or U–Th–Pb age for individual segments. (**e**) Magmatic zircon U–Pb age for the Pinghe SLIP shown for comparison. Note: (1) only zircon or monazite dates dated by *in situ* methods are plotted in (a)–(d), and the monazite dates interpreted as metamorphic ages were obtained from Indochina and Hainan Island; (2) xenocrystic zircon U–Pb dates are not plotted in (a)–(c) but are shown in (d) as sparse early Paleozoic data obtained in Hainan Island; (3) only precise SIMS/sensitive high-resolution ion microprobe (SHRIMP) zircon U–Pb ages are used for (e); (4) the bin width in each panel is 10 myr; and (5) the data sources for (a)–(d) are listed in Supplementary Table S1, and the data source for (e) is Dan *et al.* (in press).

Northern Qiangtang terranes was closed by the middle Silurian (*c.* 430 Ma) (X.Z. Zhang *et al.* 2014).

In the Sanjiang region, which consists of the Tengchong, Baoshan and Simao terranes with intervening sutures/faults (Fig. 2b), U–Pb zircon dating yielded ages of *c.* 470–450 Ma for the Tongchangjie, Mayidui and Wanhe ophiolites along the Changning–Menglian Palaeo-Tethys Suture Zone (Figs 2b & 3b) (B.D. Wang *et al.* 2013; G.C. Liu *et al.* 2021*b*). However, as the early Paleozoic zircon grains from the Wanhe mafic rocks show oscillatory zoning in CL images, and disequilibrium between zircon Hf and whole-rock Nd isotopes, these grains are reinterpreted as xenocrysts. The Tongchangjie and Mayidui ophiolites are in faulted contact with late Paleozoic sedimentary rocks, and are composed of serpentinites, gabbros and metamorphic rocks (Fig. 4a), some of which are now amphibolites and greenschists. The mafic rocks (gabbros and greenschists) have a MORB affinity but with a depletion in Nb and Ti (Fig. 4b, c) (G.C. Liu *et al.* 2021*b*), traits similar to the early Paleozoic ophiolites in central Qiangtang. Zircon U–Pb ages reveal that the oceanic lithosphere was formed between 470 and 450 Ma (B.D. Wang *et al.* 2013; G.C. Liu *et al.* 2021*b*), and metamorphosed at *c.* 440 Ma (B.D. Wang *et al.* 2013), similar in age to the *c.* 430–410 Ma metamorphism in the Qingping area (Peng *et al.* 2020, 2021). The *c.* 440–410 Ma age of metamorphism constrained by zircon U–Pb dating is broadly consistent with a *c.* 410 Ma age of metamorphism yielded by the crossite/chlorite Ar–Ar method for blueschists in the Lancang Group (Cong *et al.* 1993), which is a Cambrian–Ordovician sequence of metasedimentary rocks that was deposited in a continental margin environment (H.N. Wang *et al.* 2020*a*; Wei *et al.* 2022). A few *c.* 470–450 Ma tonalites with adakitic geochemical affinities occur as veins intruding the amphibolites and as blocks in the Lancang Group along the suture zone (D.B. Wang *et al.* 2016; Wu *et al.* 2020). Although a few *c.* 480–440 Ma felsic metavolcanics/granites have been documented in the Lancang Group and Lincang batholith (both comprising the Lincang Terrane) (Nie *et al.* 2015; Wei *et al.* 2022), only younger 440–400 Ma granites/rhyolites and mafic rocks (amphibolites and basalts) have been reported in the Simao Terrane (Fig. 2b) (Jian *et al.* 2009; H.C. Liu *et al.* 2019).

In the Indochina Block (Fig. 2c), which is further subdivided into several subterranes (Truong Son, Kontum and Southern Indochina terranes) by early Paleozoic sutures or faults, ophiolites occur as blocks within the Tam Ky-Phuoc Son Suture Zone (Izokh *et al.* 2006; Pham *et al.* 2006). These ophiolites are composed of serpentinites, metagabbros and metabasalts (Fig. 4a). Zircon U–Pb dating of plagiogranites within the suture zone suggest that

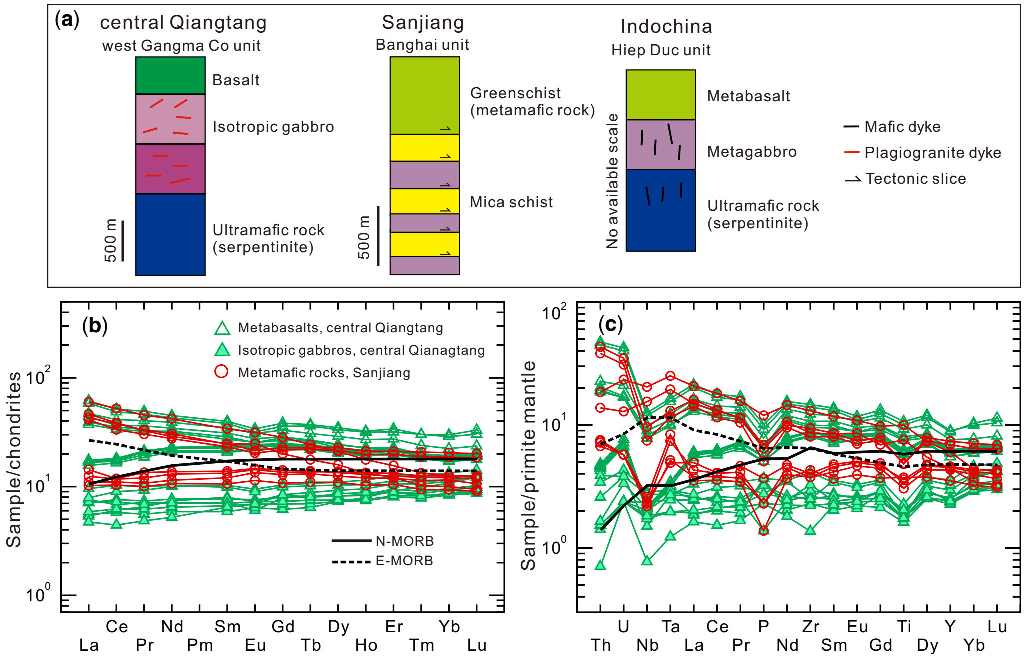

Fig. 4. Schematic columns showing the lithological make-up of (**a**) the ophiolitic units and (**b**) and (**c**) normalized non-cumulate mafic rocks of the ophiolites. Schematic columns of ophiolites are based on previous studies – central Qiangtang: Wu *et al.* (2009) and Zhai *et al.* (2016); Sanjinag: G.C. Liu *et al.* (2021*b*); Indochina: Izokh *et al.* (2006), Pham *et al.* (2006) and Nguyen *et al.* (2019). Geochemical data are from central Qiangtang (Zhai *et al.* 2016) and Sanjiang: G.C. Liu *et al.* (2021*b*). The normalized N-MORB and E-MORB values are from Sun and McDonough (1989).

oceanic crust generation occurred at *c.* 510 Ma (Figs 2c & 3c) (Nguyen *et al.* 2019). In contrast to the *c.* 500–440 Ma granitic and minor mafic magmatism documented in both the Kontum and Southern Indochina terranes, only younger (450–400 Ma) granites/rhyolites and mafic rocks were reported in the Truong Son Terrane (Jiang *et al.* 2020; T.V. Tran *et al.* 2020; Y.J. Wang *et al.* 2020, 2021*a*, *b*; Nakano *et al.* 2021). Zircon and monazite dating of paragneisses and amphibolites provide a *c.* 450–430 Ma age for amphibolite-facies metamorphism in the Tam Ky-Phuoc Son Suture Zone and the Kontum Terrane, which is interpreted to reflect a collision between the Kontum and Truong Son terranes (Roger *et al.* 2007; Usuki *et al.* 2009; Nakano *et al.* 2013; H.T. Tran *et al.* 2014).

In Hainan Island, no early Paleozoic ophiolites have been reported. A reliable determination of a *c.* 460–450 Ma age for regional amphibolite-facies metamorphism was obtained from the Precambrian Baoban Complex and Shilu Group (Figs 2d & 3d) (D.R. Xu *et al.* 2015; Y.J. Xu *et al.* 2020; H. Zhang *et al.* 2022). The recently identified metabasalts/andesites (Zhou *et al.* 2021) are likely to have formed in the Early Carboniferous (He *et al.* 2018), as samples from both studies collected from same areas yield Early Carboniferous zircon U–Pb ages (He *et al.* 2018), and the zircon grains in the former study show obvious oscillatory zoning in CL images.

In summary, early Paleozoic ophiolites preserved in the Longmuco–Shuanghu Palaeo-Tethys, Changning–Menglian Palaeo-Tethys and Tam Ky-Phuoc Son suture zones were formed and emplaced between *c.* 510 and 440 Ma. Basalts show MORB-like characteristics but with HFSE depletion (Fig. 4), implying their generation in a suprasubduction zone setting. The regional metamorphic ages in the Proto-Qiangtang Ocean realm are *c.* 460–450 Ma for Hainan Island, *c.* 450–430 Ma for Indochina, *c.* 440–410 Ma for Sanjiang and *c.* 430–420 Ma for Qiangtang, suggesting diachronous collision from the SE to the NW.

Discussion

The discovery of early Paleozoic ophiolites in Qiangtang, Sanjaing and Indochina indicates that there was an early Paleozoic ocean located south of the suture zone inferred to represent the boundary between NE Gondwana and the Proto-Tethys Ocean. This ocean has previously been given local names and has been variously interpreted as a branch of the Palaeo-Tethys or the Proto-Tethys. As the ophiolites are best preserved and were first studied in central Qiangtang, we herein propose that this early Paleozoic ocean be named the Proto-Qiangtang Ocean.

Tectonic evolution of the Proto-Qiangtang Ocean and its relationship with the Palaeo-Tethys Ocean

Based on data from different segments of the Proto-Qiangtang Ocean, most researchers consider the Proto-Qiangtang Ocean to have been generated in the early Paleozoic (B.D. Wang *et al.* 2013; Zhai *et al.* 2016), although some propose a late Neoproterozoic origin for its Indochina segment (T.V. Tran *et al.* 2020). Geochemical comparisons with the Troodos and northern Pamir plagiogranites, including a similar depletion of HFSEs (Nb and Ti), suggest that the *c.* 510 Ma plagiogranites in Indochina (Tam Ky-Phuoc Son Suture Zone) were generated in an intra-oceanic arc setting (Nguyen *et al.* 2019) that has recently been reinterpreted as a back-arc setting (Tang *et al.* 2021). No ophiolites older than these plagiogranites have been documented in the Proto-Qiangtang Ocean realm, implying that this ocean was probably formed no earlier than the middle Cambrian (*c.* 510 Ma). The Proto-Qiangtang Ocean was located south of the subduction zone documented within the Proto-Tethys, implying it was generated in a back-arc tectonic setting (Zhai *et al.* 2016; W. Xu *et al.* 2020), a scenario consistent with the suprasubduction-zone-type geochemistry of the ophiolites reported in the Proto-Qiangtang Suture Zone. A mantle plume, responsible for the generation of the *c.* 510–460 Ma Pinghe SLIP (Dan *et al.* in press), could also have played an important role in the generation of this ocean. This SLIP could be a local example of mantle plumes that were preferentially emplaced along the margins of Gondwana in the late Neoproterozoic–early Paleozoic (Murphy *et al.* 2021). Emplacement of plumes preferentially exploits weaknesses in the lithosphere (Obrebski *et al.* 2010; Coble and Mahood 2012), such as those provided by the opening of back-arc basins.

The subduction polarity of the Proto-Qiangtang Ocean is controversial, and models of northward (B.D. Wang *et al.* 2013; Faure *et al.* 2018; Jiang *et al.* 2020), southward (Y.J. Wang *et al.* 2020, 2021*b*) or even bivergent subduction have been proposed (G.C. Liu *et al.* 2021*b*; H. Liu *et al.* 2021). The model for a southward subduction polarity is mostly based on the *c.* 510–460 Ma magmatism located south of the Proto-Qiangtang Ocean. However, if these igneous rocks that constitute the Pinghe SLIP were generated by a mantle plume (Dan *et al.* in press; Murphy *et al.* 2021), there is no independent evidence that would support this model. Direct documentation of arc magmatism that would record subduction polarity remains elusive. However, as shown by studies focused on the subduction record of the Rheic Ocean (Pereira *et al.* 2017), the former existence of magmatic arcs could be preserved in detrital zircon age patterns in coeval or younger clastic deposits eroded from that arc (Cawood *et al.* 2012; Dan *et al.* 2012*a*; X.Z. Zhang *et al.* 2017). Our compilation of detrital zircon data reveals contrasting detrital zircon age spectra for different terranes on opposite sides of the Proto-Qiangtang Suture (Fig. 5). Silurian and younger sedimentary rocks north of the Proto-Qiangtang Suture, such as in the Northern Qiangtang, Simao, Truong Son and Hainan Island terranes (Fig. 5b, d, h, i), have detrital zircon age spectra characterized by a major 440 Ma peak. The coeval relationship between the 440 Ma detrital zircon peak and the Silurian strata that contain these zircons is typical of arc settings (Cawood *et al.* 2012; Dan *et al.* 2012*a*). In contrast, in Silurian or younger sedimentary rocks south of the Proto-Qiangtang Suture, such as those in the Southern Qiangtang, Baoshan–Tengchong and Kontum terranes (Fig. 5a, c, f), the dominant detrital zircon age populations are older than *c.* 500 Ma. Collectively, these data suggest that the Proto-Qiangtang Ocean underwent northward subduction, and the Ordovician–Silurian ages of detrital zircons deposited in strata to the north of this ocean were derived from coeval arc magmatism related to such subduction.

The detrital zircon age populations can be used further to clarify the tectonic affinity of some disputed terranes along the sutures. In the Sanjiang region (Fig. 2b), the Lincang Terrane, which is located between the Changning–Menglian Palaeo-Tethys Suture and the Simao Terrane, and consists of the Lancang Group and the Lincang batholiths, is considered to be tectonically linked with Gondwana (Baoshan Terrane) but not with the adjacent Simao Terrane (Feng *et al.* 1996). This interpretation is consistent with the detrital zircon age spectrum, which has no significant age peak younger than *c.* 500 Ma (Fig. 5e), indicating that these rocks were located south of the Proto-Qiangtang Ocean in a passive-margin setting. Thus, the *c.* 500–460 Ma igneous rocks in this terrane are not directly related to arc magmatism within the Proto-Qiangtang Ocean but are more likely to be part of the *c.* 510–460 Ma Pinghe SLIP (Dan *et al.* in press). A minor Silurian (*c.* 430 Ma) detrital zircon age peak occurs in the uppermost strata of the Lancang Group

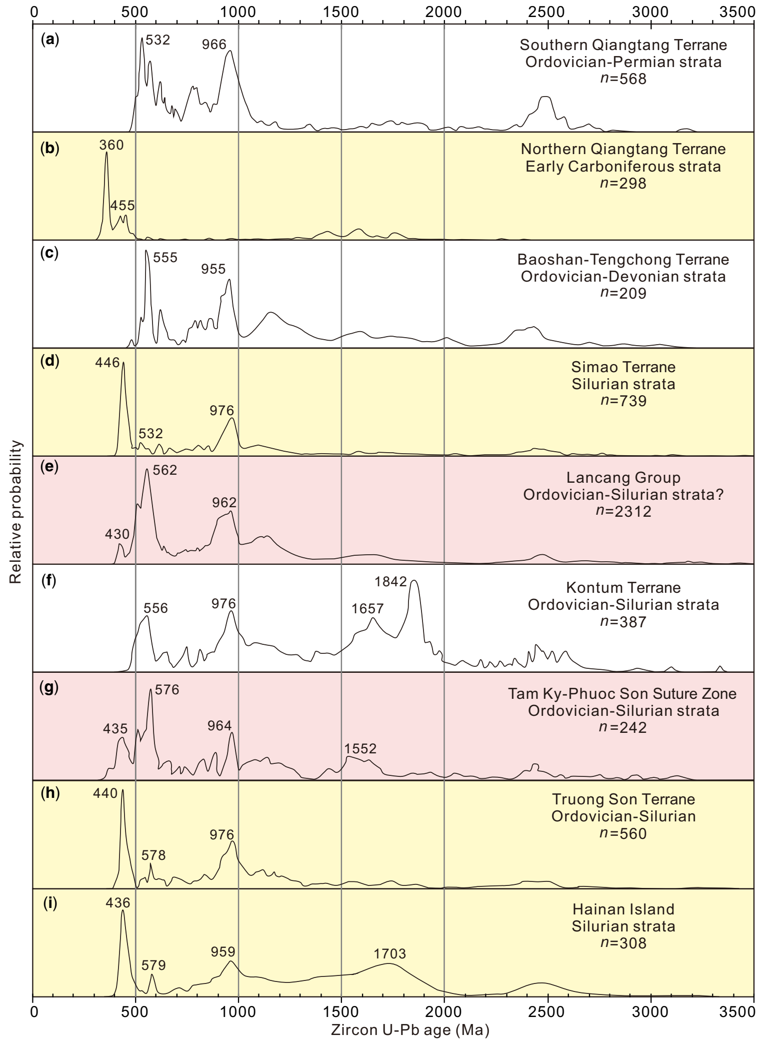

Fig. 5. Relative probability plots comparing detrital zircon age spectra. Note: (1) *n* in each panel is the number of detrital zircon ages; and (2) there are no detrital zircon age data available for Silurian–Devonian strata in Northern Qiangtang, thus we show data from Early Carboniferous strata in (b). Data sources: the Southern Qiangtang and Northern Qiangtang terranes, X.Z. Zhang *et al.* (2017) and references therein; the Baoshan–Tengchong and Simao terranes and the Lancang Group, H.N. Wang *et al.* (2020*a*) and references therein and Wei *et al.* (2022); the Kontum Terrane, Tam Ky-Phuoc Son Suture Zone and the Truong Son Terrane, Y.J. Wang *et al.* (2021*a*) and references therein; and Hainan Island, Zhou *et al.* (2015).

(Wei *et al.* 2022), which were likely to have been sourced from the magmatic arc after closure of the Proto-Qiangtang Ocean. Detrital zircon age spectra in the Tam Ky-Phuoc Son Suture Zone are similar to those in the Lancang Group (Fig. 5e, g) and indicate the suture zone was located south of the Proto-Qiangtang Ocean.

The timing of closure of the Proto-Qiangtang Ocean is controversial, with interpretations ranging from the Late Triassic to the Silurian. The Paleozoic ophiolites were initially interpreted to be relicts of the Palaeo-Tethys Ocean, in which the early Paleozoic ocean had evolved into the Palaeo-Tethys Ocean by the late Paleozoic (B.D. Wang *et al.* 2013; Zhai *et al.* 2016) and then closed in the Late Triassic (K.J. Zhang *et al.* 2006; Dan *et al.* 2018*a*; W. Xu *et al.* 2020; H.N. Wang *et al.* 2020*b*). However, more recent documentation of Middle Ordovician–Silurian metamorphic and igneous rocks along the whole belt suggests that the Proto-Qiangtang

Ocean closed during the early Paleozoic (H.T. Tran *et al.* 2014; X.Z. Zhang *et al.* 2014; Faure *et al.* 2018; Jiang *et al.* 2020; T.V. Tran *et al.* 2020; W. Xu *et al.* 2020; Y.J. Wang *et al.* 2020; H. Zhang *et al.* 2022). The *c.* 470 Ma adakitic rocks documented in the suture zones (D.B. Wang *et al.* 2016; Gardner *et al.* 2017) are indicative of the onset of arc magmatism. The *c.* 430 Ma high-pressure granulites accompanied by amphibolite-facies metamorphism in the Qiangtang region indicate this segment of the Proto-Qiangtang Ocean was closed by that time (X.Z. Zhang *et al.* 2014). No high-pressure metamorphic rocks are reported in other segments but early Paleozoic amphibolite-facies metamorphism, combined with (a) coeval magmatism with post-collisional geochemical affinities and (b) post-Silurian termination of arc magmatism based on the detrital zircon age populations (Fig. 5), suggest that the Proto-Qiangtang Ocean was closed by *c.* 430 Ma in these regions. However, younger metamorphic ages from Hainan Island to central Qiangtang indicate diachronous closure of the Proto-Qiangtang Ocean between *c.* 460 and 430 Ma. As the age of collision is similar to the detrital zircon peak in each segment (Fig. 5), arc magmatism was likely to have been of short duration.

Thus, the tectonic evolution of the Proto-Qiangtang Ocean can be summarized in the following stages (Fig. 6). The Proto-Tethys Ocean subduction zone geodynamics generated a back-arc region with inherent structural weaknesses that were exploited by one of several mantle plumes that preferentially ascended along the periphery of Gondwana. The feedback between back-arc extension and mantle-plume emplacement generated a narrow late Cambrian ocean between the Northern Qiangtang–South China–Northern Indochina terranes and the Southern Qiangtang–Baoshan–Southern Indochina terranes. This ocean underwent northward subduction beneath the Northern Qiangtang–South China–Northern Indochina terranes, probably beginning at *c.* 470 Ma, and was closed diachronously between *c.* 460 and 430 Ma from Hainan Island to central Qiangtang. Magmatism after *c.* 450–440 Ma in central Indochina, *c.* 440 Ma in Sanjiang and *c.* 430 Ma in central Qiangtang formed in a syncollisional setting, as supported by the documentation of S-type granites that formed at *c.* 450–440 Ma in the Truong Son Terrane, Indochina (Jiang *et al.* 2020) and at *c.* 436 Ma in Sanjiang (G.C. Liu *et al.* 2021*a*). Younger episodes (*c.* 420–400 Ma) of magmatism in Indochina and Sanjiang were generated in a post-collisional (Jiang *et al.* 2020) or a rift setting (Jian *et al.* 2009; H.C. Liu *et al.* 2019), possibly related to the opening the Palaeo-Tethys Ocean. The Palaeo-Tethys Suture Zone spatially overlaps with the Proto-Qiangtang Suture, especially in the Qiangtang and Sanjiang segments (Figs 1 & 2), indicating that the rifting preferentially occurred near or along a pre-existing suture (Murphy *et al.* 2006).

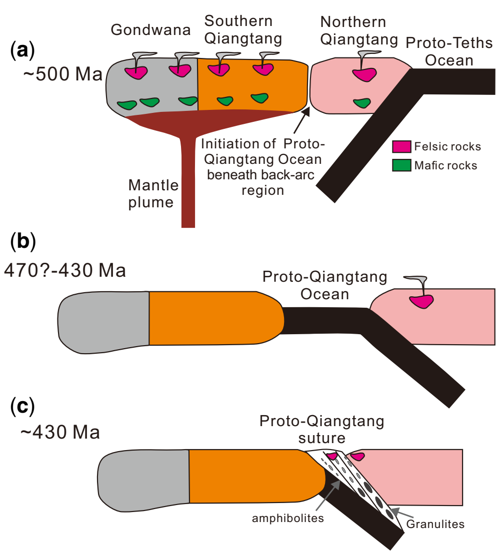

Fig. 6. Schematic model for the tectonic evolution of the Proto-Qiangtang Ocean in the Qiangtang segment.

Correlation of the Rheic Ocean with the Proto-Qiangtang Ocean

The potential geodynamic relationships between the Paleozoic oceans developed along the northern margin of Gondwana are widely debated. The Proto-Tethys Ocean is generally considered to be the eastern extension of the Iapetus Ocean (e.g. Stampfli and Borel 2002; Murphy *et al.* 2010; Stampfli *et al.* 2013). However, the identity of the eastern extension of the Rheic Ocean is controversial, and proposed counterparts include the Proto-Tethys and Palaeo-Tethys oceans (Stampfli and Borel 2002; Metcalfe 2013; Stampfli *et al.* 2013; Torsvik and Cocks 2017; Li *et al.* 2018). Here, we propose that its eastern extension is probably the Proto-Qiangtang Ocean (Fig. 7).

The Rheic Ocean formed by the separation of Carolinia–Avalonia–Ganderia from Gondwana during the late Cambrian–Early Ordovician (Nance *et al.* 2010; van Staal *et al.* 2012, 2021), as recorded in Iberia by ophiolites (Sánchez Martínez *et al.* 2012, 2021) and rift–drift successions (Sánchez-García *et al.* 2003, 2008). The northward drift of Avalonia is commonly thought to be broadly related to the southward subduction and rollback of Iapetus oceanic lithosphere, although, in detail, the mechanisms

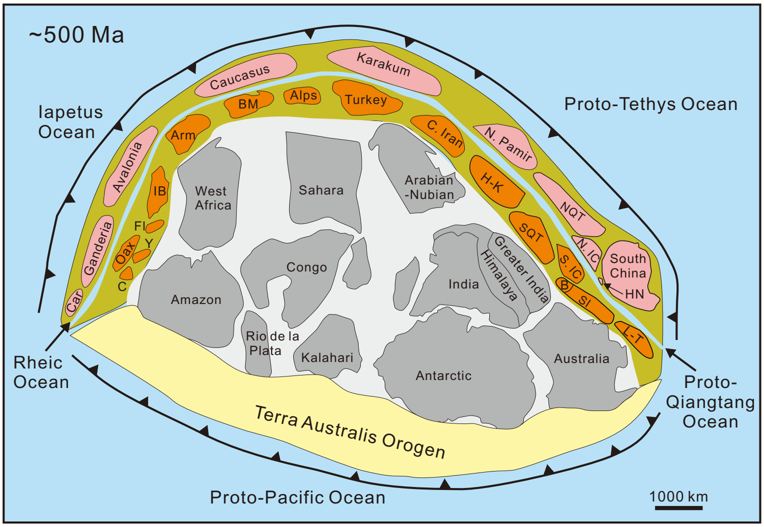

Fig. 7. Palaeogeographical reconstruction of Gondwana in the late Cambrian (*c.* 500 Ma). Note: (1) the shape of the peri-Gondwanan terranes is conjectural, and the scale is for Gondwana; and (2) abbreviations: Arm, Armorica; B, Baoshan; BM, Bohemian Massif; C, Chortis; Car, Carolina; C. Iran, central Iran; Fl, Florida; H-K, Helmand–Karakoram; HN, Hainan Island; IB, Iberia; L-T, Lhasa-Tengchong; N. IC, Northern Indochina; NQT, Northern Qiangtang; Oax, Oaxaquia; S. IC, Southern Indochina; SI, Sibumasu; SQT, Southern Qiangtang; Y, Yucatan.

proposed are highly variable (Nance *et al.* 2010). Coeval with the Rheic Ocean opening, the *c.* 495–470 Ma Ollo de Sapo SLIP was emplaced along the Gondwanan margin of this ocean (García-Arias *et al.* 2018), which is potentially another example of the importance of plume emplacement to the evolution of the Gondwanan margin (Murphy *et al.* 2021). In the Silurian–Devonian, the Rheic Ocean underwent northward subduction beneath Avalonia, with evidence for the associated magmatic arc recorded as detrital zircon populations in Late Devonian–Early Carboniferous siliciclastic rocks (Murphy *et al.* 2010; Nance *et al.* 2010; Pereira *et al.* 2017). Devonian (*c.* 400–380 Ma) ophiolites (Murphy *et al.* 2009; Arenas *et al.* 2021) and two stages of high-pressure metamorphism (*c.* 400 and *c.* 370–330 Ma) (Arenas *et al.* 2014) reported in the Variscan Orogen imply a complex or protracted collision during amalgamation of Laurussia and Gondwana (Kroner and Romer 2013; Franke *et al.* 2017; Wu *et al.* 2021).

The tectonic evolution of the Rheic Ocean described above is similar to that of the Proto-Qiangtang Ocean. First, both oceans opened in the late Cambrian–Early Ordovician along the northern margin of Gondwana by dispersal of peri-Gondwanan terranes. Second, creation of these oceans was related to the southward subduction and rollback of oceanic lithosphere (Iapetus and Proto-Tethys oceans) beneath Gondwana, and both were accompanied by emplacement of a SLIP (the *c.* 495–470 Ma Ollo de Sapo SLIP in NW Gondwana and the *c.* 510–460 Ma Pinghe SLIP in NE Gondwana), which were likely to have been generated by mantle plumes that were preferentially emplaced in zones of lithospheric weakness along the Gondwanan margin (Murphy *et al.* 2021). Third, the Rheic and Proto-Qiangtang oceans were both closed by north-directed subduction beneath the previously drifted peri-Gondwanan terranes. Fourth, the diachronous Devonian–Carboniferous closure of the Rheic Ocean (Wu *et al.* 2021) is consistent with the westward diachronous closure of the Proto-Qiangtang Ocean, and implies highly diachronous closure over 80 myr between East Asia and West Africa. Thus, we propose that the Proto-Qiangtang Ocean probably represents the eastern extension of the Rheic Ocean. Although more studies are needed to test our hypothesis and to refine the tectonic evolutions of both the Proto-Qiangtang and Rheic oceans, our model provides new constraints on the Paleozoic tectonic evolution and palaeogeography of the northern Gondwanan margin.

Conclusions

This study provides new constraints on the early Paleozoic tectonic evolution and palaeogeography along the northern Gondwanan margin. The Proto-Qiangtang Ocean, located south of the Proto-Tethys Ocean, is a short-lived (*c.* 80 myr), early Paleozoic ocean. This ocean opened in the late Cambrian (*c.* 510–500 Ma) by the northward drift of peri-Gondwanan terranes from central Qiangtang, across Sanjiang and central Indochina, to Hainan Island, and was possibly generated as a back-arc basin whose opening may have been assisted by the emplacement of a mantle plume. The Proto-Qiangtang Ocean underwent northward subduction beneath the dispersed peri-Gondwanan terranes (Northern Qiangtang–South China–NE Indochina) beginning in the Middle Ordovician (*c.* 470 Ma), and closed diachronously westwards, from Hainan Island to central Qiangtang, between *c.* 460 and 430 Ma. A Silurian closure of this ocean distinguishes it from the Silurian–Devonian opening of the Palaeo-Tethys Ocean. The Proto-Qiangtang Ocean shares a similar tectonic evolution to that of the Rheic Ocean in the early Paleozoic, and together they constitute an early Paleozoic ocean outboard of the northern Gondwanan margin.

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Author contributions **WD**: conceptualization (lead), data curation (lead), formal analysis (lead), methodology (lead), writing – original draft (lead), writing – review & editing (lead); **JBM**: conceptualization (equal), data curation (supporting), formal analysis (supporting), methodology (supporting), writing – original draft (equal), writing – review & editing (equal); **QW**: conceptualization (supporting), data curation (supporting), formal analysis (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting); **X-ZZ**: conceptualization (supporting), data curation (supporting), formal analysis (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting); **G-JT**: conceptualization (supporting), data curation (supporting), formal analysis (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting).

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Data availability All data generated or analysed during this study are included in this published article and its supplementary information file.

References

Arenas, R., Fernandez, R.D., Martinez, S.S., Gerdes, A., Fernandez-Suarez, J. and Albert, R. 2014. Two-stage collision: exploring the birth of Pangea in the Variscan terranes. *Gondwana Research*, **25**, 756–763, https://doi.org/10.1016/j.gr.2013.08.009

Arenas, R., Martínez, S.S. *et al*. 2021. 100 Ma cycles of oceanic lithosphere generation in peri-Gondwana: Neoproterozoic–Devonian ophiolites from the NW African–Iberian margin of Gondwana and the Variscan Orogen. *Geological Society, London, Special Publications*, **503**, 169–184, https://doi.org/10.1144/SP503-2020-3

Cawood, P.A., Johnson, M.R.W. and Nemchin, A.A. 2007. Early Palaeozoic orogenesis along the Indian margin of Gondwana: Tectonic response to Gondwana assembly. *Earth and Planetary Science Letters*, **255**, 70–84, https://doi.org/10.1016/j.epsl.2006.12.006

Cawood, P.A., Hawkesworth, C.J. and Dhuime, B. 2012. Detrital zircon record and tectonic setting. *Geology*, **40**, 875–878, https://doi.org/10.1130/G32945.1

Cawood, P.A., Martin, E.L., Murphy, J.B. and Pisarevsky, S.A. 2021. Gondwana's interlinked peripheral orogens. *Earth and Planetary Science Letters*, **568**, 117057, https://doi.org/10.1016/j.epsl.2021.117057

Chen, R.X., Zheng, Y.F. and Xie, L.W. 2010. Metamorphic growth and recrystallization of zircon: Distinction by simultaneous in-situ analyses of trace elements, U–Th–Pb and Lu–Hf isotopes in zircons from eclogite-facies rocks in the Sulu orogen. *Lithos*, **114**, 132–154, https://doi.org/10.1016/j.lithos.2009.08.006

Coble, M.A. and Mahood, G.A. 2012. Initial impingement of the Yellowstone plume located by widespread silicic volcanism contemporaneous with Columbia River flood basalts. *Geology*, **40**, 655–658, https://doi.org/10.1130/G32692.1

Cong, B.L., Wu, G.Y., Zhang, Q., Zhang, R.Y., Zhai, M.G., Zhao, D.S. and Zhang, W.H. 1993. Petrotectonic evolution of Paleo-Tethys in western Yunnan, China. *Science in China Series B*, **37**, 1016–1024.

Corfu, F., Hanchar, J.M., Hoskin, P.W.O. and Kinny, P. 2003. Atlas of zircon textures. *Reviews in Mineralogy and Geochemistry*, **37**, 469–500, https://doi.org/10.2113/0530469

Dan, W., Li, X.H., Guo, J.H., Liu, Y. and Wang, X.C. 2012*a*. Integrated in situ zircon U–Pb age and Hf–O isotopes for the Helanshan khondalites in North China Craton: Juvenile crustal materials deposited in active or passive continental margin? *Precambrian Research*, **222**, 143–158, https://doi.org/10.1016/j.precamres.2011.07.016

Dan, W., Li, X.H., Guo, J.H., Liu, Y. and Wang, X.C. 2012*b*. Paleoproterozoic evolution of the eastern Alxa Block, westernmost North China: evidence from in situ zircon U–Pb dating and Hf–O isotopes. *Gondwana Research*, **21**, 838–864, https://doi.org/10.1016/j.gr.2011.09.004

Dan, W., Wang, Q. *et al*. 2018*a*. Rapid formation of eclogites during a nearly closed ocean: revisiting the Pianshishan eclogite in Qiangtang, central Tibetan Plateau. *Chemical Geology*, **477**, 112–122, https://doi.org/10.1016/j.chemgeo.2017.12.012

Dan, W., Wang, Q. *et al*. 2018*b*. Magmatic record of Late Devonian arc–continent collision in the northern Qiangtang, Tibet: implications for the early evolution of East Paleo-Tethys Ocean. *Lithos*, **308**, 104–117, https://doi.org/10.1016/j.lithos.2018.03.002

Dan, W., Wang, Q., Li, X.H., Tang, G.J., Zhang, C.F., Zhang, X.Z. and Wang, J. 2019. Low $\delta^{18}O$ magmas in the carboniferous intra-oceanic arc, central Tibet: Implications for felsic magma generation and oceanic arc accretion. *Lithos*, **326**, 28–38, https://doi.org/10.1016/j.lithos.2018.12.011

Dan, W., Wang, Q., Zhang, X.Z. and Tang, G.J. 2020. Early Paleozoic S-type granites as the basement of Southern Qiantang Terrane, Tibet. *Lithos*, **356**, 105395, https://doi.org/10.1016/j.lithos.2020.105395

Dan, W., Wang, Q. *et al*. 2021. Short duration of Early Permian Qiangtang-Panjal large igneous province: implications for origin of the Neo-Tethys Ocean. *Earth and Planetary Science Letters*, **568**, 117054, https://doi.org/10.1016/j.epsl.2021.117054

Dan, W., Murphy, J.B., Tang, G.J., Zhang, X.Z., White, W.M. and Wang, Q. In press. Cambrian–Ordovician magmatic flare-up in NE Gondwana: a silicic large igneous province? *Geological Society of America Bulletin*, https://doi.org/10.1130/B36331.1

Dong, Y.P. and Santosh, M. 2016. Tectonic architecture and multiple orogeny of the Qinling Orogenic Belt, Central China. *Gondwana Research*, **29**, 1–40, https://doi.org/10.1016/j.gr.2015.06.009

Dong, Y.P., He, D.F. *et al*. 2018. Subduction and accretionary tectonics of the East Kunlun orogen, western segment of the Central China Orogenic System. *Earth-Science Reviews*, **186**, 231–261, https://doi.org/10.1016/j.earscirev.2017.12.006

Doucet, L.S., Li, Z.X. *et al*. 2020. Distinct formation history for deep-mantle domains reflected in geochemical differences. *Nature Geoscience*, **13**, 511–515, https://doi.org/10.1038/s41561-020-0599-9

Faure, M., Nguyen, V., Hoai, L.T.T. and Lepvrier, C. 2018. Early Paleozoic or Early–Middle Triassic collision between the South China and Indochina Blocks: the controversy resolved ? Structural insights from the Kon Tum massif (Central Vietnam). *Journal of Asian Earth Sciences*, **166**, 162–180, https://doi.org/10.1016/j.jseaes.2018.07.015

Feng, Q.L., Liu, B.P., Ye, M. and Wang, W.P. 1996. Age and tectonic setting of the Nanduan Formation and the Laba Group in Southwestern Yunnan. *Journal of Stratigraphy*, **20**, 183–189 [in Chinese with English abstract].

Franke, W., Cocks, L.R.M. and Torsvik, T.H. 2017. The Palaeozoic Variscan oceans revisited. *Gondwana Research*, **48**, 257–284, https://doi.org/10.1016/j.gr.2017.03.005

Gao, L.E., Zeng, L.S., Hu, G.Y., Wang, Y.Y., Wang, Q., Guo, C.L. and Hou, K.J. 2019. Early Paleozoic magmatism along the northern margin of East Gondwana. *Lithos*, **334**, 25–41, https://doi.org/10.1016/j.lithos.2019.03.007

García-Arias, M., Díez-Montes, A., Villaseca, C. and Blanco-Quintero, I.F. 2018. The Cambro-Ordovician Ollo de Sapo magmatism in the Iberian Massif and its Variscan evolution: a review. *Earth-Science Reviews*, **176**, 345–372, https://doi.org/10.1016/j.earscirev.2017.11.004

Gardner, C.J., Grahama, I.T., Belousova, E., Booth, G.W. and Greig, A. 2017. Evidence for Ordovician subduction-related magmatism in the Truong Son terrane, SE Laos: implications for Gondwana evolution and porphyry Cu exploration potential in SE Asia. *Gondwana Research*, **44**, 139–156, https://doi.org/10.1016/j.gr.2016.11.003

He, H.Y., Wang, Y.J., Qian, X. and Zhang, Y.Z. 2018. The Bangxi-Chenxing tectonic zone in Hainan Island (South China) as the eastern extension of the Song Ma–Ailaoshan zone: evidence of late Paleozoic and Triassic igneous rocks. *Journal of Asian Earth Sciences*, **164**, 274–291, https://doi.org/10.1016/j.jseaes.2018.06.032

Hu, P.Y., Li, C., Wu, Y.W., Xie, C.M., Wang, M. and Li, J. 2014. Opening of the Longmu Co–Shuanghu–Lancangjiang ocean: constraints from plagiogranites. *Chinese Science Bulletin*, **59**, 3188–3199, https://doi.org/10.1007/s11434-014-0434-z

Izokh, A.E., Tran, T.H., Ngo, T.P. and Tran, Q.H. 2006. Ophiolite ultramafic–mafic associations in the northern structure of the Kon Tum block (central Vietnam). *Journal of Geology Hanoi*, **28**, 20–26.

Jian, P., Liu, D.Y., Kroner, A., Zhang, Q., Wang, Y.Z., Sun, X.M. and Zhang, W. 2009. Devonian to Permian plate tectonic cycle of the Paleo-Tethys Orogen in southwest China (II): insights from zircon ages of ophiolites, arc/back-arc assemblages and within-plate igneous rocks and generation of the Emeishan CFB province. *Lithos*, **113**, 767–784, https://doi.org/10.1016/j.lithos.2009.04.006

Jiang, W., Yu, J.H., Wang, X.L., Griffin, W.L., Pham, T., Nguyen, D. and Wang, F.Q. 2020. Early Paleozoic magmatismin northern Kontum Massif, Central Vietnam: insights into tectonic evolution of the eastern Indochina Block. *Lithos*, **376**, 105750, https://doi.org/10.1016/j.lithos.2020.105750

Kroner, U. and Romer, R.L. 2013. Two plates – many subduction zones: the Variscan orogeny reconsidered. *Gondwana Research*, **24**, 298–329, https://doi.org/10.1016/j.gr.2013.03.001

Li, C. 1987. The Longmu Co-Shuanghu-Lanchangjiang plate suture and the north boundary of distribution of Gondwana affinity Permian-Carboniferous system in northern Tibet, China. *Journal of Changchun College of Geology*, **17**, 155–166 [in Chinese with English abstract].

Li, S.Z., Zhao, S.J. *et al*. 2018. Closure of the Proto-Tethys Ocean and Early Paleozoic amalgamation of microcontinental blocks in East Asia. *Earth-Science Reviews*, **186**, 37–75, https://doi.org/10.1016/j.earscirev.2017.01.011

Liu, G.C., Chen, G.Y. *et al*. 2021*a*. Tracking Prototethyan assembly felsic magmatic suites in southern Yunnan (SW China): evidence for an Early Ordovician–Early Silurian arc–back-arc system. *Journal of the Geological Society London*, **178**, https://doi.org/10.1144/jgs2020-221

Liu, G.C., Sun, Z.B. *et al*. 2021*b*. Proto-Tethys ophiolitic mélange in SW Yunnan: constraints from zircon U–Pb geochronology and geochemistry. *Geoscience Frontiers*, **12**, 101200, https://doi.org/10.1016/j.gsf.2021.101200

Liu, H., Wang, B.D., Chen, L., Huang, F., Zeng, Y.C. and Wang, L.Q. 2021. Silurian intermediate–felsic complex in the Xiangtaohu area of central Qiangtang, northern Tibet: evidence for southward subduction of the Longmuco–Shuanghu Prototethys oceanic plate. *Lithos*, **404–405**, 106465, https://doi.org/10.1016/j.lithos.2021.106465

Liu, H.C., Bi, M.W., Guo, X.F., Zhou, Y.Z. and Wang, Y.K. 2019. Petrogenesis of Late Silurian volcanism in SW Yunnan (China) and implications for the tectonic reconstruction of northern Gondwana. *International Geology Review*, **61**, 1297–1312, https://doi.org/10.1080/00206814.2018.1506947

Liu, Y.M., Xie, C.M., Li, C., Li, S.Z., Santosh, M., Wang, M. and Fan, J.J. 2019. Breakup of the northern margin of Gondwana through lithospheric delamination: evidence from the Tibetan Plateau. *Geological Society of America Bulletin*, **131**, 675–694, https://doi.org/10.1130/B31958.1

Metcalfe, I. 2013. Gondwana dispersion and Asian accretion: tectonic and palaeogeographic evolution of eastern Tethys. *Journal of Asian Earth Sciences*, **66**, 1–33, https://doi.org/10.1016/j.jseaes.2012.12.020

Murphy, J.B., Gutierrez-Alonso, G. *et al*. 2006. Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture? *Geology*, **34**, 325–328, https://doi.org/10.1130/G22068.1

Murphy, J.B., Gutiérrez-Alonso, G. *et al*. 2009. Rheic Ocean mafic complexes: overview and synthesis. *Geological Society, London, Special Publications*, **327**, 343–369, https://doi.org/10.1144/SP327.15

Murphy, J.B., Keppie, J.D., Nance, R.D. and Dostal, J. 2010. Comparative evolution of the Iapetus and Rheic Oceans: A North America perspective. *Gondwana Research*, **17**, 482–499, https://doi.org/10.1016/j.gr.2009.08.009

Murphy, J.B., Nance, R.D. *et al*. 2021. Pannotia: in defence of its existence and geodynamic significance. *Geological Society, London, Special Publications*, **503**, 13–39, https://doi.org/10.1144/SP503-2020-96

Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Charusiri, P. and Khamphavong, K. 2013. Tectonic evolution of high-grade metamorphic terranes in central Vietnam: constraints from large-scale monazite geochronology. *Journal of Asian Earth Sciences*, **73**, 520–539, https://doi.org/10.1016/j.jseaes.2013.05.010

Nakano, N., Osanai, Y., Owada, M., Binh, P., Hokada, T., Kaiden, H. and Bui, V.T.S. 2021. Evolution of the Indochina block from its formation to amalgamation with Asia: constraints from protoliths in the Kontum Massif, Vietnam. *Gondwana Research*, **90**, 47–62, https://doi.org/10.1016/j.gr.2020.11.002

Nance, R.D., Gutiérrez-Alonso, G. *et al*. 2010. Evolution of the Rheic Ocean. *Gondwana Research*, **17**, 194–222, https://doi.org/10.1016/j.gr.2009.08.001

Nguyen, Q.M., Feng, Q.L. *et al*. 2019. Cambrian intra-oceanic arc trondhjemite and tonalite in the Tam Ky-Phuoc Son Suture Zone, central Vietnam: implications for the early Paleozoic assembly of the Indochina Block. *Gondwana Research*, **70**, 151–170, https://doi.org/10.1016/j.gr.2019.01.002

Nie, X.M., Feng, Q.L., Qian, X. and Wang, Y.J. 2015. Magmatic record of Prototethyan evolution in SW Yunnan, China: geochemical, zircon U–Pb geochronological and Lu–Hf isotopic evidence from the Huimin metavolcanic rocks in the southern Lancangjiang zone. *Gondwana Research*, **28**, 757–768, https://doi.org/10.1016/j.gr.2014.05.011

Obrebski, M., Allen, R.M., Xue, M. and Hung, S.H. 2010. Slab–plume interaction beneath the Pacific Northwest. *Geophysical Research Letters*, **37**, L14305, https://doi.org/10.1029/2010gl043489

Peng, Z.M., Fu, Y.Z. *et al*. 2020. The results of geochronological, geochemical and Sr–Nd–Hf isotopic investigations on amphibolites in the Qingping Region, Changning–Menglian suture zone. *Acta Geologica Sinica*, **94**, 511–526 [in Chinese with English abstract], https://doi.org/10.19762/j.cnki.dizhixuebao.2019113

Peng, Z.M., Guan, J.L., Fu, Y.Z., Zhang, Z., Wang, G.Z., Ren, F. and Zhang, X.F. 2021. The evolution of Changning–Menglian Ocean in the Qingping area of Shuangjiang County, western Yunnan: constraints from age and geochemistry of plagioclase amphibolite. *Geological Bulletin of China*, **40**, 1905–1919 [in Chinese with English abstract], https://doi.org/10.12097/j.issn.1671-2552.2021.11.009

Pereira, M.F., Gutierrez-Alonso, G., Murphy, J.B., Drost, K., Gama, C. and Silva, J.B. 2017. Birth and demise of the Rheic Ocean magmatic arc(s): combined U–Pb and Hf isotope analyses in detrital zircon from SW Iberia siliciclastic strata. *Lithos*, **278**, 383–399, https://doi.org/10.1016/j.lithos.2017.02.009

Pham, T.D., Tran, T.H., Ngo, T.P., Tran, T.A. and Bui, A.N. 2006. Characteristics of mineral composition (Olivine, Pyroxene, Chromian Spinel) of ultramafic intrusions in the edge of the Kon Tum block. *Journal of Geology Hanoi*, **28**, 47–57.

Roger, F., Maluski, H., Leyreloup, A., Lepvrier, C. and Thi, P.T. 2007. U–Pb dating of high temperature metamorphic episodes in the Kon Tum Massif (Vietnam). *Journal of Asian Earth Sciences*, **30**, 565–572, https://doi.org/10.1016/j.jseaes.2007.01.005

Sánchez-García, T., Bellido, F. and Quesada, C. 2003. Geodynamic setting and geochemical signatures of Cambrian–Ordovician rift-related igneous rocks (Ossa-Morena Zone, SW Iberia). *Tectonophysics*, **365**, 233–255, https://doi.org/10.1016/S0040-1951(03)00024-6

Sánchez-García, T., Quesada, C., Bellido, F., Dunning, G.R. and González del Tánago, J. 2008. Two-step magma flooding of the upper crust during rifting: The Early Paleozoic of the Ossa Morena Zone (SW Iberia). *Tectonophysics*, **461**, 72–90, https://doi.org/10.1016/j.tecto.2008.03.006

Sánchez Martínez, S., Gerdes, A., Arenas, R. and Abati, J. 2012. The Bazar Ophiolite of NW Iberia: a relic of the Iapetus–Tornquist Ocean in the Variscan suture. *Terra Nova*, **24**, 283–294, https://doi.org/10.1111/j.1365-3121.2012.01061.x

Sánchez Martínez, S., Arenas, R., Albert, R., Gerdes, A. and Fernández-Suárez, J. 2021. Updated geochronology and isotope geochemistry of the Vila de Cruces Ophiolite: a case study of a peri-Gondwanan back-arc

ophiolite. *Geological Society, London, Special Publications*, **503**, 497–530, https://doi.org/10.1144/SP503-2020-8
Şengör, A.M.C. 1979. Mid-Mesozoic closure of Permo-Triassic Tethys and its implications. *Nature*, **279**, 590–593, https://doi.org/10.1038/279590a0
Song, S.G., Niu, Y.L., Su, L. and Xia, X.H. 2013. Tectonics of the North Qilian orogen, NW China. *Gondwana Research*, **23**, 1378–1401, https://doi.org/10.1016/j.gr.2012.02.004
Song, S.G., Bi, H.Z. *et al*. 2018. HP–UHP metamorphic belt in the East Kunlun Orogen: Final closure of the Proto-Tethys Ocean and formation of the Pan-North-China continent. *Journal of Petrology*, **59**, 2043–2060, https://doi.org/10.1093/petrology/egy089
Stampfli, G.M. and Borel, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**, 17–33, https://doi.org/10.1016/S0012-821x(01)00588-X
Stampfli, G.M., Hochard, C., Verard, C., Wilhem, C. and von Raumer, J. 2013. The formation of Pangea. *Tectonophysics*, **593**, 1–19, https://doi.org/10.1016/j.tecto.2013.02.037
Steinberger, B. and Torsvik, T.H. 2012. A geodynamic model of plumes from the margins of Large Low Shear Velocity Provinces. *Geochemistry, Geophysics, Geosystems*, **13**, Q01W09, https://doi.org/10.1029/2011gc003808
Sun, S.-s. and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and process. *Geological Society, London, Special Publications*, **42**, 313–354, https://doi.org/10.1144/GSL.SP.1989.042.01.19
Tan, E., Gurnis, M. and Han, L.J. 2002. Slabs in the lower mantle and their modulation of plume formation. *Geochemistry, Geophysics, Geosystems*, **3**, 1–24, https://doi.org/10.1029/2001gc000238
Tang, G.J., Cawood, P.A., Wyman, D.A., Dan, W., Wang, Q. and Yang, Y.N. 2021. The missing magmatic arc in a long-lived ocean from the western Kunlun–Pamir Paleo-Tethys realm. *Geophysical Research Letters*, **48**, e2021GL095192, https://doi.org/10.1029/2021GL095192
Torsvik, T.H. and Cocks, L.R.M. 2017. *Earth History and Palaeogeography*. Cambridge University Press, Cambridge, UK.
Tran, H.T., Zaw, K. *et al*. 2014. The Tam Ky-Phuoc Son Shear Zone in central Vietnam: Tectonic and metallogenic implications. *Gondwana Research*, **26**, 144–164, https://doi.org/10.1016/j.gr.2013.04.008
Tran, T.V., Faure, M. *et al*. 2020. Neoproterozoic to Early Triassic tectono-stratigraphic evolution of Indochina and adjacent areas: a review with new data. *Journal of Asian Earth Sciences*, **191**, 104231, https://doi.org/10.1016/j.jseaes.2020.104231
Usuki, T., Lan, C.Y. *et al*. 2009. Early Paleozoic medium-pressure metamorphism in central Vietnam: evidence from SHRIMP U–Pb zircon ages. *Geosciences Journal*, **13**, 245–256, https://doi.org/10.1007/s12303-009-0024-2
van Staal, C.R., Dewey, J.F., MacNiocaill, C. and McKerrow, W.S. 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *Geological Society, London, Special Publications*, **143**, 199–242, https://doi.org/10.1144/GSL.SP.1998.143.01.17
van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A. and Rogers, N. 2009. Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians. *Geological Society, London, Special Publications*, **327**, 271–316, https://doi.org/10.1144/SP327.13
van Staal, C.R., Barr, S.M. and Murphy, J.B. 2012. Provenance and tectonic evolution of Ganderia: constraints on the evolution of the Iapetus and Rheic oceans. *Geology*, **40**, 987–990, https://doi.org/10.1130/g33302.1
van Staal, C.R., Barr, S.M., Waldron, J.W.F., Schofield, D.I., Zagorevski, A. and White, C.E. 2021. Provenance and Paleozoic tectonic evolution of Ganderia and its relationships with Avalonia and Megumia in the Appalachian–Caledonide orogen. *Gondwana Research*, **98**, 212–243, https://doi.org/10.1016/j.gr.2021.05.025
Wang, B.D., Wang, L.Q., Pan, G.T., Yin, F.G., Wang, D.B. and Tang, Y. 2013. U–Pb zircon dating of Early Paleozoic gabbro from the Nantinghe ophiolite in the Changning–Menglian suture zone and its geological implication. *Chinese Science Bulletin*, **58**, 920–930, https://doi.org/10.1007/s11434-012-5481-8
Wang, D.B., Luo, L., Tang, Y., Yin, F.G., Wang, B.D. and Wang, L.Q. 2016. Zircon U–Pb dating and petrogenesis of Early Paleozoic adakites from the Niujingshan ophiolitic melange in the Changning–Menglian suture zone and its geological implications. *Acta Petrologica Sinica*, **32**, 2317–2329 [in Chinese with English abstract].
Wang, H.N., Liu, F.L., Santosh, M. and Wang, F. 2020*a*. Subduction erosion associated with Paleo-Tethys closure: deep subduction of sediments and high pressure metamorphism in the SE Tibetan Plateau. *Gondwana Research*, **82**, 171–192, https://doi.org/10.1016/j.gr.2020.01.001
Wang, H.N., Liu, F.L. *et al*. 2020*b*. A new HP–UHP eclogite belt identified in the Southeastern Tibetan Plateau: tracing the extension of the main Palaeo-Tethys suture zone. *Journal of Petrology*, **61**, egaa073, https://doi.org/10.1093/petrology/egaa073
Wang, Y.J., Qian, X. *et al*. 2018. Closure of the East Paleotethyan Ocean and amalgamation of the Eastern Cimmerian and Southeast Asia continental fragments. *Earth-Science Reviews*, **186**, 195–230, https://doi.org/10.1016/j.earscirev.2017.09.013
Wang, Y.J., Wang, Y.K., Qian, X., Zhang, Y.Z., Gan, C.S., Seneebouttalath, V. and Wang, Y. 2020. Early Paleozoic subduction in the Indochina interior: revealed by Ordo-Silurian mafic-intermediate igneous rocks in South Laos. *Lithos*, **362**, 105488, https://doi.org/10.1016/j.lithos.2020.105488
Wang, Y.J., Zhang, Y.Z., Qian, X., Wang, Y., Cawood, P.A., Gan, C.S. and Seneebouttalath, V. 2021*a*. Early Paleozoic accretionary orogenesis in the northeastern Indochina and implications for the paleogeography of East Gondwana: constraints from igneous and sedimentary rocks. *Lithos*, **382**, https://doi.org/10.1016/j.lithos.2020.105921
Wang, Y.J., Zhang, Y.Z. *et al*. 2021*b*. Ordo-Silurian assemblage in the Indochina interior: geochronological,

elemental, and Sr–Nd–Pb–Hf–O isotopic constraints of early Paleozoic granitoids in South Laos. *Geological Society of America Bulletin*, **133**, 325–346, https://doi.org/10.1130/B35605.1

Wei, Y.H., Zi, J.W. *et al*. 2022. Reconstructing the Lancang Terrane (SW Yunnan) and implications for early Paleozoic Proto-Tethys evolution at the northern margin of Gondwana. *Gondwana Research*, **101**, 278–294, https://doi.org/10.1016/j.gr.2021.08.009

Wu, L., Murphy, J.B. *et al*. 2021. The amalgamation of Pangea: Paleomagnetic and geological observations revisited. *Geological Society of America Bulletin*, **133**, 625–646, https://doi.org/10.1130/B35633.1

Wu, Y.W., Li, C., Dong, Y.S., Xie, C.M. and Hu, P.Y. 2009. Petrological characteristics of Taoxinghu Early Paleozoic ophiolite in central Qiangtang, northern Tibet, China. *Geological Bulletin of China*, **28**, 1290–1296 [in Chinese with English abstract].

Wu, Z., Wang, B., Wang, D., Liu, H. and Zhou, F. 2020. Zircon U–Pb dating of early paleozoic adakites from nantinghe ophiolitic melange in Changning–Menglian suture zone and its geological implications. *Earth Science*, **45**, 3003–3013 [in Chinese with English abstract], https://doi.org/10.3799/dqkx.2020.141

Xu, D.R., Kusiak, M.A. *et al*. 2015. Microstructural observation and chemical dating on monazite from the Shilu Group, Hainan Province of South China: implications for origin and evolution of the Shilu Fe–Co–Cu ore district. *Lithos*, **216**, 158–177, https://doi.org/10.1016/j.lithos.2014.12.017

Xu, W., Liu, F. and Dong, Y. 2020. Cambrian to Triassic geodynamic evolution of central Qiangtang, Tibet. *Earth-Science Reviews*, **201**, 103083, https://doi.org/10.1016/j.earscirev.2020.103083

Xu, X., Song, S., Su, L., Li, Z., Niu, Y. and Allen, M.B. 2015. The 600–580 Ma continental rift basalts in North Qilian Shan, northwest China: links between the Qilian-Qaidam block and SE Australia, and the reconstruction of East Gondwana. *Precambrian Research*, **257**, 47–64, https://doi.org/10.1016/j.precamres.2014.11.017

Xu, Y.J., Cawood, P.A., Zhang, H.C., Zi, J.W., Zhou, J.B., Li, L.X. and Du, Y.S. 2020. The Mesoproterozoic Baoban Complex, South China: a missing fragment of western Laurentian lithosphere. *Geological Society of America Bulletin*, **132**, 1404–1418, https://doi.org/10.1130/B35380.1

Zhai, Q.-G., Jahn, B.-M. *et al*. 2013. The Carboniferous ophiolite in the middle of the Qiangtang terrane, Northern Tibet: SHRIMP U–Pb dating, geochemical and Sr–Nd–Hf isotopic characteristics. *Lithos*, **168–169**, 186–199, https://doi.org/10.1016/j.lithos.2013.02.005

Zhai, Q.-G., Jahn, B.M. *et al*. 2016. Oldest Paleo-Tethyan ophiolitic melange in the Tibetan Plateau. *Geological Society of America Bulletin*, **128**, 355–373, https://doi.org/10.1130/B31296.1

Zhang, C.L., Zou, H.B., Ye, X.T. and Chen, X.Y. 2018. Timing of subduction initiation in the Proto-Tethys Ocean: evidence from the Cambrian gabbros from the NE Pamir Plateau. *Lithos*, **314**, 40–51, https://doi.org/10.1016/j.lithos.2018.05.021

Zhang, C.L., Zou, H.B., Ye, X.T. and Chen, X.Y. 2019. Tectonic evolution of the West Kunlun Orogenic Belt along the northern margin of the Tibetan Plateau: implications for the assembly of the Tarim terrane to Gondwana. *Geoscience Frontiers*, **10**, 973–988, https://doi.org/10.1016/j.gsf.2018.05.006

Zhang, H., Xu, Y., Cawood, P.A., Zang, Y. and Du, Y. 2022. Ordovician amphibolite-facies metamorphism in Hainan Island: A record of early Paleozoic accretionary orogenesis along the northern margin of East Gondwana? *Journal of Asian Earth Sciences*, **229**, 105161, https://doi.org/10.1016/j.jseaes.2022.105161

Zhang, K.J., Zhang, Y.X., Li, B., Zhu, Y.T. and Wei, R.Z. 2006. The blueschist-bearing Qiangtang metamorphic belt (northern Tibet, China) as an in situ suture zone: Evidence from geochemical comparison with the Jinsa suture. *Geology*, **34**, 493–496, https://doi.org/10.1130/G22404.1

Zhang, X.Z., Dong, Y.S., Li, C., Deng, M.R., Zhang, L. and Xu, W. 2014. Silurian high-pressure granulites from Central Qiangtang, Tibet: constraints on early Paleozoic collision along the northeastern margin of Gondwana. *Earth and Planetary Science Letters*, **405**, 39–51, https://doi.org/10.1016/j.epsl.2014.08.013

Zhang, X.Z., Dong, Y.S. *et al.* 2016. Carboniferous and Permian evolutionary records for the Paleo-Tethys Ocean constrained by newly discovered Xiangtaohu ophiolites from central Qiangtang, central. *Tectonics*, **35**, 1670–1686, https://doi.org/10.1002/2016tc004170

Zhang, X.Z., Dong, Y.S., Wang, Q., Dan, W., Zhang, C.F., Xu, W. and Huang, M.L. 2017. Metamorphic records for subduction erosion and subsequent underplating processes revealed by garnet–staurolite–muscovite schists in central Qiangtang, Tibet. *Geochemistry, Geophysics, Geosystems*, **18**, 266–279, https://doi.org/10.1002/2016gc006576

Zhou, Y., Liang, X.Q., Liang, X.R., Jiang, Y., Wang, C., Fu, J.G. and Shao, T.B. 2015. U–Pb geochronology and Hf-isotopes on detrital zircons of Lower Paleozoic strata from Hainan Island: New clues for the early crustal evolution of southeastern South China. *Gondwana Research*, **27**, 1586–1598, https://doi.org/10.1016/j.gr.2014.01.015

Zhou, Y., Sun, S.Y. *et al*. 2021. A new insight into the eastern extension of the Proto-Tethyan margin of Gondwana by Early Paleozoic volcanic rocks in South China. *Lithos*, **398**, 106328, https://doi.org/10.1016/j.lithos.2021.106328