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Tethyan evolution from early Paleozoic to early Mesozoic in southwest Yunnan

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Abstract The Tethys orogenic belt in SW Yunnan constitutes a critical part of the expansive Tethys-Himalayan tectonic domain. The abundant, well-preserved geologic records make it an ideal area for studying the tectonic evolution of Proto- and Paleo-Tethys. In this paper, we focus on several major tectonic units in SW Yunnan and reconstruct the Tethyan evolution from the early Paleozoic to the early Mesozoic, based on stratigraphic, sedimentologic, and magmatic evidences. The recently discovered early Paleozoic Yunxian-Menghai ophiolitic belt in the Lincang Terrane situated east of the Changning-Menglian Belt represents the suture zone of the Proto-Tethys. The oceanic basin of Proto-Tehtys opened in the latest Neoproterozoic and subsequently began subducting in the late Miaolingian of the Cambrian (about 505 Ma). From the late Late Ordovician to the ealiest Silurian (about 450–442 Ma), the Proto-Tethys basin gradually closed resulting in the collision of the continental plates on both sides of the Proto-Tethyan ocean. The main collision stage occurred in the early Silurian (about 442–430 Ma) and the post-collision stage lasted from the mid-Silurian to the early Carboniferous (430–355 Ma). The earliest record of Paleo-Tethyan oceanic crust was generated in the late Devonian, and the ocean was then subducted in an eastward direction in the middle Late Carboniferous (about 310 Ma). The initial collision stage in the Paleo-Tethys took place at the end of the Permian (about 253 Ma), and the main stage of the collision persisted into the early Ladinian (about 253–238 Ma). This was followed by post-collision extension from the late Ladinian to the early Jurassic (ca. 238–196 Ma). We suggest that the opening of Paleo- Tethyan Ocean in SW Yunnan was a result of the extensional rift basin of the Proto-Tethys. Additionally, the activity of the Manxin mantle plume was likely a crucial factor in the rapid expansion of the Paleo-Tethyan Ocean.

Keywords Historical tectonics, Stratigraphic sequence, Proto-Tethys, Paleo-Tethys, Tectonic evolution, SW Yunnan

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1. Introduction

The term “Tethys” was first proposed by the Austrian geologist Suess (1893) to name an oceanic basin between Laurentia and Gondwana. According to the evolutionary stages of the oceanic basin, it has been divided into Proto-Tethys (Late Sinian-Silurian), Paleo-Tethys (Devonian-Triassic), and Neo-Tethys (since Cretaceous) (Şengör, 1979; Huang and Chen, 1987; Zhong, 1998; Metcalfe, 2013; Wu F Y et al., 2020).

Qinghai-Tibet and western Sichuan-Yunnan are core areas of the eastern segment of the Tethyan tectonic domain, which extends further into SE Asia. Numerous previous studies have established an archipelagic model for the eastern

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Palaeo-Tethys, which is characterized by multiple transformations between continental and oceanic settings and the development of sea-mounts and oceanic islands. The main suture of the eastern Paleo-Tethys Ocean is represented by the Longmucuo-Shuanghu Belt in northern Tibet, the Changning-Menglian Belt in western Yunnan, the Chiang Mai Belt in Thailand, and the Bentong-Raub Belt in Malaysia. A roughly parallel suture including the Xijinwulan Belt in northern Tibet, the Jinshajiang Belt in western Sichuan, the Ailaoshan Belt in southwest Yunnan, the Song Ma Belt in northern Vietnam, the Lang Prabang Belt in northern Laos, and the Nan-Uttaradit Belt in northeastern Thailand is considered to represent a branch ocean of the Paleo-Tethys (Liu et al., 1991; Pan et al., 1997; Zhong, 1998; Wang Y J et al., 2018).

The concepts of "Paleo-Tethyan archipelagic Ocean" and "Paleo-Tethyan main Ocean" stemmed from the Changning-Menglian Belt in SW Yunnan. However, early Paleozoic magmatic rocks have been identified in the belt over the last decade (Wang B D et al., 2013, 2018). Particularly, numerous rock components of early Paleozoic ages were found in an N-S striking corridor to the east of the Changning-Menglian belt (Xing et al., 2015; Nie et al., 2016; Liu et al., 2021a, 2021b; Wang et al., 2022), indicating the existence of an earlier ocean (i.e., the Proto-Tethys) predated the Paleo-Tethys. Nevertheless, it remains unclear how the Proto-Tethys and Paleo-Tethys evolved in space and time, and whether there existed a connection between them. This paper attempts to address these questions by compiling the results of our detailed field investigation and available data.

2. Tectonic units and their geological records

SW Yunnan can be divided into a series of tectonic units bounded by major faults, from west to east, including the Tengchong Block, the Nujiang Belt, the Baoshan Block, the Changning-Menglian Belt, the Lincang Terrane, the Yunxian-Menghai Belt, the Simao Block, the Ailaoshan Belt and the Yangtze Block (Figure 1). Among them, the Yunxian-Menghai Belt had undergone intense metamorphism and deformation as a result of the Paleo-Tethyan subduction and collision, during which the belt was extensively remelted to form the Lincang granitoid batholith, and only small amounts of the original rocks survived as xenoliths/enclaves within the batholith and along its margin. In order to reconstruct the evolution of the Proto- and Paleo-Tethys and their transition processes, the geological records of the individual units in SW Yunnan are summarized as follows.

2.1 Baoshan Block

The Baoshan Block is bounded by the Nujiang Belt in the west and the Changning-Menglian Belt in the east. The oldest strata are exposed on both sides of the block. Along the western side, they are represented by the Gongyanghe Group, which comprises a suite of epimetamorphic clastic rocks containing several tuff layers, intermediate-acid volcanic rocks, and siliceous rocks. Tuff layers in the lower and upper segments of the group yielded zircon U-Pb ages of 925–812 and 550 Ma, respectively, whereas metabasic volcanic rocks in the top part are dated to 499 Ma. Thus, these data indicate the age of the Gongyanghe Group is constrained to the Neoproterozoic to the middle Cambrian (Yang et al., 2012; Li et al., 2018). The upper Cambrian stara above the Gongyanghe Group, including the Hetaoping, Shahechang, and Baoshan formations, consist of slate, siltstone, shale, and limestone with a minor amount of basalts. These sediments were deposited in shallow marine environment during the late Cambrian. The basalts of the Hetaoping and Baoshan formations have been interpreted to have formed in an island arc setting (Zhang et al., 2015) (Figure 2).

The oldest strata along the eastern margin of the Baoshan Block are the Mengtong and Mengdingjie groups, which are predominated by thick terrigenous clastic rocks. The age of the Mengtong Group ranges from the Neoproterozoic to the Cambrian, similar to the Gongyanghe Group, whereas the Mengdingjie Group is considered to belong to Ordovician to Silurian (Mao, 2016). The Ordovician strata within the Baoshan Block are composed of purplish red, gray fine grained clastic rocks with marl. The interval from the top of the Ordovician to the bottom of the Silurian is mainly composed of black shale with graptolites, while most of the Silurian is purple marl and mudstone. The Devonian and Lower Carboniferous are characterized by carbonate rocks. The Upper Carboniferous is absent in the region. The Lower Permian stara is composed of tillite containing cold water biota and basalt, indicating that the Baoshan Block had an affinity to Gondwana at that time (Wang et al., 2001).

Early Paleozoic magmatic records are abundant in the Baoshan Block. The basalt was first found in the Hetaoping Formation belonging to the upper Miaoling Series, indicating that the Baoshan Block was an active continental margin in the late Middle Cambrian (Zhang et al., 2015). Early Paleozoic granites, represented by the Luxi batholith, are mainly composed of early adamellites (502–461 Ma) and late leucogranites (475–446 Ma) that were formed within the Proto-Tethyan magmatic arc (Dong et al., 2013; Zhao et al., 2014; Li et al., 2016; Huan et al., 2017).

The early Paleozoic tectonic evolution records in the Baoshan Block can be divided into three stages. During the early to middle Cambrian, both the Gongyanghe and Mengtong groups were characterized by thick marine sediments dominated by terrigenous clastic deposits, with rare magmatic rocks, indicating a passive continental margin setting. From the late Cambrian (about 502 Ma) to the Or-

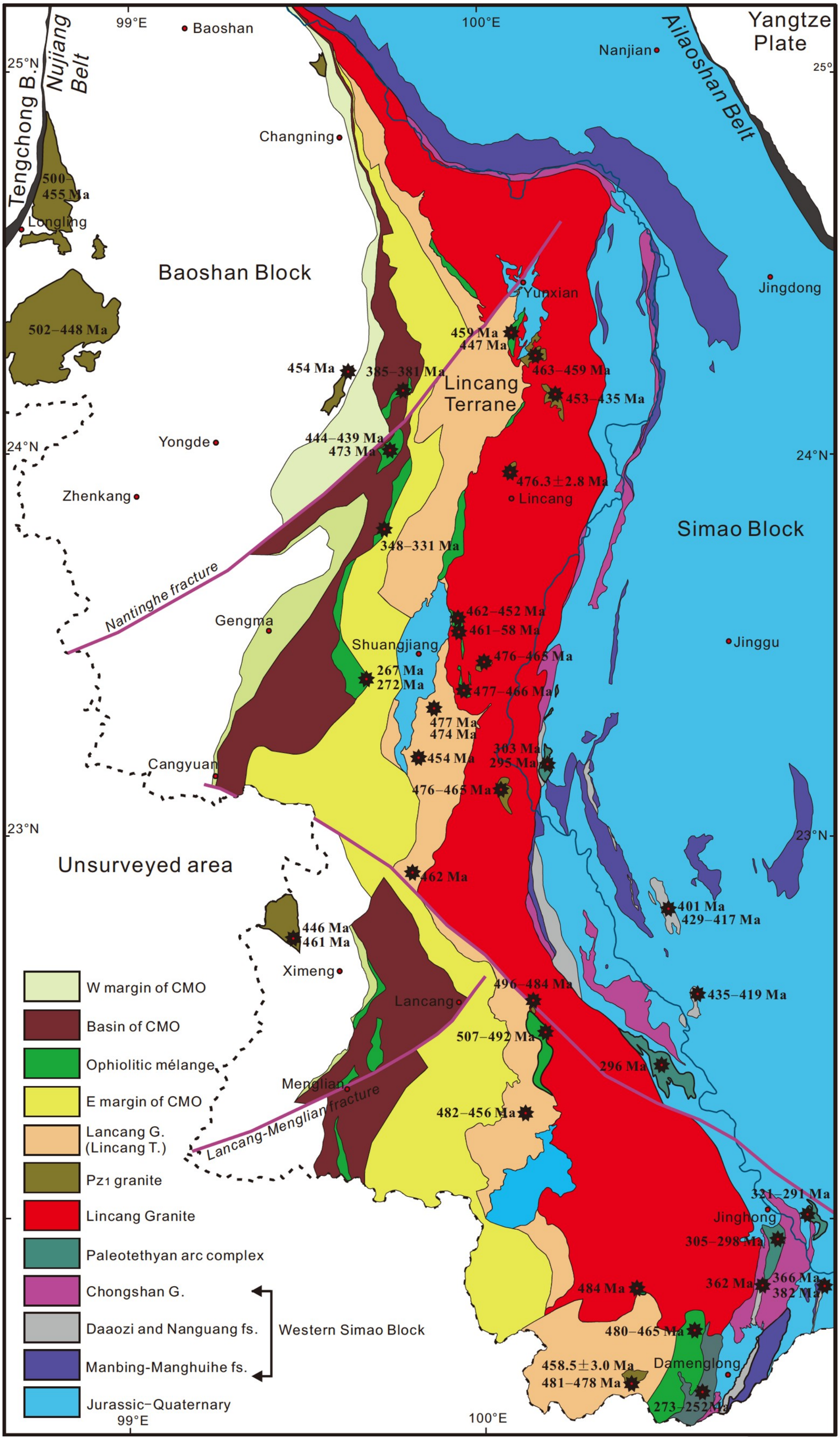

Figure 1 Sketch map showing the distribution of major tectonic/stratigraphical units in the Tethyan orogenic zone, SW Yunnan (after Liu et al., 2021a). CMO, Changning-Menglian Ocean, G., Group, fs., formations, T., Terrane.

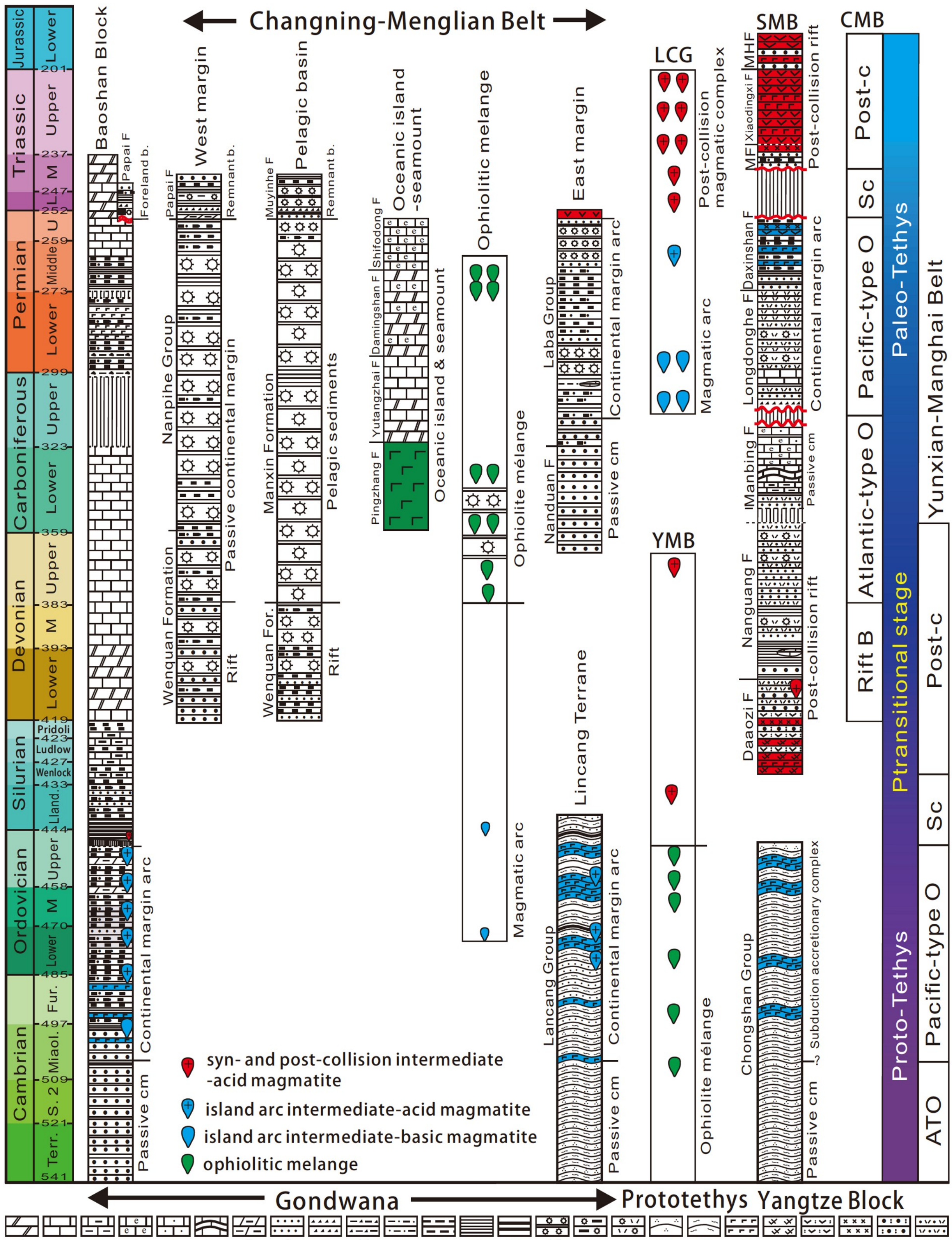

Figure 2 Stratigraphic sequences and tectonic attributes of Tethyan units in western Yunnan. 1, dolomite; 2, limestone; 3, argillaceous limestone; 4, bioclastic limestone; 5, Sandy limestone; 6, Chert-banded limestone; 7, marl; 8, sandstone; 9, breccia; 10, argillaceous breccia; 11, siltstone; 12, mudstone; 13, shale; 14, Carbonaceous mudstone; 15, radiolarite; 16, radiolarian-bearing siliceous mudstone; 17, tuffaceous siliceous rock; 18, quartzite; 19, schist; 20, basalt; 21, dacite; 22, tuff; 23, rhyolite; 24, tuff sandstone; 25, rhyolitic tuff. LCG, Lincang granite; SMB, Simao Block; CMB, Changning-Menglian Belt; YMB, Yunxian-Menghai Belt; b, basin; F, Formation; cm, continental margin; MF, Manghuai Formation; MHF, Manghuihe Formation; ATO, Atlantic-type Ocean; O, Ocean; Sc, Syn-collision; Post-c, Post-collision.

dovician, basic volcanic rocks of island arc origin were interspersed with sedimentary strata, indicating a continental arc stage. From the latest Ordovician to the earliest Silurian, deep-marine facies graptolite shales were widely deposited in the block, accompanied by contemporaneous granite emplacement (Lu et al., 2015), suggesting this area might have entered the syn-collisional stage. In the late Paleozoic, the Baoshan Block was in a stable tectonic setting, and volcanic activity during this period was limited with the exception of the Woniusi basalt (Figure 2).

2.2 West margin of Changning-Menglian Ocean

The stratigraphic sequence of the western continental margin of the Changning-Menglian Ocean is represented by three stratigraphic units, namely the Wenquan Formation, the Nanpihe Group, and the Papai Formation, in ascending order. These units are exposed in the eastern Ximeng and central-eastern Gengma areas.

The Wenquan Formation crops are exposed along the highway in the Lila Village, Ximeng, and are mainly composed of terrigenous clastic sandstone, mudstone, shale, and layered siliceous rocks that make up a complete Bauma sequence. The mudstone and shale contain Early Devonian graptolites, which are similar to the graptolite fauna of South China, Qomolangma, and Australia, but different from those from North America, Central Europe, and Central Asia (Zhang et al., 1998). The chert has abundant fossil radiolarians, of which the albaillellids are only found in this section and in Australia (Feng and Liu, 1993). Thus, the Wenquan Formation is assigned an Early Devonian age according to the graptolite biostratigraphy, and is the oldest known strata in the Changning-Menglian Belt.

The Nongba section in the eastern part of Gengma was initially named the Nanpihe Formation and was assigned a Late Permian age (Bureau of Geology and Mineral Resources of Yunnan Province (BGMRY), 1996). Further studies revealed that the section was composed of Devonian-Permian stratigraphic slices. The Devonian strata consist of terrigenous clastic turbidites, bedded chert, and mudstone (Wenquan Formation). The chert and siliceous mudstone contain the Devonian conodonts, graptolites, plants, spore, and radiolarian fossils. The spore assemblage shows an affinity to the Gondwana biota. Paleoecological data and sedimentary structures indicate that the strata were deposited in bathyal to abyssal basins at a passive continental margin (Yang and Jia, 1995; Duan et al., 2003). The Carboniferous and Permian strata are composed of mudstone, marl, basalt, chert, etc, which was renamed the Nanpihe Group. The marl contains late Permian foraminifera fossils and the chert contains Carboniferous and Permian radiolarian fossils. The chert is deposited in the bottom of continental slopes to the edge of ocean basins (Feng et al., 1997; Duan et al., 2003; Zhang et al., 2003; Yang et al., 2007).

South of the Gengma County, near Nanpihe Bridge, the Nanpihe Group is covered by chert conglomerate and mudstone (Feng et al., 1997). Similar strata were also discovered in the Papai area of Cangyuan and named the Papai Formation (Xiao, 1987). The formation unconformably overlies the Permian limestone deposited on the eastern margin of the Baoshan Block, and chert gravels from the conglomerate contain the Devonian-Permian radiolarian fossils, which indicate a derivation from the Changning-Menglian Ocean (Feng et al., 1997). The black bedded chert at the bottom of the Papai Formation contains Changhsingian fossil radiolarians, while Early Triassic bivalves have been found in the yellow mudstone in its lower part (Feng et al., 1998). Therefore, the age of the formation is bracketed between the latest Permian to the early Middle Triassic and is considered to have formed in a peripheral foreland basin (Figure 2).

2.3 Changning-Menglian Ocean

The Changning-Menglian Belt has long been recognized as an archetypal Paleo-Tethyan orogenic belt where the oceanic sedimentary-magmatic records are well preserved. It contains not only pelagic stratigraphic sequences rich in radiolarian fossils, but also a complete succession of oceanic island and sea mount sequences, as well as ophiolite mélanges representing remnants of oceanic crust.

2.3.1 Pelagic stratigraphic sequences

The pelagic stratigraphic sequences are widely distributed in the Changning-Menglian Belt, all of which are in the form of stratigraphic slices, as reconstructed on the basis of radiolarian biostratigraphy. The oldest graptolite-rich formation is in the Lower Devonian, mainly composed of siliceous shale, silty mudstone, and siltstone. The Middle and Upper Devonian predominantly consists of bedded chert, siliceous shale, and argillaceous rock, lacking terrigenous clastic components. Pillow basalt is occasionally present in its upper part. The chert and siliceous shale contain the Devonian radiolarian fossils. The Carboniferous-Permian is mainly composed of thin bedded chert, siliceous shale, mudstone, and tuffaceous mudstone, without terrigenous clastic components. The chert and siliceous shales are rich in the Carboniferou and Permian radiolarian fossils. The Lower Triassic consists mainly of black mudstone and silty mudstone with siliceous shale and siltstone, and the Middle Triassic of gray-black thin layered chert, tuffaceous siliceous rocks, silty mudstone, and feldspathic lithic greywacke (Feng et al., 2001; Duan et al., 2012).

Petrogeochemical data of radiolarites from the Late Devonian to early Late Permian strata show obvious characteristics of a pelagic basin without input of terrigenous materials. In contrast, the late Late Permian to Middle

Triassic strata show sedimentary characteristics of a deep-sea basin that are significantly influenced by terrigenous materials (Ding and Zhong, 1995; Zhang et al., 2001; Ito et al., 2016).

2.3.2 Oceanic island-seamount stratigraphic sequences

The oceanic island-seamount stratigraphic sequences are composed of volcanic rocks (the Pingzhang Formation) in the lower part and carbonate rocks in the upper part, forming a typical double-layer stratigraphic structure with a volcanic basement and a carbonate cap. The Pingzhang Formation consists mainly of basic volcanic lava, tuff, volcanic breccia, tuffaceous sand (mud) rock, and a few lenticular limestone, and is in conformable contact with the underlying Devonian Manxin Formation. Based on coral and foraminifera fossils in limestone lens, the Pingzhang Formation is grouped into the Lower Carboniferous (BGMRY, 1996; Ueno et al., 2003). Petrological and geochemical studies have indicated that the basalts of the Pingzhang Formation were formed in an oceanic island setting, similar to the Hawaiian lavas (Mo et al., 1993).

A carbonate sequence conformably overlies the Pingzhang Formation and is characterized by the absence of terrigenous clastic deposits. This sequence is divided into the Yutangzhai, Damingshan, and Shifodong formations. The Yutangzhai and Damingshan formations are widely distributed in the Changning-Menglian Belt, but the Shifodong Formation, containing Changhsingian fusulinids: *Palaeofusulina sinensis* Sheng, is only found in the middle of the belt, Gengma and Cangyuan areas (BGMRY, 1996; Ueno et al., 2003). The Shifodong Formation is unconformably covered by Upper Triassic strata, indicating that the deposition of oceanic island-seamount in the Changning-Menglian Tethyan basin had ceased in the latest Changhsingian.

2.3.3 Ophiolitic mélanges

The distribution of ophiolitic mélange zone extends from Tongchangjie in Yunxian in the north and southward to Manxin in Menglian. It is composed of multiple ophiolite mélanges intermittently exposed at Tongchangjie, Nantinghe, Ganlongtang, Niujingshan, and Manxin. The Tongchangjie ophiolitic mélange is distributed in the Guodazhai-Tongchangjie-Mahuangqing area, and is mainly composed of metamorphic plagiopyroite, cumulate, gabbro, and oceanic island tholeiitic and alkaline basalts. These rocks are considered to represent fragments of ancient oceanic crust (Zhang et al., 1985; Lai et al., 2010). Cong et al. (1993) reported an amphibole K-Ar isotopic age of 385–381 Ma for a gabbro from the mélange.

The Nantinghe ophiolite mélange, located in the Nantinghe fault zone, is mainly composed of plagioamphibolite, serpentinized olivine pyroxenite, serpentinized pyrolite, cumulate gabbro, metagabbro, and metabasalt. The cumulate gabbro yielded zircon U-Pb ages of 473 and 444 Ma, and the gabbro yielded a zircon U-Pb age of 439 Ma. These rocks are interpreted to have formed in a backarc basin, indicating that the Changning-Menglian Belt was in a backarc tectonic setting during 444–439 Ma (Wang B D et al., 2013).

The Ganlongtang ophiolitic mélange is distributed in the Ganlongtang, Dabanwei, and Mengyong areas in Gengma. It is mainly composed of plagioamphibolite-schist, strong slice basalt, chlorite schist, and a small amount of metamorphic (middle) basaltic volcanic rocks and mafic rocks. The petrology and geochemistry of the ophiolitic mélange show characteristics of the oceanic crust. The zircon ages of the plagioclase amphibolite range from 331 Ma to 329 Ma, representing the ages of their protoliths (Li, 2003; Duan et al., 2006).

The Niujingshan ophiolitic mélange is located south of the Ganlongtang ophiolitic mélange and is distributed in the Niujingshan, Mangguan, Damanghuangfang, and Bankangdazhai areas. Both the Ganlongtang and Niujingshan melanges are cut by faults and have similar rock assemblages. Jian et al. (2009) obtained a zircon age of 267 Ma for the metamorphosed gabbro from the Damangguangfang area, and interpreted it as the closure time of the Changning-Menglian Ocean. Wang et al. (2017) yielded a zircon U-Pb age of 272 Ma for a plagioamphibolite interpreted to have metamorphosed from an N-MORB type gabbro.

The Manxin ophiolite in Menglian, exposed on both sides of the Nanlai River, is mainly composed of picrite, olivine tholeiitic basalt, basic volcanic breccia, basaltic aggregate tuff, vitric tuff, thin layered chert, and siliceous shale. These volcanic rocks, pyroclastic rocks, and bedded chert constitute multiple sedimentary cycles. The picrite is characterized by high Mg contents (up to 26–31% MgO) and spinifex textures. The basalt has pillow structure, while thin bedded chert and siliceous shale are intermingled with a large number of apatite nodules. The siliceous rock contains abundant radiolarian fossils, and its age is constrained to the Tournaisian of the Early Carboniferous. The geochemical characteristics of the volcanic rocks indicate an affinity to ocean ridge and ocean island settings (Zhang et al., 1995; Shen et al., 2002). The petrology, petrochemistry, and stratigraphic sequence indicate that the strata were formed in the ocean floor plateau.

Fang and Feng (1996) and Fang et al. (1998) proposed that these picrite-basalt assemblages may be related to large igneous activities, and Zhong (1998) further documented the similarities of these rocks to the Hawaiian basalts and and tied them to an ocean island setting related to mantle plume activity. Zhu and Zhang (1999) concluded that the picrite was subaqueous aborted cumulate in the ocean ridge setting. Furthermore, Fang and Niu (2003) considered that the igneous rocks were formed under high temperature melting conditions related to mantle plume activity in the ocean basin. Shi and Fang (2019) calculated the mantle potential temperature of these picrites using olivine-spinel thermometers, and yielded results falling in the temperature range of plume activity. Geochemical characteristics show that similar picrites may have formed in different tectonic environments: some of them have MORB-like characteristics likely reflecting a mixture of mantle plume melts with the mid-ocean ridge basaltic magma; the rest have characteristics similar to oceanic island basalts and were formed by magma from the center of mantle plume. Based on the above evidences, we favor an ocean floor plateau model associated with mantle plume activity, although Xie et al. (2022) suggested that the basic-ultrabasic volcanic rocks may have formed in an extension-setting at the passive continental margin of Gondwana.

2.4 Eastern margin of Changning-Menglian Ocean

The stratigraphic sequence of the eastern continental margin is divided into the Nanduan Formation and the Laba Group, which are in a concealed unconformity relationship with the underlying Lancang Group. The Nanduan Formation is mainly composed of quartz sandstone, feldspar quartz sandstone and argillaceous slate. Evidences from ammonoids and palynophytes constrain its age to the early Carboniferous. Sedimentological evidence suggests that the Nanduan Formation represents a bathyal-abyssal turbidite succession formed in a passive continental margin environment.

The Laba Group is divided into five members (Feng et al., 1996). The lower clastic rock member is mainly yellow-green, gray, purplish red mudstone, siltstone, fine-grained sandstone, and the upper sandstone contains 10–15% volcanic clasts. The chert-marl-mudstone member consists of yellow-green argillaceous rocks, lithic quartz sandstone and bedded siliceous rock, interspersed with marl and bioclastic limestone lens. Fusunilids from the lens indicate that its age ranges from late Late Carboniferous to the Early Permian. The upper clastic rock member is mainly composed of yellowish-green, light gray mudstone, fine-grained lithic quartzose sandstone, containing Middle Permian ammonoids and conodonts. The chert-mudstone member is mainly composed of black bedded chert and purplish red mudstone with lithic quartzose sandstone on the top. The siliceous rocks contain late Middle Permian to Late Permian radiolarian fossils. The tuff member, only seen in Tuanjie drawbridge Section, is a brownish-red, gray-green rhyolitic tuff (Xie and Liu, 1992), which may be the uppermost Permian or the lowermost Triassic based on stratigraphic correlation.

2.5 Lincang Terrane

The Lincang Terrane is located between the Changning-Menglian Belt and the Lincang granitoid batholith. It is distributed in a north-south strip (Figure 1) and extends southward to Myanmar and Thailand. It is mainly composed of the Lancang Group, which is the basement of the eastern continental margin in the Changning-Menglian Belt. It was previously considered to be a subunit of the Simao block (Cong et al., 1993), or a terrane with Gondwana affinity (Liu et al., 1993).

The Lancang Group is a suite of low-grade metamorphic-sedimentary rocks with volcanic interlayers. Despite strong modification by later tectonic events, the original stratigraphic sequence of the group is still clear. It can be divided into five subunits including, in ascending order, the Nanmuling, Mengjingshan, Manlai, Huimin, and Nankenghe formations. These formations can be traced and compared laterally, and volcanic rocks are present in the Manlai and Huimin formations. The Lancang Group has long been considered as a Proterozoic unit (BGMRY, 1996; Zhong, 1998). However, recent zircon U-Pb geochronology study has shown that the youngest detrital zircon age peaks of the Nanmuling and Mengjingshan formations are 576 Ma (n=2) and 554 Ma (n=20), respectively, indicating that both formations were probably formed during the Ediacaran Period (Wei et al., 2022). Moreover, zircon from calc-alkaline volcanic rocks of the Manlai Formation yielded U-Pb ages of 505–490 Ma, constraining this formation to the Miaolingian-Furongian of the Cambrian (Liu, 2020). Zircon U-Pb isotopic ages of volcanic rocks from the Huimin Formation range from 482 Ma to 442 Ma (Ordovician). The youngest detrital zircon age peak of 436 Ma for the Nankenghe Formation, in combination with age constraints from the underlying Huimin volcanics, suggests an early Silurian depositional age for the formation (Nie et al., 2015; Xing et al., 2015; Wei et al., 2022). In addition, similar volcanic rocks in the Shuangjiang area, which are equivalent to the Huimin Formation volcanics, yielded zircon U-Pb ages of 477–474 Ma (Han et al., 2020; Hu et al., 2020). Therefore, the formation age of the Lancang Group is bracked to between the latest Neoproterozoic and the early Silurian. Petrological and geochemical studies have shown that the volcanic-clastic rocks of the Manlai and Huimin formations formed in an active continental margin setting (Nie et al., 2015; Xing et al., 2015; Wang H N et al., 2019a). The Manlai Formation in the Bulangshan area of Menghai is intruded by 481–459 Ma granites with island-arc signatures (Sun et al., 2018; Zhao, 2019).

In summary, based on evidences from sedimentary, volcanic and intrusive rocks, it is evident that the lower parts of the Lancang Group were deposited in a passive continental margin setting, whereas the upper units were formed in an active continental margin, indicating a transition of tectonic regime in the upper Miaoling Series (about 505 Ma).

2.6 Ophiolitic mélanges in Yunxian-Menghai Belt

The N-S striking Yunxian-Menghai ophiolitic mélange zone occurs to the west of the Lincang batholith, and consists of discontinuous ophiolite blocks. It represents the remnant of the Proto-Tethyan suture zone, which was strongly affected by tectonic-magmatic overprinting and modification during the Paleo-Tethyan subduction and collision (Figure 1). The ophiolite zone is mainly composed of the Mayidui and Damenglong ocean ridge ophiolites, the Yinchanghe ocean island ophiolite, the Wanhe ocean inner-arc ophiolite, and the Qianmai forearc ophiolite (Liu et al., 2017; Liu et al., 2021b).

Metamagmatic rocks of the Mayidui ophiolitic mélange in Yunxian are mainly gabbro, gabbro diorite, and greenschist, whereas its metasedimentary sequence includes sericite quartz-schist, two-mica quartz-schist, and plagioclase two-mica schist. Protoliths of the metasedimentary rocks are inferred to be siliceous rocks and mudstones based on field and petrographic observations. Zircon U-Pb ages from the gabbro and gabbro diorite range from 459 Ma to 447 Ma. The Damenglong ophiolitic mélange in Menghai is dominated by granulite, two-mica quartz-schist, plagioamphibolite and metamorphosed gabbro. Zircon from the metagabbro yielded U-Pb ages in the range of 480–465 Ma. Mafic rocks from the Mayidui and Damenglong ophiolites are similar in geochemistry, characterized by low to moderate potassium, high Ti tholeiite, relatively flat REE and trace element patterns, and very high zircon $\varepsilon_{Hf}(t)$ (+6.1–+9.9) and whole-rock $\varepsilon_{Nd}(t)$ values (+2.6–+6.0), indicating that the primary magma was originated from a MORB-type mantle source. The geochemical characteristics and stratigraphical sequences of the sedimentary-magmatic assemblages allow us to conclude that the Mayidui and Damenglong ophiolitic mélanges represent the Yunxian-Menghai ocean ridge-oceanic crust ophiolitic mélange assemblage, which further corroborates the existence of the early Paleozoic Proto-Tethyan Ocean in SW Yunnan.

The Yinchanghe ophiolite mélange in Shuangjiang is mainly composed of greenschist, plagioamphibolite, plagioamphibole-schist, sericite-schist, and metamorphosed cumulate gabbro, gabbro, gabbro diorite and tuff. The metamorphosed gabbro and cumulatic gabbro yielded zircon U-Pb ages of 462–452 Ma. The main rock types of the Wanhe ophiolite mélange in Shuangjiang include metamorphosed cumulate gabbro and gabbro, plagioamphibolite, two-mica quartz-schist, two-mica albite-schist, epidote-chlorite-actinolite-schist, and phengite quartz-schist. Generally, they form an assemblage composed of strongly deformed mafic cumulate, ocean floor basalt and pelagic sediments, which have undergone high- to ultrahigh-pressure metamorphism (Li et al., 2015, 2017; Wang et al., 2019b). The metagabbro and gabbro diorite have been dated to 461–458 Ma by zircon U-Pb geochronology. The mafic magmatic rocks in the Yinchanghe ophiolite are low-moderate-K, high-Ti alkaline and tholeiitic basalts, which are relatively rich in LREEs and LILEs. Their zircon $\varepsilon_{Hf}(t)$ values of −3.2 –−1.2 and whole-rock $\varepsilon_{Nd}(t)$ of +6.4–+8.8 show that their parental magmas were derived from an enriched mantle source. Based on their rock assemblages and geochemical characteristics, it is concluded that Yinchanghe and Wanhe ophiolitic mélanges represent the intra-oceanic arc ophiolitic assemblages in the Yunxian-Menghai Ocean.

The Qianmai ophiolitic mélange in Lancang includes chlorite-sericite-quartz schist, sericite-schist, metadiorite, gamet amphibolite (metabasalt), hornblende-gamet bistagite, metabasalt, epidotic amphibolite (metamorphosed ultrabasic rock), etc. The zircon U-Pb ages of the metamorphosed basic volcanic rock, granite, and tonalite range from 507 Ma to 492 Ma. The basic rocks are characterized by high Sr, MgO, Nb and low Y. The intermediate-acidic rocks are characterized by high Mg# and Sr, low Al_2O_3 and Y. All these rocks are characterized by enrichment of the LREEs and LILEs, flat heavy rare earth elements, and significant depletion of Nb, Ta, Sr, and Eu elements. The rock assemblage and geochemical characteristics of the Qianmai mélange suggest an island arc setting. The basic magma is inferred to have been derived from a subduction-enriched mantle, whereas the intermediate and acidic rocks are thought to have formed through remelting of the lower induced by basic magma upwelling or by the heat flow generated by subduction. Based on the geochemical characteristics and sequence stratigraphy of the sedimentary-magmatic assemblage, it can be concluded that the Qianmai mélange represents an ophiolite assemblage formed in a forearc extensional setting near the subduction zone, likely resulting from the subduction of the Yunxian-Menghai Ocean in the earliest Paleozoic (Zhao, 2019; Liu, 2020).

Moreover, a large number of intermediate-acidic intrusive rock remnants have been identified in the Lincang batholith, which are related to late Cambrian and Ordovician island arc setting. These rock fragments show deformed and metamorphosed nature with gneissic structures, as represented by the Mayidui gneissic granite and its dark-color enclaves in Yunxian (463–459 Ma; Zhao, 2019), granitic gneiss in Lincang (476 Ma; Xiao et al., 2018), granitic gneiss in the Qingping area of Shuangjiang (476–465 Ma; Peng et al., 2018), and Qianmai gneissic granite in Lancang (496–484 Ma; Zhao, 2019).

2.7 The Lincang granitoid batholith

Lincang granitoid batholith is exposed within a north-south striking belt extending from Changning, through Shuangjiang and Lancang, to Menghai. It is the largest granitoid batholith in western Yunnan, and intrudes into the Lancang Group and Carboniferous-Triassic sedimenraty strata. The batholith was formed by multi-stage intrusion during 261–203 Ma, with the main emplacement concentrated at 230–210 Ma, and peaked at about 220 Ma. This reflects that the main body of the batholith was formed in the Middle-Late Triassic, but some components might have formed as early as in the Late Permian. Petrologically, the Late Permian components are granodiorites, and the Middle-Late Triassic intrusive bodies are mainly monzogranites, with subordinate alkali-feldspar granites. From the perspective of petrogenesis and tectonic setting, the Lincang batholith contains a variety of granitoids, including S-, I-, and A-types. The peraluminous, I- and S-type granitoids were mainly formed by the melting of metasandstones during 261–225 Ma. The A-type granitoids were mainly formed during the later stage at 224–203 Ma. Therefore, the magmatic activities of the Lincang Batholith recorded the process of Paleo-Tethys closure: the ocean closed at about 252 Ma, followed by syncollisional orogeny at 250–237 Ma, and post-collisional extension at 235–203 Ma (Fan et al., 2009; Wang et al., 2014; Zhao et al., 2017; Deng et al., 2018; Wang Y J et al., 2018; Yuan et al., 2021).

The para-metamorphic rocks, dominated by schists, are sporadically distributed in the Lincang batholith, and were previously mapped as the Damenglong Group and assigned to the Mesoproterozoic. The protoliths are inferred to be argillaceous and sandy flysch, and the youngest detrital zircon U-Pb ages of 550–451 Ma from the quartz schist correspond to the early Cambrian to the late Ordovician (Chen, 2020). The age peak of the zircon core from the Triassic granites in Menghai, Yunnan and Kengtung, Myanmar is 443 Ma (Catlos et al., 2017; authors' unpublished data). These results indicate that the Lincang batholith in Yunnan and eastern Myanmar is mainly formed by melting of early Paleozoic intermediate-acidic volcanic rocks and clastic rocks.

Along the east side of the Lincang granitoid batholith, there are a number of mafic-ultramafic and diorite bodies distributed intermittently from south to north, including the Paleng, Nanlianshan, Manxiu, Yakou (Reshuitang), Banpo rock bodies. These rocks have been regarded as fragmented ophiolitic components of the Paleo-Tethyan main ocean or its remnant back-arc ocean basin. The zircon U-Pb ages of 273–252 Ma for the Paleng pluton indicate that it likely formed in the Paleo-Tethyan island arc setting (Wang W et al., 2021). Diorites in the Nanlianshan mélange in Jinghong yielded zircon U-Pb ages of 305–298 Ma, and geochemical characteristics show that the mélange was also formed in an island arc setting (Li et al., 2011; Xu et al., 2016). The zircon U-Pb ages of the Manxiu diorite distributed parallel to the Nanlianshan pluton are 321–291 Ma, and its trace and rare earth element characteristics indicate that the pluton was formed in an oceanic subduction zone (Sun et al., 2015a). Gabbro and gabbro-diorite in the Banpo mélange yielded zircon U-Pb ages of 303 and 295 Ma, respectively. Geochemical characteristics of the gabbro show that the Banpo mélange was formed in an island arc related to plate subduction (Li G Z et al., 2012; Zhang et al., 2013). Zircon ages of 296–295 Ma for gabbro in the Yakou pluton, along with whole-rock geochemical and zircon Hf isotopic data, indicate that the pluton formed in a geological setting related to the subduction of the Changning-Menglian oceanic crust beneath the Simao Block (Jin et al., 2014).

2.8 Western Simao Block

The western Simao Block lies to the east of the Lincang Batholith, across both sides of the Lancang River, giving it the alternative name of southern Lancangjiang Belt. The belt contains Precambrian to Cenozoic strata, which record the Proto-Tethyan and Paleo-Tethyan evolution as well as Mesozoic-Cenozoic deformation history.

The lower part of stratigraphic sequence in the western Simao Block consists of metamorphic rock series, including the Damenglong, Chongshan, and Wuliangshan groups and the Tuanliangzi Formation. The Tuanliangzi Formation is distributed to the east of the Lancangjiang Fault and is mainly composed of phyllites with abundant quartz veins, interspersed with greenschists. Zircon U-Pb age data from sericite-quartz-phyllite (protolith: rhyolite) constrain the sedimentary age of this formation to the Mesoproterozoic era. Therefore, the formation has been regarded as a constituent of the Yangtze Block basement (Sun et al., 2015b; Liu et al., 2018). Zircon geochronology results from the quartz veins confirm that the strata were impacted by tectonothermal activities associated with Proto-Tethyan and Paleo-Tethyan subduction and collision (Zhao et al., 1994; Liang et al., 2009; Liu G C et al., 2019).

The Chongshan Group is mainly composed of migmatites, gneiss, schist, variolite, and minor marble and plagioclase amphibolite. The protoliths of these rocks are predominantly are sandy, argillaceous and calcareous sedimentary rocks displaying flysch characteristics. The Damenglong Group is well-known for the occurrence of iron ores in metamorphosed sodic basic volcanic rocks. It is mainly composed of schist, metamorphic granulite, gneiss, marble, and amphibolite, with a small amount of intermediate-basic volcanic rocks, carbonate rocks, and carbonaceous rocks. The Chongshan and Damenglong groups are separately distributed in the areas west of the Lancangjiang fault zone, with the former in the north and the latter in the south. Based on their lithologies and distribution patterns, the two groups are considered to be possible lateral equivalents. According to metamorphic grades, micropaleoplant assemblages and radiometric ages, the protoliths of the metamorphic strata were generally thought to be of Paleo- to Mesoproterozoic ages (Zhai et al., 1990; Luo, 1994; Zhong, 1998). However, zircon U-Pb ages of clastic rocks from the quartz schist, biotite schist, and biotite K-feldspar gneiss indicate that the depositional age of the strata ranges from the early Paleozoic to the Devonian. Provenance analysis and geochemical features of the intermediate-basic rocks suggest an island arc tectonic setting (Chen, 2020; Bai et al., 2021; Huang et al., 2021).

The Wuliangshan Group, located east of the Lancangjiang fault zone, is mainly composed of schist, quartzite, carbonaceous sericitic phyllite, slate, metamorphic sandstone, with a small amount of metadacite and dacite tuff. The age of the Wuliangshan Group has been reported as Cambrian, Late Carboniferous-Early Permian, or Permian. Recent studies conducted by the Geological Survey Institute of Yunnan Province have yielded zircon U-Pb ages of 450–440, 427 and 429 Ma from metamorphosed pyroclastic rocks, sericite-schist (with a protolite of dacite) and metadacite, respectively. The original sedimentary rocks of the group were deposited during the Silurian, making it comparable with the Daaozi Formation (Liu J P et al., 2019).

Based on the compilation of published data, it is obvious that there are significant differences between the Damenglong, Chongshan, Wuliangshan groups and the Tuanliangzi Formation in terms of formation age, but some preliminary agreement can be reached as summarized below. Firstly, they all contain arc volcanic rocks and turbidites. Secondly, their ages are mainly early Paleozoic and a small number of the Precambrian, late Paleozoic, and even Triassic strata are locally involved because of long-term deformation and metamorphism. Thirdly, two stages of deformation at 461–395 and 260–240 Ma can be identified, corresponding to the Paleo- and Proto-Tethyan orogenic cycles, respectively (Wei et al., 1984; Wu et al., 1984; Zhao et al., 1994; Liang et al., 2009; Xu et al., 2018; Liu G C et al., 2019; Liu J P et al., 2019; Huang et al., 2021). Based on the aforementioned factors, we think that these strata were mainly formed by metamorphism of the lower Paleozoic accretional complex at the continental margin of the Simao Block and suggest that they are collectively referred to as the Chongshan Group.

Silurian and Devonian strata are sparsely exposed in a narrow north-south striking zone in this area (Figure 1). Previous studies have been focused on the Daaozi, Dapingzhang, Dazhonghe and Nanguang areas. The strata in first three areas were collectively referred to the Daaozi Formation, while the strata in the Nanguang area, named the Nanguang Formation. The type section of the Daaozi Formation is located at the riverbank of the Xiaoheijiang River north of the Daaozi Village. Although the section is mapped as a continuous stratum, it is actually exposed intermittently due to the presence of faults. This section is dominated by dacite, andesitic basalt and pyroclastic rocks with interspersed tuffaceous mudstone and siliceous rock. The siliceous rock contains Late Devonian radiolarian fossils.

In the Dappingzhang mining area, Feng et al. (2000) identified early Early Carboniferous radiolarian fossils in a chert interlayer of the Daaozi Formation and Early Devonian conodontes in limestone lenses. Zircon U-Pb dating has constrained the dacite of the Daaozi Formation to 429–428 Ma, and the rhyolite and tuff to 421 Ma and 417 Ma, respectively, but a granodiorite porphyry from the formation was dated at 401 Ma (Li J B et al., 2012; Ru et al., 2012; Lehmann et al., 2013). These magmatic rocks have been interpreted to have formed in an island arc or back-arc extensional rifted basin setting (Li et al., 2003; Zhong et al., 2004; Li J B et al., 2012). Similarly, Mao et al. (2012) reported zircon U-Pb ages of 421–419 Ma from the dacitic tuff of the Daaozi Formation in the Dazhonghe area, and also proposed an island arc setting for the unit. Wei et al. (2021), on the basis of detailed mapping of the Daaozi Formation in the Dazhonghe area, pointed out that the formation is composed of multiple stratigraphic slices. The latter authors also reported zircon ages of 428–421 Ma for the andesitic tuffs and unimodal detrital zircon ages peaked at 418 and 429 Ma for two sandstone samples. The tuffaceous siliceous rocks contain Late Devonian and early Early Carboniferous radiolarian fossils.

In the Nanguang area, the middle and lower parts of the Nanguang Formation are mainly composed of lithic sandstone, tuffaceous sandstone, tuff, and mudstone, the upper part is pebbled sandstone mixed with silty mudstone, and the top is compound conglomerates. According to plant fossils, the Nanguang Formation was considered as a terrestrial molarite (Wang Y Z et al., 2013). However, recent remapping of the type section revealed sedimentary structures of Bauma sequences, containing Late Devonian plant fossil *Leptophloeum rhombicum* Dawson in members A and B, and radiolarian fossils in member E. This formation is dominated by marine turbidites (Yu et al., 2013; Liu et al., 2014). The zircon ages of the tuff are 382–366 Ma, and of the two detrital samples are unimodal 367 and 366 Ma, respectively (Nie et al., 2016).

In summary, the Silurian and Devonian strata in these areas exhibit fragmentation and mixing, and their stratigraphical sequences are reconstructed through isotopic geochronology data and biostratigraphy results. Of them, the Silurian and lowermost Devonian is mainly composed of volcanic rocks and pyroclastic rocks, which are collectively assigned to the Daaozi Formation. Specifically, the lower part of the formation mainly comprises dacite, andesite, dacitic pyroclastic rock with interlayers of basalt and basaltic andesite, which are dated at 430–420 Ma, and its upper part is mainly rhyolite and acid pyroclastic rocks dated at 420–410 Ma. The rest of the Devonian to the bottom of the Carboniferous are mainly composed of clastic rocks, which are grouped into the Nanguang Formation: its lower part is interspersed with limestone lenses containing Early Devonian conodonts formed in coastal and shallow marine environments, whereas the middle and upper parts have Bauma sequence structures and radiolarian fossils, indicating a deep-sea basin setting. Therefore, the formation was deposited in a gradually deepening basin. The unimodal detrital zircon age peak at 367–366 Ma is consistent with the tuff zircon ages and biostratigraphic constraints, indicating that the clastic rocks were deposited by turbidity current and that the clastics were sourced from contemporaneous volcanic eruption (Figure 2).

The Carboniferous and Permian strata are divided into the Manbing, Longdonghe, and Daxinshan formations. The Manbing Formation is composed of limestone with argillaceous siltstone, feldspathic lithic sandstone, and tuff, assigned to late Early Carboniferous to early Late Carboniferous according to the coral fossils. The Longdonghe Formation, unconformably overlying the Manbing Formation, is composed of sandstone, conglomerate, limestone in its lower part, and of intermediate-acid tuff, volcanic breccia, tuffaceous siltstone, lithic arkose, with radiolarite interlayers in its upper part. The formation is considered to be late Late Carboniferous to Early Permian according to its radiolarian and fusulinids fossils. The Daxinshan Formation distributed in western Simao Block, overlying the Longdonghe Formation with unconformable contact, comprises slightly metamorphosed clastic rocks sandwiched with basic volcanic rocks and limestone, and belongs to the Middle and Upper Permian. The Middle Permian in eastern Simao Block is called the Lazhuhe Formation, which is in unconformable contact with the Longdonghe Formation and mainly consists of shallow marine carbonate and clastic rocks. The Upper Permian in this area can be divided into the Yangbazhai and Naqing formations. The former is mainly clastic and pyroclastic deposits with occasional occurrences of coal seams or coal lines. The latter is dominated by carbonate deposits, which are in unconformable contact with the overlying the Middle Triassic Manghuai Formation or the Upper Triassic Waiguncun Formation. In summary, the strata from late Late Carboniferous to Permian in this area are mainly coastal and shallow marine clastic rocks and carbonate deposits, intermingled with intermediate-basic and intermediate-acidic volcanic rocks and pyroclastic rocks that display continental island arc affinities (Shen et al., 2006).

Lower Triassic strata are missing in this area, and Middle and Upper Triassic strata are divided into the Manghuai, Xiaodingxi, and Manghuihe formations. The lower part of the Manghuai Formation is mainly clastic rocks with basic-volcanic rock interbeds, from which zircon yielded a U-Pb age of 241.0±4.9 Ma (Peng, 2006; Wang et al., 2010). The upper part is a suite of acidic volcanic rocks, including rhyolite, rhyolite porphyry, quartz porphyry, rhyolite tuff, which gave zircon U-Pb ages of 238–231 Ma. Therefore, this formation is constrained to the late Middle Triassic to the early Late Triassic in age, and was deposited in a post-collision tectonic setting (Peng, 2006; Wang et al., 2010; Luo et al., 2018; Nie, 2018). The Xiaodingxi Formation is composed of grey-green, purplish red intermediate-basic volcanic lavas and volcanic breccia with tuffaceous sandstone, and is assigned to the Late Triassic according to its zircon age of 230–213 Ma. The Manghuihe Formation is characterized by intermediate-basic volcanic rocks, polymictic conglomerate and mudstone, and is grouped to the Early Jurassic on the basis of zircon U-Pb ages of 198–196 Ma. Both the Xiaodingxi and Manghuihe formations are proposed to have formed in an extensional rifting basin setting (Lv, 2013; Wei et al., 2016; Du, 2018).

3. The Tethyan evolution

The distribution of rock records of the Proto-Tethys, its tectonic evolutionary history, and its relationship with the Paleo-Tethys have long been debated. For more than a decade, a series of early Paleozoic geological records, including magmatic rocks, high-pressure metamorphic rocks, ophiolites and stratigraphic sequences in SW Yunnan have been extensively studied, which helps to gradually uncover the mystery of the Proto-Tethys. As summarized above, the abundant geological records of the Proto-Tethys recognized in SW Yunnan, allow us to reconstruct the evolutionary history of the greater Tethys orogen in this region.

3.1 Location of the Proto-Tethys Ocean

Early Paleozoic geological records are widely distributed in SW Yunnan, across multiple tectonic domains including, from west to east, the Baoshan Block, the Changning-Menglian Belt, the Lincang Terrane, the Yunxian-Menghai Belt, and the Simao Block. The Yunxian-Menghai Belt is characterized by a series of dismembered ophiolitic blocks, including mafic oceanic crust gabbro, oceanic island basalt, and overlying pelagic chert and mudstone (Figure 1; Liu et al., 2021a, 2021b). We propose that the Yunxian-Menghai ophiolitic belt represents the suture of the Proto-Tethys. This ophiolite mélange belt can be traced southward to eastern Myanmar and northern Thailand.

Although the Changning-Menglian Belt contains minor early Paleozoic magmatic rocks that might be related to the Proto-Tethys, the available evidences do not support the presence of the Proto-Tethys oceanic basin in the belt: (1) The Nantinghe ophiolites in the Changning-Menglian Belt are mainly composed of mafic and ultramafic magmatic rocks but lack oceanic basin sediments. Wang B D et al. (2013) suggested that the Nantinghe mafic and ultramafic magmatic rocks formed in a back-arc rift setting at 444–439 Ma, possibly associated with the Proto-Tethys oceanic subduction. (2) The discovery of Ordovician adakite-like tonalites in the Changning-Menglian Belt has led some researchers to relate it with the subduction of the Proto-Tethys Ocean (Wang et al., 2016; Wu Z et al., 2020). However, it remains uncertain whether these tonalites are related to the subduction of the Changning-Menglian or the Yunxian-Menghai Oceans. Considering the fact that the former lacks Ordovician oceanic crust records, a relation to subduction of the Yunxian-Menghai Ocean is more favorable. (3) The detrital zircon age spectra and Hf isotopic data from the Lancang Group of the Lincang Terrane closely resemble those from the Mengtong and Mengdingjie groups in the Baoshan Block, suggesting that they were deposited in a uniform sedimentary basin and shared common detrital sources (Zhao et al., 2017; Zheng et al., 2019, 2021; Wei et al., 2022). Thus, the Lincang Terrane likely had a tectonic affinity to the Baoshan Block, rather than to the Simao Block, during the Cambrian-Ordovician period. By contrast, the detritus of the Damenglong and Chongshan groups were mainly originated from the Simao Block (Bai et al., 2021). Hence, we believe that the Proto-Tethys Ocean was located between the Simao Block and the Lincang Terrane, and its remnant is represented by the Yunxian-Menghai Belt. (4) The Nanduan Formation located in the eastern Changning-Menglian Belt is characterized by typical passive continental margin clastic rock assemblages. This formation can be traced northward to NW Yunnan and eastern Tibet (the Mode Group) and southward to northern Thailand (lower part of the Mae Tha Group), and together they represent the passive continental margin of the Paleo-Tethys oceanic basin during the Late Devonian to the early Late Carboniferous. Thus, the Ordovician-Permian stratigraphic records do not support a continuous subduction process in the Changning-Menglian Belt.

3.2 The evolution of the Proto-Tethys

Due to the tectonothermal overprinting related to Paleo-Tethys subduction and collision, the primary geologic records of the Proto-Tethys have been strongly altered and destroyed, making it very difficult to reconstruct its evolutionary history. Based on a compilation of published data, particularly those obtained in the recent decade, we attempt to decipher the evolutionary history of the Proto-Tethys in SW Yunnan.

3.2.1 Conversion from Atlantic- to Pacific-type oceanic basin

Zhao G C et al. (2018) proposed that the dispersal of the Rodinia supercontinent was driven by mantle plume activity between 750 and 600 Ma, resulting in the formation of several Proto-Tethys oceanic basins. The South China, North China, North Qiangtang, Tarim, and Indochina blocks were separated from the northern margin of the Rodinia supercontinent through the opening of the Proto-Tethys Ocean, leaving behind some smaller blocks, such as the Sibumasu and South Qiangtang blocks located at the northern margins of the Australian and Indian cratons (Zhao et al., 2017). The Yunxian-Menghai Belt in SW Yunnan is considered to be a remnant of the Proto-Tethys Ocean. The ophiolitic components, representing oceanic crust and island arc basalts, found in this belt can be traced back to the late Cambrian to the late Ordovician (507–447 Ma; Liu, 2020) (Figure 3), while the adjoining continental terranes on its both sides contain rock records as old as Neoproterozoic.

Stratigraphical records suggest that the Yunxian-Menghai Proto-Tethys Ocean underwent bidirectional subduction, as documented in the Baoshan Block and Lincang Terrane. In the Baoshan Block, the early-middle Cambrian Gongyanghe and Mengtong groups are characterized by thick marine sedimentary sequences primarily composed of terrigenous clastic materials without volcanic rocks, indicating a relatively stable passive continental margin tectonic setting. The oldest arc-related volcanic rocks in the Baoshan Block are represented by the Hetaoping Formation (Zhang et al., 2015), which contains the Guzhangian trilobite fossils, *Blackwelderia* in sedimentary interlayers of basaltic andesite (Zhu et al., 2019). The arc-related intrusions are dated at 502–446 Ma, contemporaneous with the volcanic rocks. Therefore, during the middle-late Cambrian to the Ordovician, the western margin of the Proto-Tethys Ocean transformed into an active continental margin (Figure 3a).

Similar to the Baoshan Block, the Lincang Terrane also records the regime transformation of the Proto-Tethyan continental margin. The oldest metamorphose volcanic rocks, including basalt and basaltic andesite, found in the Manlai Formation of the Lancang Group, have been dated at 505±4 and 492±4 Ma by U-Pb zircon geochronology. In the Ordovician Huimin Formation, basalt, basaltic andesite, and andesite with island arc features have become widespread. The geochemical characteristics show that Cambrian-Ordovician volcanic rocks of the Lancang Group have an arc-like signature, suggesting that they formed in a subduction-related island arc setting (Nie et al., 2015; Xing et al., 2015; Wei et al., 2022).

In the eastern Yunxian-Menghai Belt, similar island arc-related metamorphosed mafic volcanic rocks are found in the Chongshan, Damenglong, and Wuliangshan groups. However, due to the lack of robust isotopic geochronology data, they are only tentatively regarded as early Paleozoic rocks (Chen, 2020; Bai et al., 2021; Huang et al., 2021).

In conclusion, we infer that initial subduction of the Yunxian-Menghai Proto-Tethys Ocean occurred at the late Miaolingian (ca. 505 Ma), resulting in the transition from an Atlantic-type basin to a Pacific-type one (Figures 2, 3b, 4, and 5).

3.2.2 The closure of the Proto-Tethys Ocean

The Proto-Tethys Ocean, represented by the Yunxian-Men-

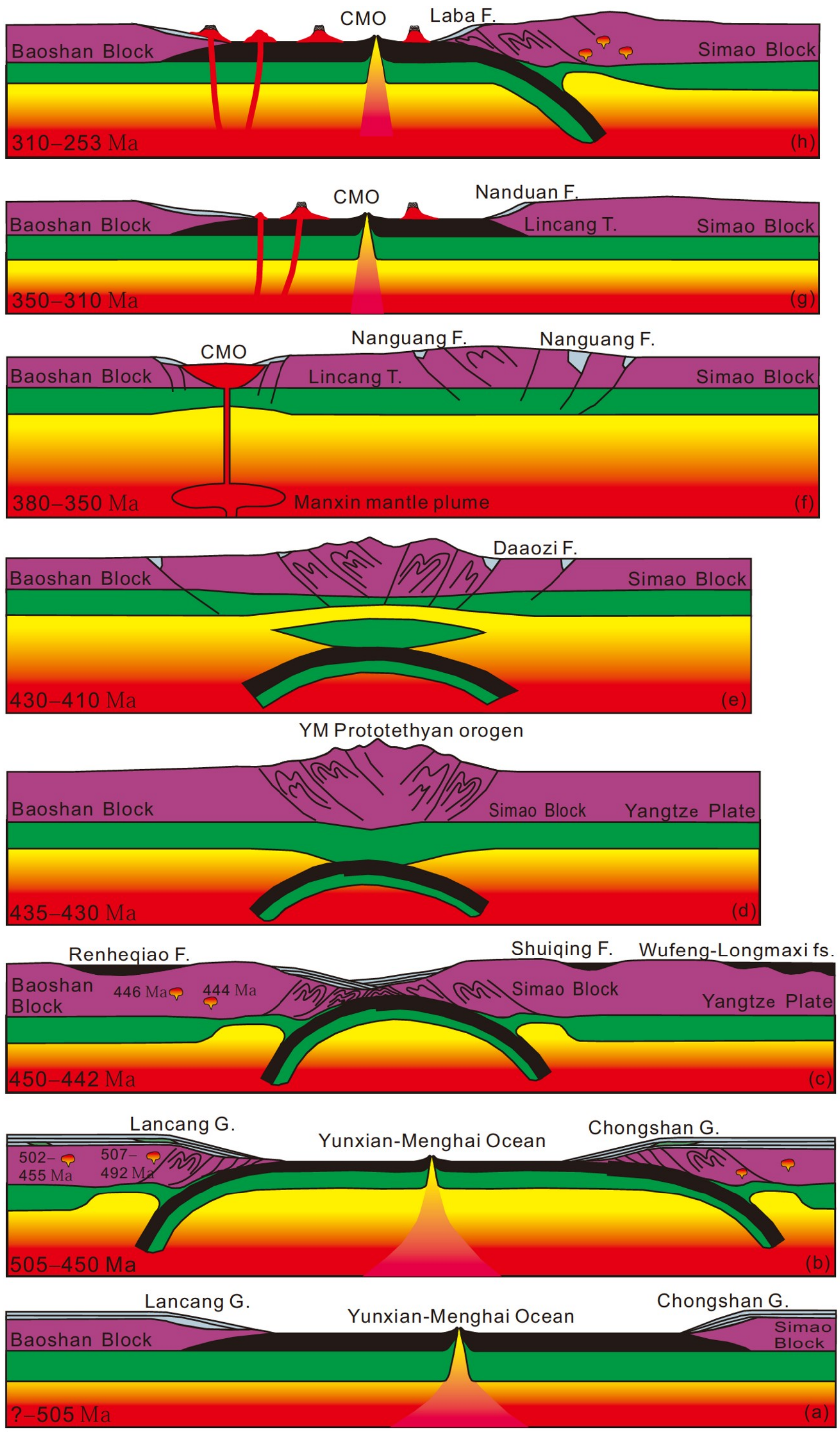

Figure 3 Tectonic cartoons displaying the evolutionary history of the Tethys oceans in SW Yunnan during the Paleozoic Era. CMO, Changning-Menglian Ocean; F., Formation; G., Group; fs., formations; YM, Yunxian-Menghai.

ghai Belt, was closed during the late Ordovician, leading to the collision of the bounding continents, as supported by the following evidences: (1) During the Katian period (ca. 450 Ma), there was a dramatic change in lithological paleogeography, from a shallow-water carbonate platform to a deep-water basin depositing siliceous and mud sediments. Widespread unconformities were developed in the Baoshan Block to the west and in the Yangtze, North China, and Tarim blocks to the northeast (Chen et al., 2014; Zhang et al., 2021), indicating significant tectonic deformation during this period. During the late Katian to the early Rhuddanian (ca. 450–442 Ma), the deep-water basins were characterized by very slow sedimentation of organic-rich mud with abundant biogenic siliceous rocks and tuffs, and scarce terrigenous

Cycle	Stage	Age (Ma)	Intrusive rock	Igneous rock	Sedimentary basin and sedimentation	Strata
Paleotethys	Post-collision	196 ↑ 238	Granite batholith	Potassium basalt, high potassium calc alkaline - calc alkaline rocks	Extensional faulting basin; fluvial-lacustrine pyroclastic rocks	Manghuihe, Xiaodingxi, Sanchahe formations
				Upper: acid volcanic rock; lower: basic volcanic rock	Extensional faulting basin; fluvial-lacustrine clastic rocks, pyroclastic rocks	Manghuai, Sanchahe formations
	Major-c.	238 ↑ 253	Syn-collision granite	Tuff, pyroclastic rocks	Regional unconformity, lacking stratigraphic records	
	Initial-c.				Turbidite in remnant basin; Black siliceous shale and clastic rocks in passive margin	Papai, Muyinhe formations Laba Group
	Pacific-type ocean	253 ↑ 310	Island arc intermediate-acid, mafic-ultramafic magmatite	Island arc basalt, andesite MORB, IOB	Turbidite composed of volcanic debris and terrigenous Pelagic siliceous-argillaceous rocks, carbonate on oceanic island-seamount	Manxin, Daxinshan, Longdonghe formations Laba Group
	Atlantic-type ocean	310 ↑ 380	?	MORB, IOB	Turbidite, pelagic siliceous-argillaceous rocks, carbonate on oceanic island-seamount	Nanpihe, Manxin, Wenquan, Pingzhang, Nanduan formations
	Rift	380 ↑ 420	?	?	Turbidite, detritus came from both blocks	Wenquan Formation
Prototethys	Post-collision	355 ↑ 430	Basic, intermediate, acid magmatites with island arc geochemical characteristics	Late stage: pyroclastic rocks with island arc geochemical characteristics Early stage: basic to acid volcanic rocks with island arc geochemical characteristics	Extensional faulting basin. Early: fluvial-lacustrine clastic rocks; middle: shallow marine clastic rock with limestone lens; late: deep-sea turbidite with chert bearing radiolarian fossil. Clastic rock is mainly composed of volcanic detritus and was deposited along with eruption. The volcanic clast is with island arc geochemical characteristics.	Nanguang, Daaozi formations
	Major-c.	430 ↑ 450	?	?	Regional unconformity, lacking stratigraphic records	
	Initial-c.		Syn-collision granite	Tuff, volcanic clastic rock	Turbidite in remnant basin Siliceous rock, siliceous shale, black rich-organic shale in interior of both side blocks	Renheqiao, Shuijing, Wufeng, Longmaxi formations
	Pacific-type O	450 ↑ 505	Island arc intermediate-acid, mafic-ultramafic magmatite	Island arc basalt and andisite MORB, OIB	Pelagic siliceous-argillaceous rocks and turbidite	Lancang Group and others
	Atlantic-type O	505 ↑ ?	?	MORB, OIB	Pelagic siliceous-argillaceous rocks and turbidite	Lancang Group and others

Figure 4 Geological records and evolutionary processes of the Tethys orogenic belst in SW Yunnan.

clastic materials. During the late Rhuddanian to the early Aeronian (ca. 442–440 Ma), the emergence of paleo-uplift and deepening of the sedimentary basins indicate enhanced intracontinental structural deformation. This process is also marked by the increasing supply of terrigenous clastic materials to the basin and by the widespread turbidites and contourites. During the late Aeronian to the early Telychian (ca. 440–434 Ma), the blocks on both sides of the Proto-Tethys Ocean were characterized by shallow marine clastic rocks. The absence of upper Telychian to Ludfordian strata in the Tarim, North China, South China, and Hainan blocks suggests that intracontinent tectonic deformation became insignificant and that the sedimentary basins gradually matured and disappeared (Wang Y et al., 2021). (2) Collision-related granites occurred during the late Ordovician (ca. 446 Ma; Lu et al., 2015). (3) The youngest island arc-type metavolcanic rocks from the Huimin Formation yielded a zircon U-Pb age of ca. 442 Ma. Thus, the initial continental colli-

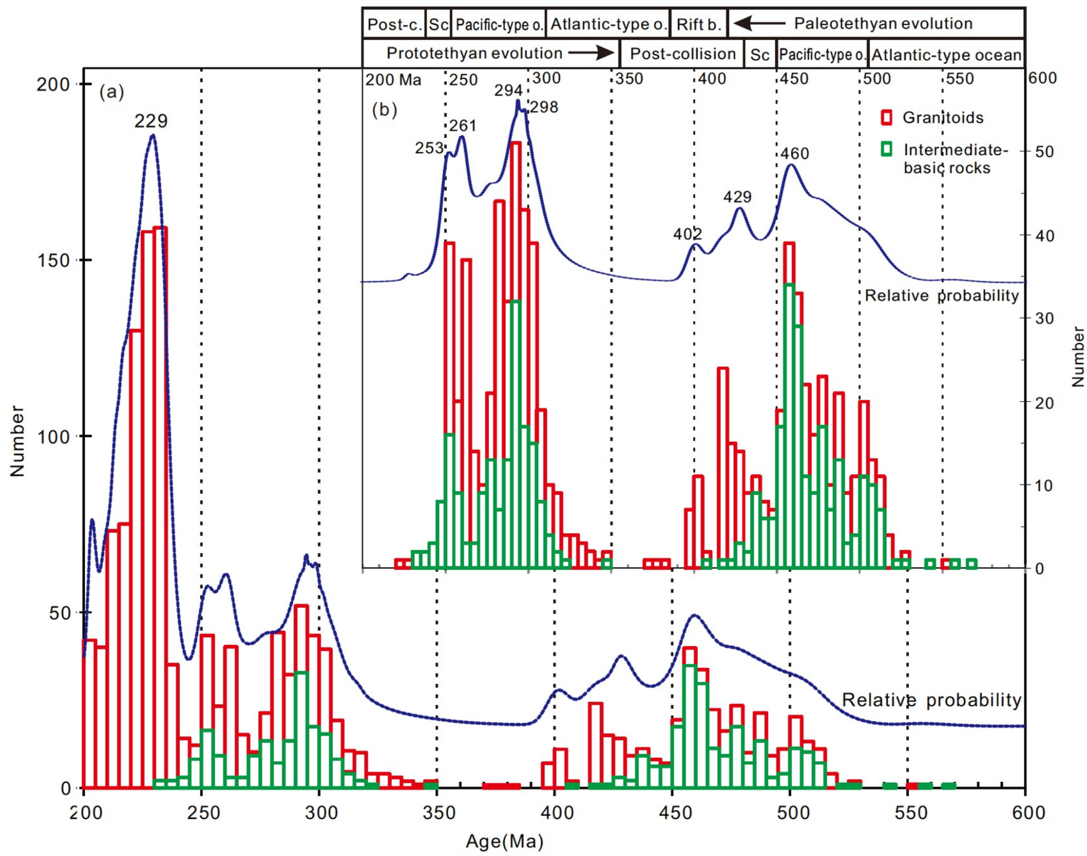

Figure 5 Zircon crystallization age-spectra for Neoproterozoic-Triassic igneous rocks in the Lincang Terrane and Simao Block. The abbreviation is shown in Figure 2. After Jian et al., 2009; Lehmann et al., 2013; Nie et al., 2015; Xing et al., 2015; Deng et al., 2018; Li et al., 2011; Li J B et al., 2012; Ru et al., 2012; Zhang et al., 2013; Sun et al., 2015a; Xu et al., 2016; Liu et al., 2017; Liu, 2020; Wei et al., 2021; Wang W et al., 2021. (b) is a magnified portion of (a).

sion following the closure of the Yunxian-Menghai Proto-Tethys took place at the end of the Ordovician (ca. 450 Ma), and the collision persisted throughout the early Silurian (ca. 442–430 Ma) (Figures 2, 3c, 4, 5).

3.2.3 *Post-collisional stage*

During the middle Silurian, a volcanic debris-dominated extensional fault basin developed in the Proto-Tethys orogenic belt and its neighboring areas, as evidenced by the ca. 430 Ma interbedded basalt at the bottom of the Daiwazi Formation. The development of extensional fault systems suggests a transition from syn-collision compression to post-collision extension. The extensional faults were likely associated with a thinned underlying continental lithosphere mantle, which facilitates the intrusion and eruption of mafic lavas in the basin (Figures 2, 3e).

During the late Silurian, the upper Dawazi Formation (ca. 430–410 Ma) was characterized by a sequence of continental volcanic and pyroclastic rock assemblages, including dacite, andesite, rhyolite, intermediate-acidic volcaniclastic rocks and sandstone, with interbedded tuff. During the early Devonian, the lower part of the Nanguang Formation (ca. 410–390 Ma) was characterized by a sequence of shallow marine sedimentary assemblages, including volcanoclastic rocks and mudstone with interlayered limestone lenses containing Early Devonian conodont fossils. These sedimentary assemblages indicate the transformation of the region into a shallow marine sedimentary basin. During the Middle-Late Devonian to the earliest Carboniferous, the middle-upper part of the Nanguang Formation (ca. 390–355 Ma) was characterized by a sequence of deep-sea turbidites, including tuffaceous greywacke, feldspathic sandstone, lithic quartz sandstone interlayered with tuffaceous siliceous rocks. The tuffaceous siliceous rocks contain Middle-Late Devonian and earliest Carboniferous radiolarian fossils (Feng et al., 2000; Wei et al., 2021). Zircon U-Pb ages of the tuffs range from 382 Ma to 366 Ma, and detrital zircons from the sandstone give a unimodal age peak at 367–366 Ma. The detrital components are mainly andesitic and rhyolitic debris. Moreover, the coincidence of the detrital zircon and tuff zircon ages suggests that the detritus were derived from a single Late Devonian volcanic source and that deposition of the turbidite kept in pace with volcanic eruption (Nie et al., 2016).

In conclusion, middle Silurian to earliest Carboniferous strata are mainly composed of volcanic and pyroclastic rocks. The gradual deepening of the basin, marked by lithologic transition from continental, to shallow- to deep-sea facies, indicates that the tectonic regime of the studied area transformed from compression to extension. The volcanic and pyroclastic rocks from the Dawazi and Nanguang formations show geochemical characteristics similar to typical arc magmatic rocks, likely suggesting the collapse and extensional thinning of the continental crust due to lithospheric delamination, accompanied by upwelling and underplating of hot, mantle-derived magma into the crust. Therefore, during the middle Silurian to the earliest Carboniferous (430–355 Ma), the tectonic setting of the western margin of the Simao Block was characterized by post-orogenic extension following the closure of Proto-Tethys ocean (Figures 2, 3e, 4, 5).

3.3 Evolution of the Paleo-Tethys

3.3.1 Initial opening of the Paleo-Tethys Ocean

Ophiolitic mélange represents fragments of old oceanic lithosphere. Although ophiolitic mélanges have been found in the Changning-Menglian Belt, their ages are still not well constrained. The oldest ages are hornblende K-Ar isochron ages of 385–381 Ma from gabbros of the Tongchangjie ophiolitic mélange (Cong et al., 1993), roughly corresponding to the Middle-Late Devonian transitional period. Based on a geochemical study of the radiolarian chert, Ding and Zhong (1995) suggested that the Changning-Menglian Belt had already developed an open oceanic basin in the Middle Devonian (Cong et al., 1993).

Yang et al. (2007) recognized pelagic radiolarian cherts and pillow basalts in the Manxin Formation in the Gengma area. The cherts contain abundant radiolarian and conodont fossils, with the latter belonging to the *Palmatolepis triangularis* Zone of Frasnian age (ca. 372–370 Ma). The pillow basalts have geochemical characteristics similar to oceanic island basalts, supporting that the Changning-Menglian Paleo-Tethys Ocean had already opened in the Late Devonian. Moreover, the lack of terrigenous clastic materials in the Manxin Formation is consistent with the existence of a mature ocean in the region during the Late Devonian.

We have recently collected petrographic and detrital zircon data from terrestrial clastic turbidites of the Lower Devonian Wenquan Formation in the Gengma area of western Changning-Menglian Belt. Our new findings reveal the presence of Silurian (430 Ma) andesitic clasts from the Simao Block, suggesting that the Paleo-Tethys basin was relatively restricted in scale during the early Devonian and that the clasts could have been transported from the Simao Block to the opposite side of the basin (Gan et al., 2021).

In summary, the Changning-Menglian Paleo-Tethys was a restricted basin receiving terrestrial clastic sediments during the early Devonian. Subsequently, the basin rapidly expanded to form a large-scale open ocean lacking terrestrial clastic input during the late Devonian. The earliest oceanic crust formed during the Late Devonian (Figures 2, 3f, 4, 5).

3.3.2 Initial subduction of the Paleo-Tethys

The western margin of the Changning-Menglian Paleo-Tethys Ocean was a passive continental margin, whereas its eastern margin was initially a passive continental margin which turned into an active continental margin at a later stage. Some disputes regarding the transition from passive to active continental margin are outlined as follows.

Provenance analysis indicates that the Nanduan Formation and the lower part of the lower clastic rock member of the Laba Group in the Changning-Menglian Belt were deposited in a passive continental margin basin. Moreover, volcanic debris was initially observed in the upper part of the lower clastic rock member, accounting for 10–15%, and become more abundant in the chert-marl-mudstone member and the upper clastic rock member. This change in provenance indicates a transition from a passive continental margin to an active continental margin setting during the Late Carboniferous (Xie and Liu, 1992).

Along the west margin of the Simao Block, from Jinghong in the south to Deqin in the north, there are numerous mafic-ultramafic and dioritic plutons, including the Nianlianshan, Manxiu, Yakou, Banpo and Jicha plutons, which are believed to have formed in a continental island arc setting. Zircon U-Pb ages from these plutons show that there are four stages of magmatism at 307–300, 297–295, 292–280 and 262–258 Ma. Therefore, the island arc magmatism commenced no later than 307 Ma (mid Late Carboniferous).

The Longdonghe Formation, distributed along the western margin of the Simao Block, is in unconformable contact with the underlying Manbing Formation, which is composed of stable carbonate platform sediments. The Longdonghe Formation is characterized by deep-water facies volcanic turbidite, and is thought to have formed in a back-arc basin of the Paleo-Tethys (Liu et al., 1993; Jia, 1995; Tan et al., 1999). Thus, the unconformity between the two formations is considered to mark the initial opening of the Paleo-Tethys back-arc basin during the mid Late Carboniferous.

In summary, the geological evidences outlined above, including fore-arc basin sedimentary assemblages, island arc magmatic rocks, and back-arc basin sedimentary assemblages, indicate that the onset of eastward subduction of the Changing-Menglian Paleo-Tethys Ocean took place in the mid-late Carboniferous (ca. 310 Ma) (Figures 2, 3h, 4, 5).

3.3.3 Timing of initial collision

When did the Changning-Menglian Paleo-Tethys Ocean close? When did the Baoshan Block initially collide with the eastern arc zone? Many geologists have conducted extensive researches employing multidisciplinary approaches in order to answer these questions. Based on data from the Lincang batholith, some scholars suggest that the subduction of the Changning-Menglian Paleo-Tethys Ocean terminated at the Permian-Triassic boundary (ca. 252–250 Ma; Peng, 2006; Deng et al., 2018; Zhao F et al., 2018), while others argue that the closure of the main Paleo-Tethy Ocean took place in the late Early Triassic (Fan et al., 2009), or even later (Wang Y J et al., 2018; Yuan et al., 2021).

Recent studies on metamorphic rocks led Wang H N et al. (2019b, 2020, 2021) to propose that the Changning-Menglian Paleo-Tethys Ocean had already closed by 246–245 Ma, but continuing deep subduction of the downgoing plate likely persisted until ca. 234 Ma. The high- and ultrahigh-pressure metamorphic rocks underwent rapid exhumation during the Late Triassic (227–225 Ma). Therefore, the closure and initial collision of the Changning-Menglian Paleo-Tethys Ocean occurred in the early Triassic (ca. 246 Ma).

Stratigraphic evidence indicates an angular unconformity between Permian and Middle Triassic strata in the Simao block, which is traditionally interpreted to mark the Lanchang Movement. This angular unconformity provides strong evidence for the existence of a collisional orogeny (Fang et al., 1992). In addition, in the Cangyuan area of the Baoshan Block, there is an unconformable contact between the early Triassic Papai Formation and the underlying Permian limestone (Xiao, 1987). Black siliceous shales at the bottom of the Papai Formation contain late Changxingian radiolarian fossils (Feng et al., 1998). Moreover, Early Triassic bivalves have been discovered within yellow mudstones in the lower part of the Papai Formation. Therefore, the Papai Formation is believed to have been deposited in a continental margin foreland basin. The presence of an unconformity between the Papai Formation and the underlying strata signifies the closure of the Paleo-Tethys and the oneset of initial collision along the Changning-Menglian Belt during the late Changhsingian.

In conclusion, the terminal-stage subduction of the Changning-Menglian Paleo-Tethys ocean was accompanied by the collision of the Baoshan Block with the eastern arc zone at the end of the Permian (ca. 253 Ma) (Figures 2, 4, 5).

3.3.4 Age constraints on syn- and post-collision

Largely based on data from igneous rocks, it is generally accepted that the Early Triassic corresponds to the syn-collisional tectonic stage of the Paleo-Tethys orogenic belt, which evolved into the post-collisional stage in the Late Triassic to the Early Jurassic. The Middle Triassic Manghuai Formation plays a crucial role in providing significant insights for distinguishing between these tectonic stages.

The lower part of the Manghuai Formation (Ladinian) consists of gray to gray-yellow shales, sandstones, conglomerates, and interbedded mafic volcanic rocks, which were deposited in a fluvial-lacustrine faulted basin (Luo et al., 2018). These sedimentary and volcanic rock formations indicate that the Paleo-Tethys orogenic belt in the SW Yunnan evolved into a tectonic extension stage, characterized by the development of faults and intermittent eruption of mafic lavas. The upper part of the Manghuai Formation is composed of felsic volcanic rocks and clastic rocks containing terrestrial Ladinian conchostracans fossils. The volcanic rocks, dated at 238–231 Ma, show geochemical characteristics of arc magmatism. Data from stratigraphy, sedimentology, and whole-rock geochemistry indicate that the Manghuai Formation formed in a post-collisional extension setting. Therefore, the tectonic transition from syn- to post-collision of the Paleo-Tethys orogenic belt in SW Yunnan took place in the Ladinian. Furthermore, based on the conchostracans and zircon U-Pb age of rhyolites, the timing of this transition is constrained to ca. 238 Ma (Figures 2, 4).

3.4 Geological features of the Tethys orogeny

The tectonic evolution from the Proto-Tethys to the Paleo-Tethys is reconstructed using the well-preserved, relatively complete geological records in SW Yunnan. Both oceans went through a full Wilson Cycle from rifting and seafloor spreading, subduction, to eventual closure and collision. The orogenic evolution from terminal subduction to collision can be subdivided into initial collision, syn-collision, and post-collision stages.

3.4.1 Initial collision stage

The term "initial collision" refers to a point of time when the oceanic crust was completely subducted (at least locally) along the plate boundary, leading to initial continent-continent contact. The initial collision process and its geological features are described below.

During the initial collision stage, the main oceanic basin has disappeared, while the remnant oceanic basin characterized by the deposition of turbidites and/or siliceous rocks (mudrocks) may still exist. The clastic materials of the turbidites are mainly derived from subduction accretionary complex, including pelagic cherts and oceanic crust volcanics. For example, the lower Muyinhe Formation contain detritus from the pelagic-cherts and volcanic rocks of oceanic crust and island arc affinities, and these detritus were also transported to, and deposited in, the peripheral foreland basin located at the Baoshan Block passive margin, forming sedimentary sequence represented by the Papai Formation. The geochemical characteristics of the Muyinhe Formation siliceous rocks suggest a typical continental margin sedimentary environment.

Continent-continent collision leads to tectonic compressional deformation, disappearance of carbonate platforms, and the formation of weathering crust in some cases. The resultant regional unconformities are commonly marked by the discontinuity of fossil zones and stratigraphic gaps. For example, late Ordovician parallel unconformities have been widely recognized in the Sibumasu, Yangtze, North China, and Tarim blocks based on detailed studies of graptolite biozones (Chen et al., 2014; Zhang et al., 2021). Detailed studies of conodont biostratigraphic zones have also revealed the latest Permian parallel unconformity in South China (Du et al., 2009; Yin et al., 2014). During the collision stage, regional crustal subsidence leads to deepening of the sedimentary basin characterized by siliceous-mud deposits lacking terrigenous clastic materials, which results in low sedimentation rates, enrichment of organic matter and formation of hydrocarbon source rocks, represented by the Wufeng Formation and the bottom parts of the Renheqiao and Longmaxi formations. With increasing intensity of tectonic deformation, weathering and erosion in the uplifted areas were enhanced and the sedimentary basin was deepened, leading to the formation of terrigenous clastic turbidites and contourite, represented by the upper sections of the Renheqiao and Longmaxi formations.

3.4.2 Main collision stage

The main collision refers to significant and comprehensive interaction between two tectonic plates or continents (Pan and Xiao, 2017). This stage is characterized by a scarcity of sedimentary and volcanic rocks in the orogenic belt and its surrounding areas, and rare occurrences of intrusive rock, resulting in a distinct regional angular unconformity. In the case of the study area, Lower Triassic strata are commonly absent in the Paleo-Tethys orogenic belt in SW Yunnan and the Simao Block.

3.4.3 Post-collision stage

The post-collision refers to the stage that is subsequent to the main collision stage, and is characterized by the formation of sedimentary basins in association with stress relaxation and fault development. In SW Yunnan, the initial stage of post-collision is represented by the lower parts of the Daaozi and Manghuai formations, and is marked by the development of terrigenous sandstones and conglomerates unconformably atop the underlying strata. The overlying strata are composed of fluvial-lacustrine clastic rocks with interbedded basalts, indicating reappearance of sedimentary basins. Moreover, mantle-derived melts reached the crustal surface through lithospheric scale faults. The early stage of post-collision is characterized by the development of intermediate to felsic volcanic rocks interbedded with volcaniclastic deposits, as represented by the upper parts of the Dawazi and Manghuai formations. The petrogenesis of these rocks suggests an island-arc tectonic setting and may be related to the interaction between the mantle and the lower crust due to lithospheric delamination.

The geological records of the late post-collision stages of the Proto- and Paleo-Tethys are significantly different. The rock records of the Paleo-Tethys are represented by the Xiaodingxi and Manhuihe formations, which are characterized by potassium volcanic rocks and terrigenous volcanic clastic deposits. These rock assemblages are very similar to those of the Neotethys in the Tibet Plateau (Mo, 2009). In contrast, the corresponding rock formations within the Proto-Tethyan stratigraphy exhibit marine sedimentation within faulted basins. The sedimentary facies in these formations progressively transition from coastal and shallow-sea environments to deep-sea settings, as evidenced by the Nanguang Formation. The geochemistry of both the pyroclastic detritus and the limited magmatic intrusions and lavas shows island arc affinities (Hu et al., 2022; Win et al., 2022).

4 An alternative model for the tectonic evolution from Proto- to Paleo-Tethys

Two models have been proposed to explain the evolutionary relationship between the Proto- and Paleo-Tethys oceans: One features that the Paleo-Tethys was developed from a back-arc basin of the Proto-Tethys or at its passive continental margin, while the other favors that the Proto-Tethys is the antecedent to the Paleo-Tethys, with the two oceans being connected and evolving continuously in space and time. Based on the discussions outlined above, we suggest that the spatial distribution and evolutionary histories of the Proto- and Paleo-tethys oceans are distinctly different. Firstly, the two oceans show systematic differences in tectonic stages, sedimentary sources and magmatic-metamorphic histories, thereby precluding a continuous evolutionary scenario or an inherited linkage between them. Secondly, the tectonic cycle of the Proto-Tethys involves late Cambrian to Ordovician subduction, early Silurian collision, and late Silurian to Devonian post-collisional extension, whereas the Paleo-Tethys belt in SW Yunnan lacks Silurian stratigraphic records, and its early Devonian strata indicate a rift basin setting. Thirdly, the opening of the Paleo-Tethys occurred during the post-collisional extension stage of the Proto-Tethys, and spatially the Paleo-Tethys ocean basin was located to the west of the Proto-Tethys suture, along the eastern margin of the Sibumasu Block. From a global perspective, the Paleo-Tethys Ocean opened in the aftermath of the Proto-Tethys closure and was situated at the northern margin of the Gondwana supercontinent.

Based on evidences from magmatic rocks and sedimentary stratigraphy, we propose that the opening and rapid spreading of the Paleo-Tethys Ocean in the Changning-Menglian

Belt in SW Yunnan was facilitated by mantle plume activity. This is supported by the following observations: (1) The Tongchangjie ophiolitic mélange contains both MORB- and OIB-type basalts, interpreted as products of normal mid-ocean ridge and mantle plume or hotspot magmatism (Zhang et al., 1985; Lai et al., 2010). The OIB-type basalts in the Tongchangjie ophiolitic mélange show typical intra-plate trace element patterns. (2) The abundant ultramafic-mafic volcanic rocks exposed in the Manxin area, including picrites, cumulate peridotites and basalts, show petrological and geochemical features indicative of the interaction of oceanic ridge magmatism with mantle plume activity (Fang and Niu, 2003; Shi and Fang, 2019). Radiolarian biostratigraphy indicates that most of the strata are Carboniferous in age, although the age of the lowermost strata is uncertain due to a lack of biostratigraphic data. (3) Late Devonian-early Carboniferous intraplate ocean island-seamount volcanics have been widely identified in the Changning-Menglian and the Chiang Mai belt in Thailand (Feng, 2002) and consistent with the rapid spreading stage of the Paleo-Tethys Ocean.

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