

Stratigraphic correlation of the Givetian (late Middle Devonian) deposits in Qujing, Yunnan, southwestern China and the paleogeographic implications

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Received: 28.11.2021 • Accepted/Published Online: 03.02.2022 • Final Version: 18.05.2022

Abstract: Detailed description of spatio-temporal framework of fossil-bearing strata is of fundamental significance for understanding the evolution of organisms and regional tectonics. The Qujing and Haikou formations are two lithological units exposed in eastern Yunnan, southwestern China, and both bear rich fossils indicative of a Middle Devonian age, while their relationship or lateral correlation remains unclear. Based on detailed observations of outcrops of these two formations in Qujing, eastern Yunnan, and as well as their typical rock characteristics and fossil contents, we propose that the two formations are basically contemporaneous heterotopic facies. From north to south of the Qujing area, the transition from the Haikou Formation to the Qujing Formation is gradual and shows an increase of carbonate component (in terms of the cumulative thickness of carbonate rocks) and as offset, a decrease of the siliciclastic component. The distribution of the Haikou/Qujing Formation indicates the development of a marine environment in the Qujing area during the Givetian, as a part of the South China Sea connected to the Paleo-Tethys Ocean, and supports that the transgression might have peaked in southwestern China during the late Middle Devonian. The available biostratigraphic evidence favors an expansion of the Paleo-Tethys Ocean prior to or during the Middle Devonian.

Key words: Middle Devonian, the Haikou Formation, the Qujing Formation, stratigraphic correlation, Paleo-Tethys Ocean

1. Introduction

The Qujing area, eastern Yunnan, southwestern China is one of the well-studied areas with respect to the Devonian sequence and fossils in the South China Block (SCB) (Grabau, 1923; Fang, 1963; Yang et al., 1981; Zhu et al., 1994; Zhu and Wang, 1996; Zhu and Zhao, 2005; Wang et al., 2002; Zhao and Zhu, 2010 and references therein; Zhao et al., 2011, 2021; Peng et al., 2016; Xue et al., 2016, 2018 and references therein). As early as 1913–1914, Dr. V. K. Ting had collected some fish fossils from the Devonian of Qujing (Bian, 1947). In 1938, B. X. Xiong discovered the fish *Bothriolepis* from a locality near Kunming, then H. Z. Wang subsequently collected abundant fossils of this taxon from many sites in eastern Yunnan, discussed the age of *Bothriolepis*-bearing strata in eastern Yunnan and the comparison with the Tiaomachien Formation (Fm.) of Hunan Province (Wang, 1942). Discoveries of abundant fossils from the Devonian of the Qujing area have been documented in a lot of later reports (Zhao and Zhu, 2010; Xue et al., 2018 and references therein).

The Devonian Period is a critical interval during the evolution of the Paleo-Tethys Ocean (Torsvik et al., 2012; Wu et al., 2020). Lots of data have been accumulated concerning the Paleo-Tethys evolution in the SCB (e.g., Charvet et al., 2010; Cawood et al., 2017; Wu et al., 2020), while some remain controversial. Studies on the sea-land configuration on the western margin of the SCB (for example, the eastern Yunnan) have been very limited. Since 2018, we have carried out intensive geological field surveys on the widely distributed Middle Devonian sequence in the Qujing area, and discovered a rich collection of fossils, including brachiopods, corals, plants, and fishes. These data, along with previous reports, are of significance for clarifying the distribution and division of the late Middle Devonian strata in the Qujing area, and for understanding the evolution of the Paleo-Tethys Ocean in western SCB.

2. Materials and methods

Severn sections, namely Shangchuanghe, Zhujiangyuan, Gaozhai, Longtan-Chengjiawan, Xiaoqingkou,

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Langmushan, and Zhangjiaying, have been investigated (Figure 1). More than sixty samples have been collected including fossils and rock hand specimens. Samples for petrographic analyses were mainly collected from the Gaozhai section.

In the seven sections mentioned above, abundant fossils have been collected, including plants (from Shangchuanghe, Zhujiangyuan, Gaozhai, and Longtan-Chengjiawan), brachiopods (from Gaozhai, Xiaoqingkou, Langmushan, and Zhangjiaying), crinoids (from Gaozhai, Xiaoqingkou, Langmushan, and Zhangjiaying), corals (from Gaozhai, Xiaoqingkou, Langmushan, and Zhangjiaying) and fishes (mainly are *Bothriolepis* and *Hunanolepis*). The Gaozhai, Zhujiangyuan, and Zhangjiaying sections are more productive.

3. Middle Devonian sequences in Qujing

The Middle Devonian sequence in the Qujing area has been assigned to two stratigraphic subregions, namely the northwest and southeast subregions, based on the differences of lithology (SRGST, 1978). Different researchers put forward different schemes concerning the division and nomenclature of the strata (Table). The Haikou Fm. was initially derived from the Haikou Member, which was firstly named by Deprat (1912). Xie (1941) named the sandstone beds containing *Bothriolepis* near the Haikou Village in Kunming as the Haikou Fm. The Haikou Fm. in Kunming and Qujing is beneath the Zaige Fm. (Liu, 2002). In Zhanyi and Zhujiangyuan, the Haikou Fm. is covered by the Zaige Fm. and overlying the Shangchuanghe Fm. or the Lower Devonian Xitun Fm. (Figure 1C). It is mainly composed of gray, gray-brown, gray-yellow, and gray-white fine-grained quartz sandstones, with *Bothriolepis sinensis*, *Quasipetalichthys Haikouensis*, and *Hunanolepis* sp. and abundant plant fossils (Hou and Wang, 1988; Yunnan Bureau of Geology and Mineral Resources, 1996). The Qujing Fm. was initially derived from the Qujing Group named by Grabau (1923), and the Dongshan section in Qujing measured by V. K. Ting is the stratotype section. It now refers to a set of siliciclastic carbonate rocks above the clastic rocks of the Shangshuanghe Fm. and below the dolomite of the Zaige Fm. or the Carboniferous (Figure 1C). The lithology of this formation includes limestone, marlstone, dolomite, and a small amount of shale. Brachiopods, corals, stromatoporoids, and tentaculitida are common in the Qujing Fm., and amongst, *Stringocephalus burtini*, *Stringocephalus obesus*, *Borhardtina burtiniformis*, *Temnophyllum poshiense*, *Neospongophyllum tabulatum*, *Nowakia otomeri* are typical species of the late Middle Devonian (Yunnan Bureau of Geology and Mineral Resources, 1996). Liao et al. (1978) named the Xichong Fm. to represent the Middle Devonian deposits in Qujing, mainly based on the characteristics

of plants and invertebrate fossils. Previous studies indicate that the Qujing Fm. is late Middle Devonian in age (Yunnan Bureau of Geology and Mineral Resources, 1996). However, it is still controversial whether or not the Haikou Fm. includes deposits of early Middle Devonian or whether or not it is contemporaneous with the Qujing Fm. (Liu, 2002; Shen, 1991; SRGST, 1978). In addition, some studies suggested that the Haikou Fm. is part of the Qujing Fm., and thus the Haikou Fm. is subordinate to the Qujing Fm. (Liu and Wang, 1973).

4. Characteristics of late Middle Devonian sequence around the Qujing area

Our fieldwork on typical outcrops in the Qujing area shows that the rocks of the upper Middle Devonian vary from section to section. The late Middle Devonian strata in the Shangshuanghe and Zhujiangyuan sections, north of the Qujing area, are assignable to the Haikou Fm., which is characterized by sandstone and argillaceous rocks (Figure 1A). The late Middle Devonian deposits in the Gaozhai section are obviously different from the traditional Haikou Fm. in lithologic assemblages, with some characteristic carbonate components intercalated at the bottom and a trend of gradual increase of carbonate intercalation to clastic rock at the top (Figure 1B). The clastic rocks in the Xiaoqingkou section, east of the Qujing area, show a transitional trend to typical marine carbonate rocks (i.e. the Qujing Fm.). In Langmushan and Zhangjiaying sections, several kilometers south of the Xiaoqingkou section, the Qujing Fm. is mainly consisted of carbonate rocks overall (Figure 1B).

It can be inferred that, from north to south of the Qujing area, the late Middle Devonian deposits show a transition trend of decreasing siliciclastic components and as offset, increasing carbonate components (Figure 1B):

(1) The typical Haikou Fm. exposes in the Shangshuanghe, Zhanyi, and Zhujiangyuan sections. The lithology is mainly composed of quartz sandstone, with plant fossils such as *Lepidodendropsis* (Figures 2A, 3A).

(2) In the Gaozhai section, bioclastic carbonates occur in the bottom of the Haikou Fm., which is mainly composed of detrital components. Here, the CA/CL value is ca. 1:10, where CA is the cumulative thickness of carbonate rocks and CL is the cumulative thickness of siliciclastic rocks. The lithology is dominated by marlstone, which locally changes to muddy and sandy limestone (Figure 2B).

(3) In the Longtan-Chenjiawan section, the thickness of carbonate rocks increases, where carbonate and clastic strata are interbedded partially, but clastic rocks are still predominant (the CA/CL value is ca. 1:4), with abundant plant fossils (Figures 2C, 3D).

(4) In the Xiaoqingkou section, the proportion of carbonates increases further, and the CA/CL value closes

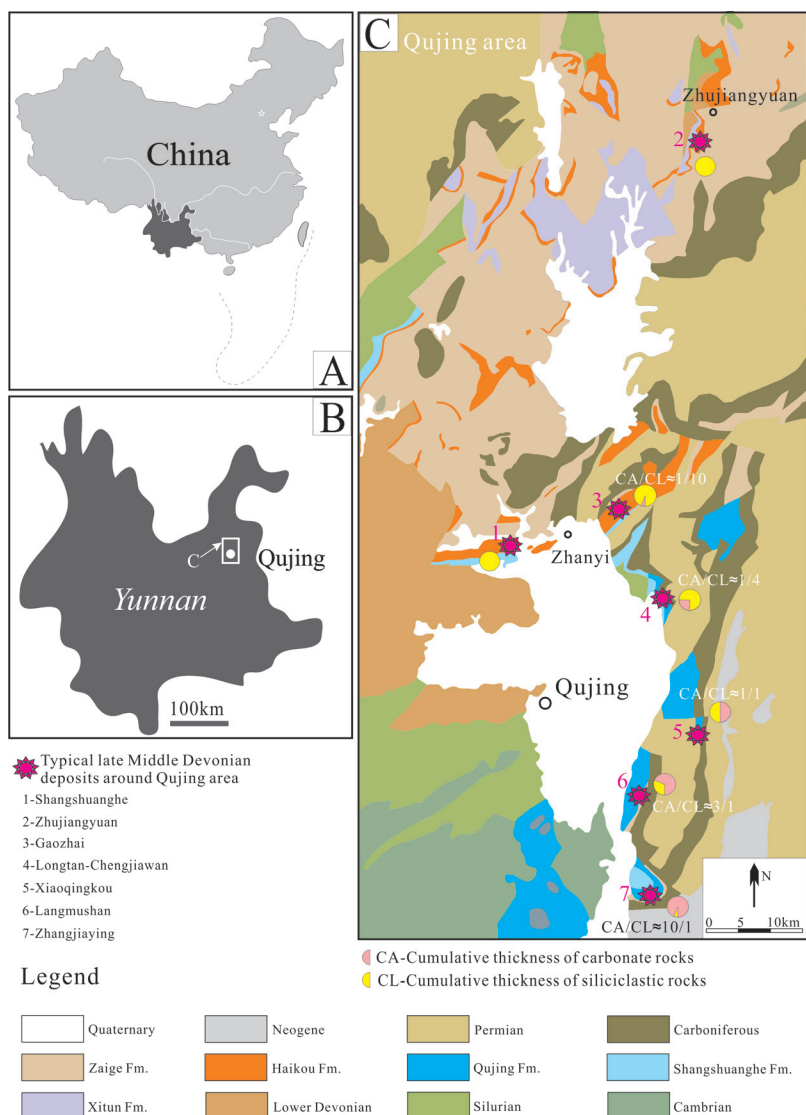


Figure 1. (A-B) Location of the study area (Qujing, eastern Yunnan, China); **(C)** Sketched geological map around Qujing, showing the location of seven representative sections of the Haikou or Qujing Formation.

to 1:1. Invertebrate fossils are common in the clastic rocks that are interbedded with carbonate rocks (Figures 2D, 3E).

(5) Further south to Langmushan, carbonate rocks become the dominant deposits, with interbedded shale at the bottom, and the CA/CL value is ca. 3:1. Fossils of invertebrates such as corals and brachiopods are common (Figures 2E, 3F).

(6) In the Zhangjiaying section, the southernmost part of the Qujing area, the deposits of the late Middle Devonian are predominantly carbonate rocks (Figure 2F). The CA/CL value is ca. 10:1.

In addition, according to regional geological investigations (SRGST, 1978), the late Middle Devonian

deposits in the Yangtianchong section, about 8 km northeast from Longtan, belong to the Qujing Fm. dominated by carbonate rocks.

The transition from clastic rocks dominated in the Haikou Fm. to carbonate rocks dominated in the Qujing Fm. at Gaozhai is particularly typical (Figures 2B; 3G~J). The rock sample GZT1-2 is mainly clastic, with quartz, a small amount of feldspar, muscovite and argillaceous, the fine sand grains are angular and 0.03-0.1 mm in size, and the grains are filled and cemented by argillaceous cement (Figure 3G). The sample GZT3-1 shows abundant dolomites, and the mineral grains are primarily cemented by dolomitic composition (Figure 3H). Nevertheless, in the sample GZT4-1 at the bottom of the section, the

Table. The stratigraphic division history of the Middle Devonian in Qujing.

Northwest subregion						
Wang (1942)	Fang (1963)	Zhang(1966)	Liu and Wang (1973); Pan et al. (1978)	Liao et al. (1978)	SRGST, 1978	Duan (1979)
Middle Devonian	Haikou member	Haikou Fm.	Haikou Fm.	Xichong Fm.	Haikou Fm.	Haikou Fm.
		Nanpanjiang Fm.	Chuangdong Fm.		Shangshuanghe Fm.	Shangshuanghe Fm.
					Xiashuanghe Fm.	Chuangdong Fm.
Northwest subregion						Southeast subregion
Yang et al. (1981)	Cai and Li (1982)	Wang (2000)	Zhu and Wang (1996); Hou and Wang (1988)	Zhao and Zhu (2010)	Peng et al. (2016)	SRGST, 1978
Haikou Fm.	Xichong Fm.	Haikou Fm.	Haikou Fm.	Haikou Fm.	Shangshuanghe Fm.	Qujing Fm.
Shangshuanghe Fm.	Chuangdong Fm.	Shangshuanghe Fm.	Chuangdong Fm.	Shangshuanghe Fm.		Shangshuanghe Fm.
Chuangdong Fm.		Chuangdong Fm.				

rocks are mainly composed of microcrystalline and sparry dolomites, which are rich in bioclasts, such as spongia, phycophyta, and foraminifera etc. (Figures 2B; 3I-J).

5. Discussion

5.1 Correlation of the late Middle Devonian in the Qujing area

As mentioned above, in the early geological survey documents, the deposits of the late Middle Devonian in Qujing were assigned to two lithological units, namely the Haikou Fm. and the Qujing Fm. Nevertheless, the relationship between the two units is unclear, and the strata exposed in the transition zone between the Qujing and Haikou formations were called the Qingfengsi Fm. in some studies (Shen, 1991). The discussion on the correlation between the late Middle Devonian strata in Qujing, and their spatial distribution and the validity of nomenclature have not been thoroughly carried out so far (Shen, 1991; SRGST, 1978; Yang and Sha, 1990). Yang and Sha (1990) noted the mixed deposition of terrestrial clastic and marine carbonate in the Middle Devonian in Qujing, and held that the two components interspersed and alternated in a small area from north to south in the east of the Qujing area. Accordingly, they proposed the

concept of “mixed rock”, and its petrological characteristics and genesis. Shen (1991) also pointed out that mixed deposition of terrestrial and marine facies occurred in the Givetian age of the Middle Devonian in Qujing.

Fieldworks in the Qujing area and typical rock characteristics revealed in this study demonstrate the occurrence of the “mixed deposition”: a transition trend from siliciclastic-dominated facies to carbonate-dominated facies from the north to south in the Qujing area. Recently, we found fish fossils with similar assemblages in both the Qujing and Haikou formations (unpublished data), which support the above view from the aspect of biostratigraphy. Combined with a variety of new fossils including plants, invertebrates and fish, and in-depth comprehensive stratigraphy research work, it could be able to sort out the problem on detailed correlation on the late Middle Devonian sequence in the Qujing area, and provide a reliable geological basis for the evolution of related paleogeography and palaeoecology.

5.2 Implications for the evolution of the Paleo-Tethys Ocean

When and how did the SCB break up from the Gondwanaland? It is a key question for understanding the evolution of the Paleo-Tethys Ocean. Current data

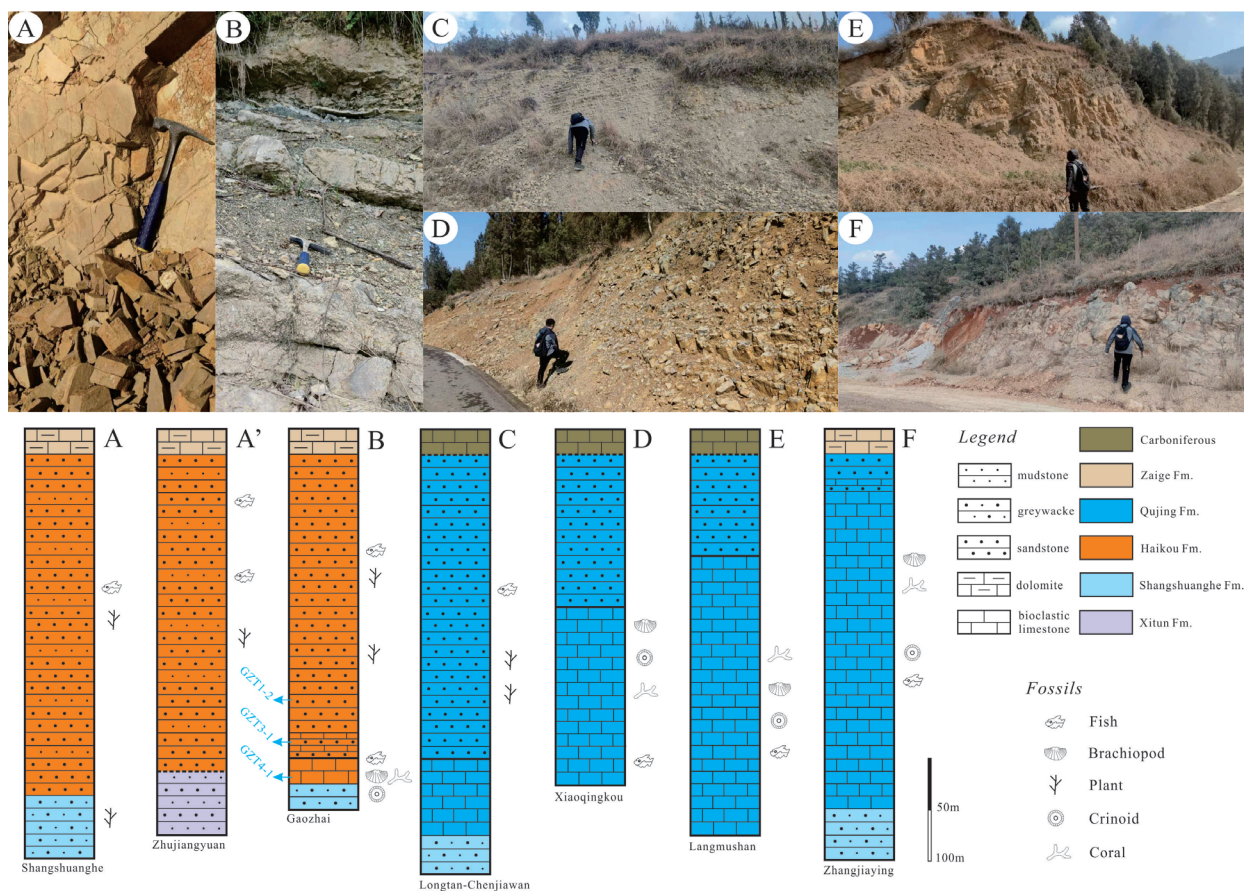


Figure 2. Typical outcrops and sketched lithological columns of late Middle Devonian deposits in Qujing. (A) Quartz sandstone of Haikou Fm. at Shangshuanghe; (B) Gaozhai (CA/CL value approximately 1:10), bioclastic carbonate interlayer at the bottom of Haikou Fm.; (C) Thin bedded bioclastic limestone interbedded in the Haikou Fm. at Longtan-Chenjiawan (CA/CL about 1:4); (D) Carbonate rock intercalated with the clastic rock of the Qujing Fm. (CA/CL value close to 1:1) at the northeast of Xiaoqingkou; (E) Clastic intercalation (CA/CL about 3:1) within carbonate rocks of the Qujing Fm. at Langmushan; (F) Carbonate rocks of the Qujing Fm. at the east of Zhangjiaying (CA/CL value about 10:1).

have proved the affinity between the SCB and the NW Gondwana in the Paleozoic (Collins et al., 2003; Cawood, 2005; Metcalfe, 2013; Khin et al., 2014). Despite the lack of detailed biozonation data such as conodonts to constrain fine-scale stratigraphic correlation, fish assemblages (endemic groups such as yunnanolepid and sinolepid antiarchs, and more widespread groups such as lungfishes, buchanoiteid arthrodiroids, and antiarchs) show a palaeogeographic similarity between the Qujing area and eastern Gondwana during the Early Devonian (Young and Lu, 2020). Paleobotanic data also indicate that, during the Early Devonian, eastern Yunnan and Australia shared a few plants (two *Zosterophyllum* species and three genera namely *Zosterophyllum*, *Baragwanathia*, and *Hedeia*), and these two regions were assigned to the northeastern Gondwanan phytogeographical unit (Hao and Gensel, 1998; Hao and Xue, 2013; Xue et al., 2018). However, the Middle Devonian floras of SCB appear to share no elements

with and are distinct from those of Australia (McLoughlin and Long, 1994; Wang et al., 2007; Xue et al., 2016, 2018), indicating the strong isolation of SCB from Australia that was probably linked to the expansion of the Paleo-Tethys Ocean (Figure 4).

Some detailed descriptions argued for an opening of the Paleo-Tethys Ocean around ~400 Ma (Torsvik et al., 2012; Torsvik and Cocks, 2013; Huang et al., 2018). A recent paleomagnetic study on the Givetian redbeds from central SCB proposed that the SCB was broken up from Gondwana during ~400-385 Ma, accompanied by the southward motion of the Gondwanan and the opening of the Paleo-Tethys Ocean (Xian et al., 2019). The spatial and temporal relationship between the two Middle Devonian lithological units in the Qujing area of southwestern SCB revealed in this study indicates that there was at least a regional sea, as indicated by the distribution of the Haikou/Qujing Fm., that should have existed in east Yunnan on

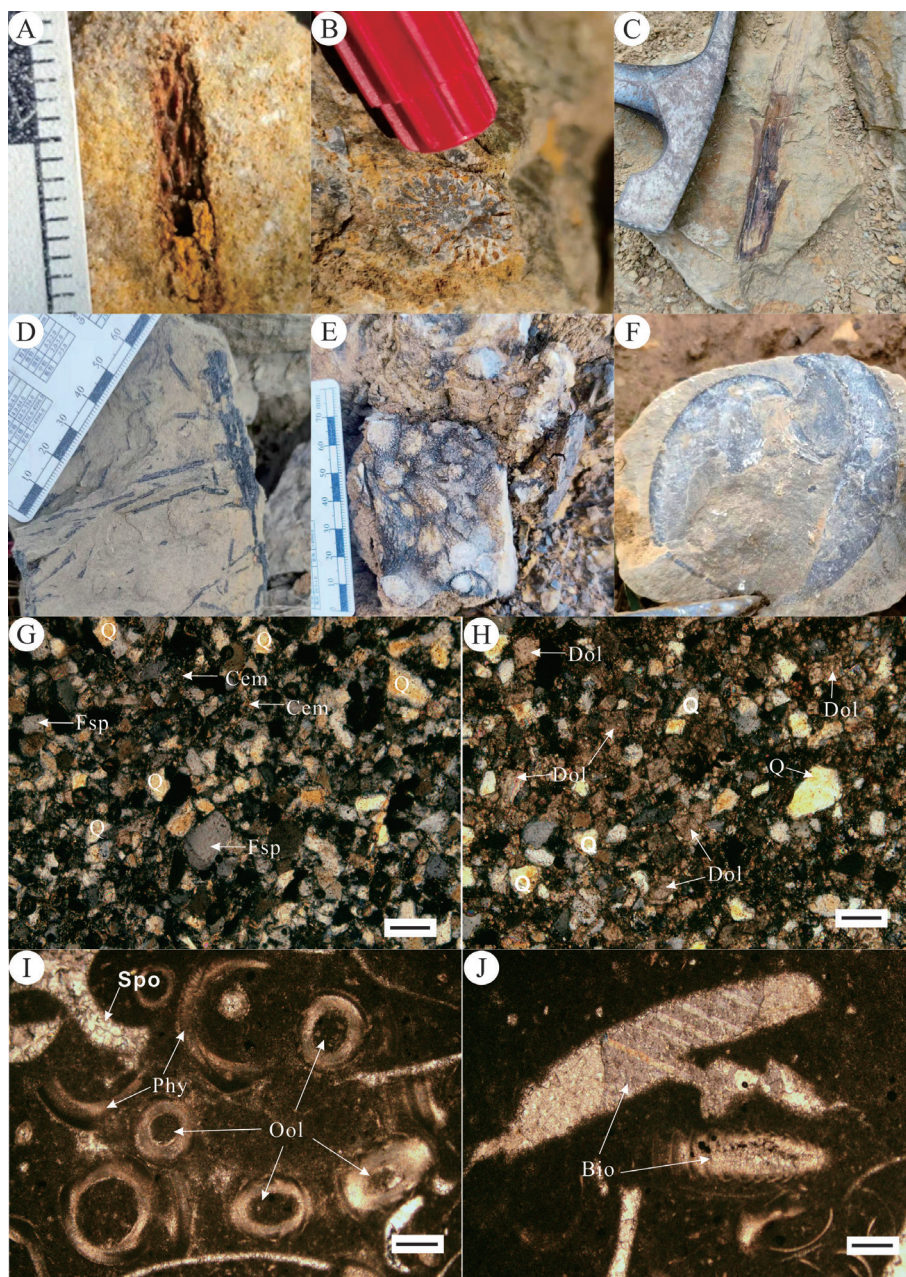


Figure 3. Fossils in the late Middle Devonian deposits of the Qujing area. (A) Plant (*Lepidodendropsis*) from the Haikou Fm. at Shangshuanghe; (B) Coral (*Cystiphyllum*) from clastic limestone in the bottom of the Haikou Fm. at Gaozhai; (C) Plant fossil from the clastic rocks of the Haikou Fm. at Gaozhai; (D) Plant fossil from the clastic rocks of the Haikou Fm. at Longtan; (E) Abundant invertebrate fossils (*Hexagonaria*) in clastic strata of the Qujing Fm. near Xiaoqingkou; (F) Brachiopods (*Stringocephalus*) from the Qujing Fm. at Langmushan; (G~J) Polarizing microscopic characteristics of the rock samples from Gaozhai (G, sample GZT1-2; H, sample GZT3-1; I~J, sample GZT4-1). Q: quartz; Fsp: feldspar; Cem: cement; Dol: dolomite; Spo: spongia; Phy: phycophyta; Ool: oolite; Bio: bioclastic. Black bars in G and H are 100 μm ; in I and J are 200 μm .

the western margin of the SCB during the late Middle Devonian.

As mentioned above, the Haikou Fm. initially defined by Xie (1941) is the horizon containing *Bothriolepis* in eastern Yunnan. *Bothriolepis* is a kind of Placodermi

widely distributed in the world and lived in the Middle to Late Devonian (Pan, 1958; Moloshnikov, 2010; Downs et al., 2016). In terms of invertebrates, *Hexagonaria* and *Cystiphyllum* are common in the Qujing Fm., with a Middle Devonian age (Shen, 1991; Figures 3B, E). The

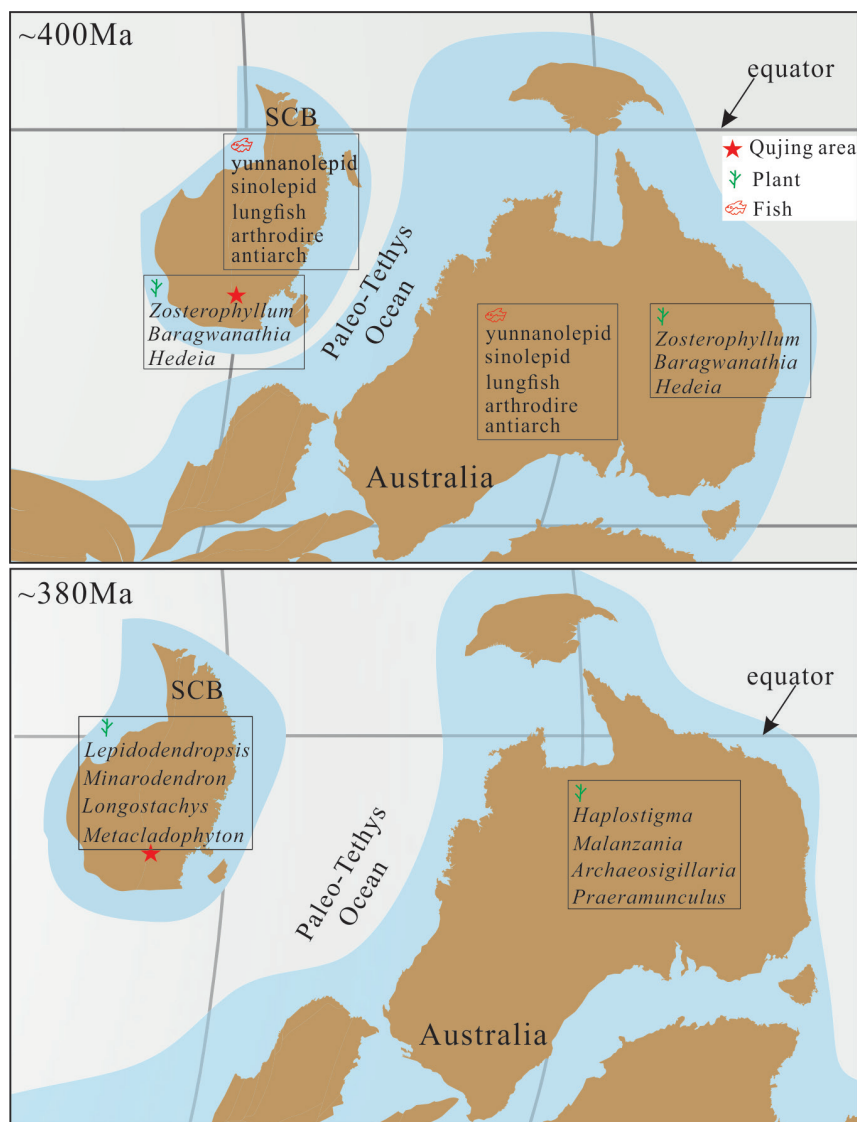


Figure 4. Palaeogeography maps illustrating the location of the South China Block (SCB) during the Early and Middle Devonian times (upper: Early Devonian; lower: Middle Devonian; modified from Huang et al., 2018). The Qijing area is located at the southwestern margin of the SCB. Note that SCB and Australia shared common species during the Early Devonian (e.g., fish: endemic groups and some more widespread groups; plants: two *Zosterophyllum* species and three genera namely *Zosterophyllum*, *Baragwanathia*, and *Hedeia*), belonging to the so-called northeastern Gondwanan phytogeographical unit proposed by Hao and Gensel, (1998); however, during the Middle Devonian (Givetian), different floras developed in South China and Australia (McLoughlin and Long, 1994; Xue et al., 2018).

brachiopod *Stringocephalus*, an index fossil for the late Middle Devonian (Givetian) worldwide, was commonly found in the Qijing Fm. at Langmushan, Qijing (Yoshida et al., 1942; Baranov, 2021; Figure 3F). Besides, the study on plant fossils in Qijing (Wang et al., 2007; Xue et al., 2016) has accumulated abundant data through long-term endeavors. *Lepidodendropsis* and *Colpodexylon* (Ma and Xu, 2017) were commonly found in the Haikou Fm., representing the age of late Middle Devonian (Balinski et al., 2010; Ma and Xu, 2017; Figure 3A). To sum up, the age of the two contemporaneous heterotopic rock units in the

Qijing area in this study can be inferred as the Givetian (late Middle Devonian), and thus collectively indicates that the opening of the Paleo-Tethys Ocean in eastern Yunnan at the west margin of SCB should have initiated before ~380 Ma. Based on previous studies (SRGST, 1978; Ma et al., 2009), a bed of dolomite (could also be observed in the Gaozhai section with a thickness of near 10 cm) is widely developed in the lower portion of the Shangchuanghe Fm. (early Givetian), and a bed of basal conglomerate can be seen at the bottom of the Chuandong Fm. (Eifelian), which in combination indicate that the seawater had existed in

Qujing at least at the beginning of Middle Devonian epoch (~390 Ma). During the late Middle Devonian, as a result of transgression, sea level reached a certain peak in the Qujing area (Ma et al., 2009), as a part of the South China Sea (Hou and Wang, 1985). It can also be inferred that the South China Sea (or regionally, the Qujing Sea) had been an ideal habitat for the blooming of corals, brachiopods, and fishes by the late stage of the Middle Devonian (Givetian; ~380Ma; Figure 4).

A few magmatic and geochemical studies (Dong and Zhu, 1999; Xie, 2002) in the Jianshui area (eastern Yunnan; ~300 km south to Qujing) argued for a branch of the Paleo-Tethys Ocean during the Carboniferous-Permian times, suggesting the late Middle Devonian South China Sea may connect with the Jianshui branch of the Paleo-Tethys Ocean; however, further discussion on the correlation of regional seas in the southwestern margin of the SCB as well as their paleobiogeographic constraints on the evolution of the broad Paleo-Tethys Ocean require more detailed studies.

6. Conclusion

The two late Middle Devonian lithological units, the Haikou Fm. and the Qujing Fm., in the Qujing area are studied.

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