2 Strata

The strata in the Area are the parts of Jiangshan–Lin'an stratigraphic subregion of the Jiangnan stratigraphic region. The exposed strata in the Area include the Nanhuan and Sinian of the Neoproterozoic; the Cambrian, Ordovician, and Silurian of the Paleozoic; the Cretaceous of the Mesozoic; and the Quaternary of the Cenozoic. Among these strata, the Paleozoic and Mesozoic developed the most. A small amount of Neoproterozoic strata outcrop in the middle west part and the east of the Area. The Paleozoic is mainly distributed in the northwest. The Mesozoic is mainly distributed in the southeast. The Quaternary of the Cenozoic is sporadically distributed in the hills in the west and east as well as the valleys in the central and northern part of the Area.

In this Project, 45 lithostratigraphic units were determined including 19 formations and 26 members in the Area based on the division scheme stated in *Lithostratigraphy of Zhejiang Province* (1996) according to lithologic association characteristics and sedimentary environment in the Area through the profile survey and the survey of geological observation traverse. They are described as follows from bottom to up. The Neoproterozoic Nanhuan is divided into Xiuning Formation (Nh_1x) and Nantuo Formation (Nh_2n). The Neoproterozoic Sinian is divided into the Lantian Formation ($Z_{1\text{-}2}l$) and Piyuancun Formation (Z_2p). The Cambrian, Ordovician, and Silurian of the Paleozoic constitute the major exposed strata in the Area. They are successively divided into 13 formations, namely Hetang ($Є_1h$), Dachenling ($Є_1d$), Yangliugang ($Є_2y$), Huayansi ($Є_3h$), Xiyangshan ($ЄOx$), Yinzhubu (O_1y), Ningguo ($O_{1\text{-}2}n$), Hule ($O_{2\text{-}3}h$), Yanwashan (O_3y), Huangnigang (O_3h), Changwu (O_3c), Wenchang (O_3w), and Xiaxiang (S_1x). The Mesozoic Cretaceous contains one formation named Huangjian (K_1h). The Cenozoic Quaternary contains one formation named Yinjiangqiao (Qhy). Some of these formations are further divided into lithological members according to the lithologic association. In detail, Lantian Formation is divided into four members ($Z_{1\text{-}2}l^1$, $Z_{1\text{-}2}l^2$, $Z_{1\text{-}2}l^3$, and $Z_{1\text{-}2}l^4$), Hetang Formation is divided into two members ($Є_1h^1$ and $Є_1h^2$), Yangliugang Formation is divided into two members ($Є_2y^1$ and $Є_2y^2$), Xiyangshan Formation is divided into three members ($ЄOx^1$, $ЄOx^2$, and $ЄOx^3$), Yinzhubu Formation is divided into three members (O_1y^1, O_1y^2, and O_1y^3), Hule Formation is divided into three members ($O_{2\text{-}3}h^1$, $O_{2\text{-}3}h^2$, and $O_{2\text{-}3}h^3$), Changwu Formation is divided into three members (O_3c^1, O_3c^2, and O_3c^3), Xiaxiang Formation is divided into two members (S_1x^1 and S_1x^2), and Huangjian Formation is divided into four members (K_1h^1, K_1h^2, K_1h^3, and K_1h^4). Therefore, there are 26 members in total in the Area (Table 2.1 and Fig. 2.1). For some lithological strata with special significance, such as potassium-bearing bentonite developing in Huangnigang Formation as well as the siltstone-bearing siliceous nodules and the black carbonaceous shale-bearing sponge and graptolite fossils in the middle part of Wenchang Formation, they were surveyed as informal stratigraphic units in the Project.

The sequence stratigraphic division in the Area was based on the observation data of the outcrops in the surveyed geological profiles. The subsequences and system tracts were divided into third-order sequences. The strata of the Nanhuan and Sinian with poor outcrops and low identification accuracy were divided into the second-order sequences (mesosequences) or sub-second-order sequences (orthosequences). The division criteria proposed by Wang and Shi (1998) were adopted to determine the age ranges of the second-order and third-order sequences. As a result, the age ranges of the second-order sequences (mesosequences), sub-second-order sequences (orthosequences), and third-order sequences (orthosequences) are 30–40 Ma, 9–12 Ma, and 2–5 Ma, respectively.

In terms of biostratigraphic division, the Project focused on the description of the biozones achieved through surveyed geological profiles due to the uneven distribution and the diverse species of the ancient organisms in the strata of the Area. Besides, other strata without available fossils were briefly described by utilizing previous achievements of the

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Table 2.1 Evolution of formations in the area achieved from various lithostratigraphic divisions

Regional geological survey of Lin'an map sheet on a scale of 1:200,000 (1967)		Lithostratigraphy of Zhejiang Province (1996)			Regional geological survey of Xuancheng map sheet on a scale of 1:250,000 (2004)			This Project	
Q_4		Qh	Yinjiangqiao		Qh	Yinjiangqiao		Qh	Yinjiangqiao
J_3	Huangjian	J_3	Huangjian		J_3	Huangjian		K	Huangjian
	Laocun		Laocun			Laocun			
S_1	Anji	S_1	Xiaxiang		S_1	Xiaxiang		S_1	Xiaxiang
O_3	Zhangcun	O_3	Wenchang		O_3	Changwu		O_3	Wenchang
	Yuqian		Changwu						Changwu
	Huangnigang		Huangnigang			Huangnigang			Huangnigang
	Yanwashan	O_2	Yanwashan			Yanwashan			Yanwashan
O_2	Hule		Hule		O_2	Hule		O_2	Hule
	Niushang	O_1	Ningguo			Ningguo			Ningguo
O_1	Ningguo				O_1			O_1	
	Yinzhubu		Yinzhubu			Yinzhubu			Yinzhubu
$\in_3$	Xiyangshan	$\in_3$	Xiyangshan		$\in_3$	Xiyangshan		$\in_3$	Xiyangshan
	Shikongshan		Huayansi			Huayansi			Huayansi
$\in_2$	Yangliugang	$\in_2$	Yangliugang		$\in_2$	Yangliugang		$\in_2$	Yangliugang
$\in_1$	Hetang	$\in_1$	Dachenling		$\in_1$	Dachenling		$\in_1$	Dachenling
			Hetang			Hetang			Hetang
Z_2	Xijianshan	Z_2	Piyuancun		Z_2	Piyuancun		Z_2	Piyuancun
			Banqiaoshan	Lantian		Banqiaoshan	Lantian		Lantian
			Doushantuo		Z_1	Doushantuo		Z_1	
Z_1	Siliting	Z_1	Nantuo		Nh_2	Nantuo		Nh_2	Nantuo
	Zhitang		Xiuning		Nh_1	Xiuning		Nh_1	Xiuning

Area and its surrounding areas, in order to ensure the integrity of the biostratigraphic part in the report. In terms of chronostratigraphic division, the division criteria described in *the Stratigraphic Guide of China and Its Explanation* (*Revision*) (2001) and *Stratigraphic Chart of China* (2014) were referred to. Therefore, the Phanerozoic strata featuring high geological survey degree are divided into stages while other strata are divided into series. The Neoproterozoic strata and Mesozoic volcanic–sedimentary rocks were divided by indicators such as tectonic movements, lithofacies, and isotopes. The Paleozoic strata were divided according to the fossil zones of graptolites, trilobites, brachiopoda, and conchostracans. According to the existing stratigraphic survey of Zhejiang Province, the division standards stated in *Stratigraphic Chart of China* (2014) issued by the National Commission on Stratigraphy of China were adopted for the division of all strata in the Area except for the Cambrian which is still divided into upper, middle, and lower series.

Geochemical analysis (ore-bearing feature) of trace elements in strata is used to analyze the rock spectra collected from the stratigraphic units of different profiles. The statistics of 14 trace elements of various stratigraphic units were made by calculating the arithmetic mean values and concentration coefficients. Vinogradov mean value theorem (1972) was adopted to determine the background value of each trace element. The concentration coefficient (k), the ratio of the mean value to the background value of each element, was divided into three levels: $k < 0.5$, $1.5 > k \geq 0.5$, and k 1.5. Furthermore, in order to discover the regional enrichment and dilution of the elements in each stratigraphic unit,

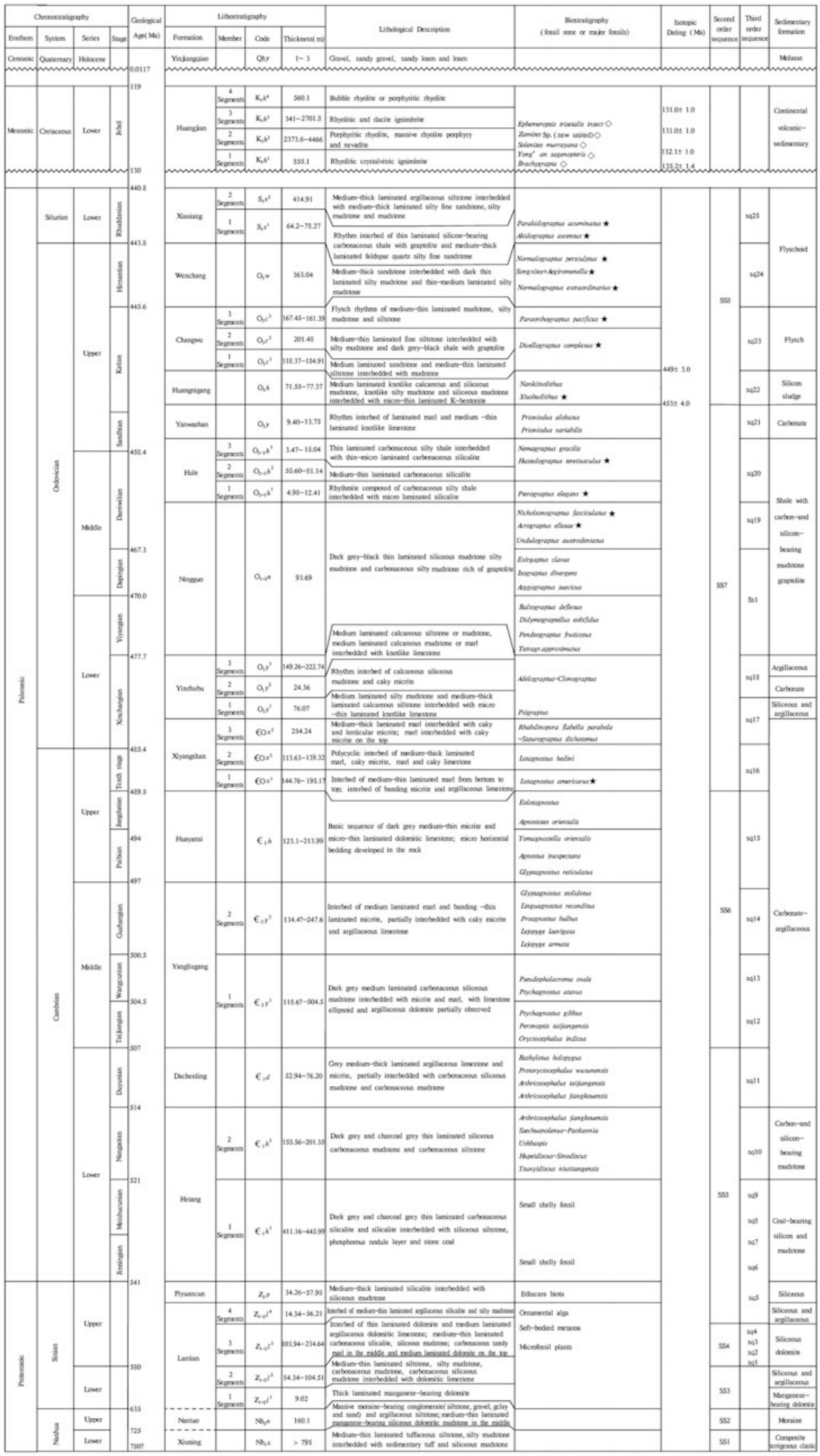


Fig. 2.1 Comprehensive stratigraphic histogram of the area

the mean values of major trace elements in each stratigraphic unit were compared with the background value of strata in the northwest of Zhejiang Province provided in the *Research Report on Regional Stratigraphic Geophysical and Geochemical Parameters of Zhejiang Province* (1991). All enriched elements can pass the normal distribution test, indicating that the content of these trace elements was high in the early stage of sedimentation.

All stratigraphic units will be successively described in the order of lithostratigraphy, sequence stratigraphy, biostratigraphy and chronostratigraphy, event stratigraphy, sedimentary environment, and geochemistry of trace elements in strata (ore-bearing feature).

2.1 Nanhuan System

The Nanhuan System in the Area contains the Xiuning (Nh_1x) and Nantuo (Nh_2n) formations. They are mainly distributed in the external contact zone of Tangshe complex in the southwest corner of Hanggai map sheet, the external contact zone in the north of Xianxia complex in the west of Xianxia map sheet, and the northern part of Gaojiatang Village in the northeast of Chuancun map sheet. The outcrop area is about 23.12 km^2 in total, accounting for 1.82% of the bedrock area.

2.1.1 Xiuning Formation (Nh_1x)

Xiuning Formation was formerly known as Xiuning Sandstone. The name Xiuning Sandstone was created by Yuyao Li in Lantian Village, Xiuning County, Anhui Province, in 1936. Then, it was renamed Xiuning Formation by Yiyuan Qian in 1964 to mean a set of amaranthine and green sandstone occasionally interbedded with celadon argillaceous siltstone. When determining the lithostratigraphy of Zhejiang Province in 1996, Guohua Yu introduced the name Xiuning Formation into Zhejiang Province to be used in the northwestern part of Zhejiang Province to replace Zhitang Formation. In this Project, the name Xiuning Formation (Nh_1x) stated in *Lithostratigraphy of Zhejiang Province* was still adopted according to the characteristics of lithologic association of the Yaocun forest farm profile (PM044) of Hanggai map sheet and the geological observation traverse in the Area.

2.1.1.1 Lithostratigraphy

As the oldest formation in the Area, Xiuning Formation features poor outcrops and undiscovered bottom. The outcrop area is about 10.44 km^2, accounting for 0.82% of the bedrock area.

Regionally, the lithology of Xiuning Formation is characterized by two parts, i.e., the upper part and the lower part of the formation. The lower part consists of celadon tuffaceous silty-fine sandstone and amaranthine feldspar–quartz sandstone interbedded with a small amount of gravel-bearing coarse sandstone and sedimentary tuff. The upper part is composed of celadon and off-white tuffaceous siltstone as well as silty mudstone interbedded with sedimentary tuff. Horizontal, wavy, and veined bedding developed in the rocks. Owing to the Early Cretaceous magmatic intrusion and firing, hornfelsic alteration and lower horizon missing occurred in Xiuning Formation in the Area, leaving an outcrop thickness of 584.6 m.

1. **Stratigraphic section**

The lithology of Xiuning Formation is described by taking the example of Nanhuanian–Xiuning Formation (Nh_1x)–Nantuo Formation (Nh_2n) profile (rough survey) (Fig. 2.2) of Hanggai map sheet in the Yaocun forest farm, Anji County, Zhejiang Province. The details are as follows.

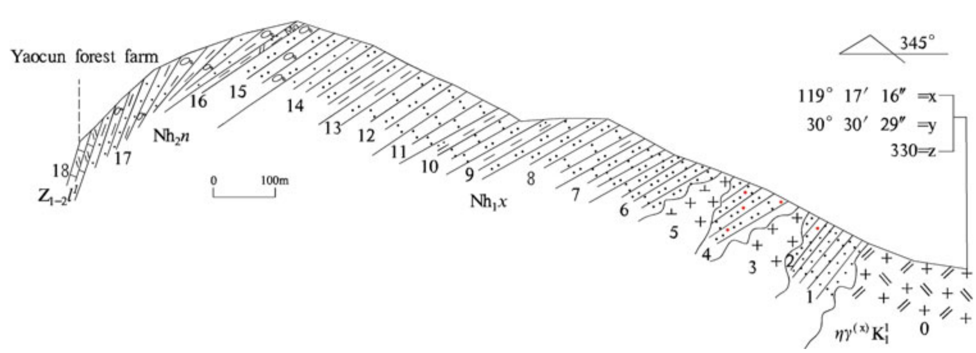


Fig. 2.2 Nanhuanian Xiuning (Nh_1x) Formation–Nantuo (Nh_2n) Formation profile in the Yaocun forest farm, Anji County, Zhejiang Province

Overlying stratum: celadon siltstone bearing moraine conglomerate of Nantuo Formation

-------------------------- Parallel unconformable contact --------------------------

Xiuning Formation Total thickness: 584.6 m

14. Celadon thin–medium laminated siltstone interbedded with silty mudstone, horizontal bedding developing; in the upper part: fine sandstone visible, wavy bedding and tabular cross bedding developing. 88.2 m

13. The upper and lower parts: celadon thin–medium laminated silty mudstone interbedded with a small amount of siltstone, horizontal bedding developing; the middle part: caesious thin–medium laminated argillaceous siltstone interbedded with banded silty mudstone, horizontal bedding developing. 21.1 m

12. Celadon medium laminated sedimentary tuff interbedded with thin banded siltstone, horizontal and wavy bedding developing. 68.5 m

11. Gray medium laminated sedimentary tuff, the thickness of a single layer: 10–30 cm. 49.3 m

10. Gray medium–thick lamellar siliceous mudstone in the upper part, rhythm interbeds of sedimentary tuff and siliceous siltstone in the middle part, tuffaceous siltstone in the lower part, horizontal and wavy bedding developing. 53.1 m

9. Celadon medium–thick laminated tuffaceous siltstone interbedded with thin laminated siliceous mudstone and sedimentary tuff; the sedimentary tuff: dot-shaped, oolite, etc.; horizontal and wavy bedding developing in the layers. 0.9 m

8. In the upper part: celadon medium laminated siltstone interbedded with tuffaceous siltstone; in the lower part: thin laminated argillaceous siltstone; small asymmetric wave ripples developing. 48.4 m

7. Celadon thin–medium laminated tuffaceous siltstone, interbedded with sedimentary tuff and thin laminated siliceous mudstone. 47.8 m

6. Celadon and gray medium laminated tuffaceous siltstone, the thickness of a single layer: 15–30 cm, horizontal bedding developing. 49.7 m

5. Off white fine-grained granodiorite dike.

4. Celadon–gray thick laminated tuffaceous siltstone, hornfelsic fuzzy bedding visible locally, appearing to be rhyolitic vitric tuff. 67.7 m

3. Flesh red fine-grained granite dike.

2. Celadon–gray medium laminated hornfelsic tuffaceous siltstone interbedded with thin laminated hornfelsic tuffaceous siltstone; the thickness of a single layer: 2 –20 cm; broken; silicification developing locally. 18.9 m

1. Rhythm interbeds of modena medium laminated hornfelsic tuffaceous fine sandstone and light celadon sedimentary tuff constitute, interbedded with celadon silty mudstone locally, horizontal and wavy bedding developing. 1.0 m

——————————— Bottom undiscovered ———————————

2. **Lithological Characteristics**

Tuffaceous siltstone, sedimentary tuff, and silty mudstone constitute the main rocks of Xiuning Formation (Nh_1x) in the Area.

The tuffaceous siltstone shows celadon–amaranthine. Felsic minerals are the main mineral components. They are equiaxed granular with a small grain size of less than 0.1 mm. Most of the siltstone is recrystallized due to thermal metamorphism, while there is a small amount still remaining the characteristics of the original rocks. The feldspar and quartz minerals remaining in the original rocks feature well-rounded shape and a slightly larger grain size of 0.1–0.2 mm.

The sedimentary tuff shows gray, mainly consisting of tuffaceous matter (75–80%) as well as siltstone and argillaceous matter (20–25%). The tuffaceous matter generally shows earthy and vitric and fine scaly locally. The siltstone and argillaceous matter have a grain size of 0.01–0.03 mm, mainly consisting of quartz.

The silty mudstone shows celadon, consisting of argillaceous matter (70%) and felsic silty matter (about 30%). The argillaceous matter has been recrystallized to be scaly mica due to thermal metamorphism. The felsic silty matter is distributed unevenly in the rocks, with a grain size of 0.02–0.04 mm.

3. **Basic Sequences**

Xiuning Formation in the Area features lower horizon missing due to rock erosion. It can be divided into two types of basic sequences according to the lithologic association exposed.

Basic sequences of type A: distributed in the lower part of Xiuning Formation, and composed of ① gray–celadon medium laminated tuffaceous (fine) siltstone and ② gray–celadon thin–medium laminated tuffaceous silty mudstone. The respective thickness of the two components is 10–40 cm and about 8–30 cm. Wavy and horizontal bedding developed in the first component, while horizontal bedding developed in the second component (Fig. 2.3a).

Basic sequences of type B: distributed in the middle and upper parts of Xiuning Formation, and composed of ① (fine) siltstone and ② (silty) mudstone. The basic sequences of this type in the middle part of Xiuning Formation are described as follows. They are about 1 cm thick, and the respective thickness of the (fine) siltstone and the (silty) mudstone is 2 mm and 5–8 mm generally. They become thinner or even wedge out sometimes. The grain sizes of the sands or silty sands in them remain unchanged generally, except that they significantly decrease near the contact interface with the underlying clay during gradual transition. Meanwhile, washing occurs on the interface while no sedimentary structures are observed in the argillaceous layer. As for the basic sequences of type B in the upper part of Xiuning Formation, the thickness is increased to be 3–5 mm

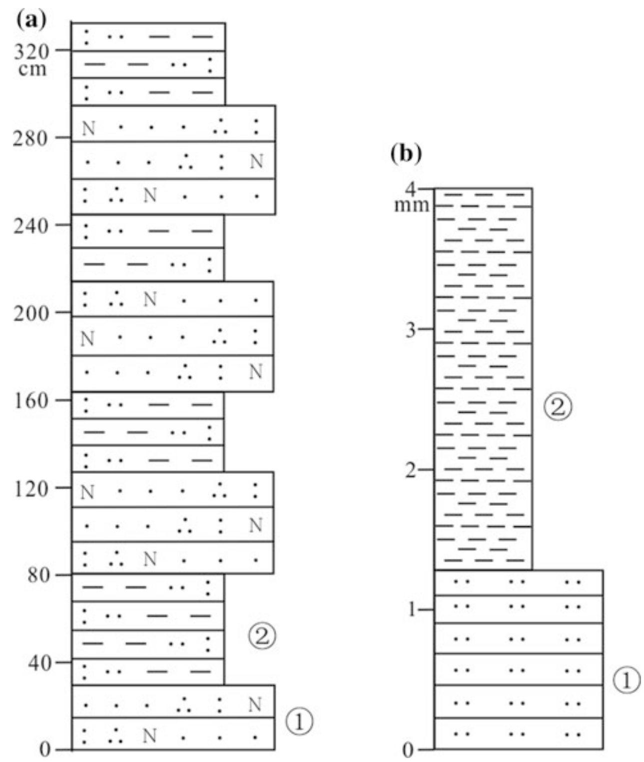


Fig. 2.3 Basic sequences of Xiuning Formation (Nh_1x)

(Fig. 2.3b) with the maximum and minimum values as 8 mm and 2 mm, respectively. Micro-fine horizontal bedding developed in the upper thicker argillaceous layer.

2.1.1.2 Sequence Stratigraphy

According to the characteristics of the lithology and lithofacies association of the profiles as well as the characteristics of the sequence boundary, there is one second-order sequence SS1 in Xiuning Formation.

Second-order sequence SS1

SS1 consists of transgressive systems tract (TST) and highstand systems tract (HST). The bottom of SS1 is missing due to the erosion of Tangshe complex. The top of SS1 is a parallel unconformity interface between silty mudstone and the overlying moraine conglomerate of Nantuo Formation, belonging to type-I sequence boundary. TST is located in the lower part of Xiuning Formation. The major sediments in TST include tuffaceous sandstone, feldspar–quartz sandstone, and tuffaceous silty mudstone, and minor sediments include siltstone, silty mudstone, and sedimentary tuff. Wavy, horizontal, and veined bedding developed in the rock layers of TST. Therefore, the sedimentary environment of TST is of littoral–tidal flat facies. HST is located in the middle and upper part of Xiuning Formation. The main sediments of HST include fine sandstone, siltstone, and mudstone. With micro-fine bedding developing in the layer, TST features the sedimentation of neritic facies. Generally, it is reflected from the sediments in SS1 that in Xiuning Formation, the sea level rose quickly in the lower part, reached the maximum in the middle part, and then gradually fell in the upper part during the period of Xiuning Formation. Therefore, the lower part of the Xiuning Formation is of retrogradation type, and the middle and upper parts of Xiuning Formation are of aggradation and progradation type.

2.1.1.3 Biostratigraphy and Chronostratigraphy

The Nanhuan paleontological research in Zhejiang Province was mainly carried out in the 1980s and focused on the profiles of the areas including Banqiao of Quzhou, Xiayabu of Jiande, Luocun of Fuyang, Heshang of Xiaoshan, Mengshan of Pujiang, and Xiaopokeng of Kaihua. No fossils were obtained in Xiuning Formation of the Area in this Project. According to the *Lithostratigraphy of Zhejiang Province* and the regional geological survey report of Changshan map sheet on a scale of 1:50,000, there are a total of 13 genera and 11 species micro-plant fossils of Xiuning Formation period (i.e., the Early Nanhuan) obtained in Xiayabu of Jiande, Shilonggang of Changshan, and Xiaopokeng of Kaihua. These micro-plant fossils are mainly of single-chlorella communities including *Leiominuscula minuta*, *Leiopsophosphaera densa*, *Lophominuscula prima*, *Lophosphaeridium* cf. *acielatum*, *Piyuanella irregutaris*, *Trachyminuscula* sp., *Trachysphaeridium* sp., *T. minor*, and *Trematosphaeridium* sp. There are also some new filamentous chlorella communities such as *Nostocomorpha prisca*, *Palaeolyngbya* cf. *barghoorniana*, and *Taeniatum verrucatum*. Among these communities, *Taeniatum verrucatum* is a characteristic molecule of the *Taeniatum-turuchanica* micro-plant association in the regions adjacent to the Area, and the geological age is the Early Nanhuan.

2.1.1.4 Analysis of Sedimentary Environment

The lithology of Xiuning Formation in the Area is mainly characterized by tuffaceous fine sandstone, siltstone, silty mudstone, mudstone, and sedimentary tuff. The sandstone in the lower part of Xiuning Formation experienced hornfelsic alteration, due to the thermal metamorphism caused by Mesozoic magma, etc. Horizontal and wavy bedding developed in the feldspar–quartz sandstone of the lower part of basic sequences of type A, indicating that water movement was strengthened by waves. Besides, the sands constitute the major rocks of the feldspar–quartz sandstone, reflecting the sedimentation of littoral neritic facies in the sand flats near and below the low water line under high-energy environment. Extremely thin and unstable argillaceous sediments tend to be deposited above the sandstone. They are low-energy sediments during slack water period, i.e., double-clay layer. The argillaceous layer with horizontal bedding developing in the upper part belongs to mudflat sedimentation of the supratidal zone during slack water period of high water. The thin silt layer was brought about by the extremely large tides. Therefore, the basic sequence of type B is of tidal flat sedimentation. Horizontal bedding is visible in the basic sequence, indicating that aggradation occurred. Besides, the sediments feature gradually smaller grain sizes and become silt, indicating the possible accumulation in low-lying areas on continental shelf.

2.1.2 Nantuo Formation (Nh_2n)

The name Nantuo Formation, formerly known as Nantuo Tillite, was created by Blackwelder et al. (1907) in Liantuo Town, Yichang City, Hubei Province, and used to mean the sandy and argillaceous tillite layer lying beneath a large set of limestone. It was introduced by Li and Zhao (1924). Yu (1996) introduced it to the northwestern part of Zhejiang Province to replace Leigongwu Formations. In this Project, the name Nantuo Formation (Nh_2n) stated in *Lithostratigraphy of Zhejiang Province* was still adopted according to the characteristics of lithologic association of the profile (PM044) of the Yaocun forest farm of the Hanggai map sheet in the Area and the geological observation traverse.

2.1.2.1 Lithostratigraphy

Nantuo Formation is associated with Xiuning Formation. The outcrop area of Nantuo Formation is about 12.68 km^2, accounting for 1% of the bedrock area.

Lithologic association of Nantuo Formation is characterized by the following three parts. The lower part of Nantuo Formation consists of caesious–celadon siltstone-bearing moraine conglomerate and silty mudstone. In this part, the grain size is 1–25 cm and the components mainly include granite and dolomite. Besides, there is a small amount of silicalite. The thickness of this part is 46.70 m. The middle part of Nantuo Formation is composed of gray thin–medium laminated siltstone and fine sandstone. In this part, horizontal bedding developed and the thickness of this part is 8.0 m. The upper part of Nantuo Formation consists of gray–celadon blocky siltstone-bearing moraine conglomerate clay. In this part, the grain size of the conglomerate is 0.5–15 cm or even 20 cm, and major and minor components of the conglomerate are dolomite and granite, respectively. The thickness of this part is 65.70 m.

1. **Stratigraphic section**

The lithology of Nantuo Formation is described by taking the example of Nanhuanian Xiuning Formation (Nh_1x)–Nantuo Formation (Nh_2n) profile (rough survey) (Fig. 2.2) of the Hanggai map sheet in the Yaocun forest farm, Anji County, Zhejiang Province. The details are as follows.

Overlying stratum: gray dolomitic limestone of the first member of Lantian Formation

------------------------------Parallel unconformable contact--------------------------

Nantuo Formation Total thickness: 120.4 m

17. Celadon blocky siltstone bearing moraine conglomerate; the content of the conglomerate in the siltstone: 3%; the conglomerate: angular, grain size: 0.5–15 cm or even 20 cm, components: dolomite (major) and granite (minor); the dolomite: hollow due to weathering, with argillaceous cementation. 65.7 m

16. Gray thin laminated argillaceous siltstone and fine sandstone, horizontal bedding developing. 8.0 m

15. Celadon siltstone bearing moraine conglomerate; the content of the conglomerate in the siltstone: 5%–10%; the conglomerate: angular–subangular, grain size: 1–5 cm, components: granite and dolomite (major) and silicalite (minor). 6.7 m

------------------------------Parallel unconformable contact--------------------------

Underlying stratum: celadon thin–medium laminated siltstone interbedded with silty mudstone of Xiuning Formation.

2. **Lithological characteristics**

The lithology of Nantuo Formation (Nh_2n) is mainly characterized by siltstone-bearing moraine conglomerate as well as silt and fine sandstone.

The siltstone-bearing moraine conglomerate: argillaceous cementation; components: sands (major) and moraine-bearing conglomerate (major); the sands: accounting for up to about 60–65%; grain size: silt and fine sand (major) and medium sands (a small amount); the components: quartz and feldspar; the argillaceous matter in the siltstone: concentrating locally, may be moraine-bearing conglomerate.

The silt and fine sandstone: subangular and subrounded; grain size: 0.01–0.25 mm; components: feldspar, quartz, and detritus; the detritus: rounded; grain size: less than 1 mm, contact and porous cementation available for argillaceous matter.

3. **Basic Sequences**

There are two types of basic sequences in Nantuo Formation according to the lithologic association of the profile (Fig. 2.4).

Basic sequences of type A: gray (silty) moraine-bearing sandstone; no sedimentary structures developing in the rock layers; the gravel: accounting for about 5% in the sandstone, angular–subangular; component: silicalite; grain size: 1–15 cm or even 25 cm. Therefore, the gravel features poor rounding, seriously different sizes, and random distribution. Furthermore, it can be observed from part outcrops that the gravel cuts along the bedding. Therefore, it can be concluded that the gravel came from falling from air but not movement and sedimentation with the detritus. Thus, very possibly, the gravel was carried to basin by ice rafting and then fell into fine-silty sediment after ice melted.

Basic sequences of type B: gray siltstone and fine sandstone; composition: silty-fine detritus; micro-fine horizontal bedding developing; no gravel visible; belonging to shallow shelf sedimentation of interglacial period.

2.1.2.2 Sequence Stratigraphy

According to the characteristics of the field survey of geological observation traverse as well as the lithology, lithofacies association, and sequence boundary of related profile (rough survey), there is one second-order sequence SS2 in Nantuo Formation in the Area. The internal structure of SS2 is described as follows:

Second-order sequence SS2

SS2 contains TST, starved section (CS), and HST. The bottom of SS2 is a parallel unconformity interface between the siltstone-bearing moraine conglomerate and the underlying silty mudstone of Xiuning Formation. The top of SS2 is a parallel unconformity interface between the conglomerate-bearing silty mudstone of Nantuo Formation and the overlying manganese-bearing dolomitic limestone of the first member of Lantian Formation. Both the top and the bottom are of type-I sequence boundary. TST is located in the lower part of the Nantuo Formation. The sediments of TST mainly consist of angular and subangular siltstone-bearing moraine conglomerate, and the main components are granite and dolomite. CS is located in the middle

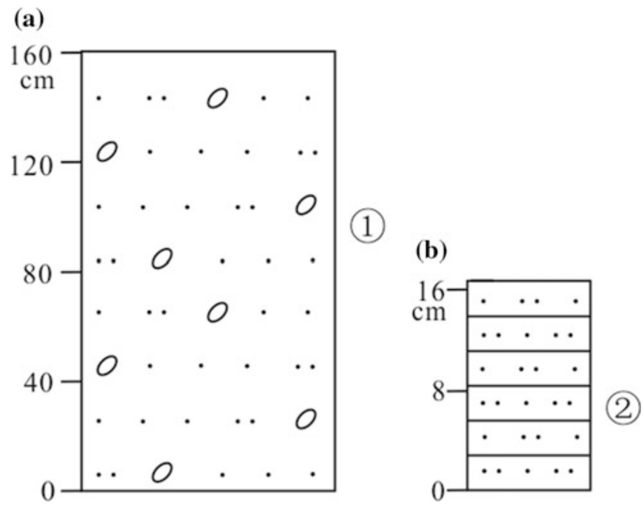


Fig. 2.4 Basic sequence of the Nantuo Formation (Nh_2n)

part of Nantuo Formation. After the early glacial period of the Nantuo Formation, the climate gradually became warm and the continental shelf sedimentary environment started in the Area. After glaciers melted, the water became deeper. As a result, the sediments decreased sharply, leaving thin sediments. HST is located in the upper part of Nantuo Formation. The siltstone-bearing moraine conglomerate constitutes the main rocks of HST. Compared with the bottom of SS2, HST features less and smaller conglomerate, indicating weaker glaciation. The sedimentary environment of this sequence successively experienced glacial period, interglacial period, and glacial period again. The age range of this sequence is 725–635 Ma, with a time span of 90 Ma. Therefore, the sedimentation time is relatively long.

2.1.2.3 Biostratigraphy and Chronostratigraphy

There are no fossils obtained in Nantuo Formation in the Area in this Project. According to previous data, there are 13 genera and 14 species of micro-plant fossils of the glacial period of Nanhuan Formation (i.e., the Early Nanhuan) obtained from Xiayabu of Jiande (Zhejiang Bureau of Geology 1965). These microfossil plants mainly include the following recurring single-chlorella communities such as *Trachysphaeridium minor*, *Trachyminuscula* sp., *Lophospaeridium* cf. *acielatum*, *Lophominuscula prima*, *Leiopsophosphaera densa*, *Leiominuscula minuta*, *Granomarginata prima*, *Asperatopsophosphaera* sp., *Nucellosphaeridum* sp., *Paleomorpha punctulata*, and *Bavlinella faveolata*. Besides, there are new spinous alga communities such as *Micrhystridium minimum*, *M. obtusum*, *M. odontodum*, and *Cymatiosphaera* sp. During the interglacial period of Nantuo Formation (i.e., the middle period of the Late Nanhuan), paleobiocenosis changed slightly and the microfossil plants obtained in the Xiayabu, Jiande, include *Leiominusculaminuta*, *Trachyminuscula* sp., *Lophominuscula prima*, *Leiopsophosphaera densa*, *Bavlinella faveolata*, *Polyporata obsoleta*, and *Paleamorpha puctulata*. In the second glacial period of Nantuo Formation (i.e., the late period of the Late Nanhuan), the microfossil plants obtained in Xiayabu, Jiande, include *Lophominuscula prima*, *Leiomarqinata* sp., *Margominuscuis* sp., *Granomarginata* cf. *prima*, *Leiopsophosphaera sp.*, *L. densa*, *Trachysphaeridium* sp., and *Polyporata obsolete.* In the Late Nanhuan, most microfossil plants were still single-chlorella communities, but some microfossil plants of new genera and species appeared including *Nucellsphaeridium*, *Granomarginata*, and *Bavliella*. Besides, spinous chlorella communities also appeared in this period such as *Gymatiosphaera* and *Micrhystridium*. Some genera and species such as *Bavlinella* are significant in comparison between regions and continents. In general, from the Early Nanhuan to the Late Nanhuan, the appearance of micro-plant association experienced slight changes which mainly include more species and more composite types.

Owing to the absence of Nanhuan fossils, stratigraphic division and comparison are mainly based on regional comparable geological events and absolute ages of related geological bodies. This requires that the division of the Nanhuan in the Area should be discussed within the northwest Zhejiang or even wider range. From bottom to top, the Nanhuan in the Area is divided into Xiuning Formation and Nantuo Formation. It is a set of highly maturated littoral neritic clastic rock–glacial rock system with small thickness (relative to the long duration of nearly 120 Ma). The weak differentiation of the lithofacies itself of the rock system in the Area indicate that the superficial part of the continental crust was at a loose and (sub-) stable state. The transgressional event in the Early Nanhuan is comparable in the whole of South China. According to previous studies, the ages obtained by zircon U-Pb isotopic dating in Xiuning Formation in Xiayabu, Jiande, the southwest Zhejiang, were 780 ± 10 Ma–776 ± 12 Ma (Yin et al. 2007), 759 ± 6 Ma (Gao et al. 2014), and 735 ± 14 Ma (Wang et al. 2015), respectively. That is, the transgressional event in the Early Nanhuan was the extensive transgression event around 750 Ma indicated by the bottom of Xiuning Formation. The glacial event in the Late Nanhuan (around 680 Ma) is prominent in the history of the earth, and it involves two glacial periods and one interglacial period. The moraine-bearing sediment in this period is comparable globally. According to the study on west Hunan Province–southwest Hubei Province area conducted by Yang et al. (1997), the Sm–Nd isochron age of the manganese carbonate deposit in the interglacial period of Nantuo Formation is 696 ± 52 Ma.

2.1.2.4 Analysis of Sedimentary Environment

In conclusion, Nantuo Formation of the Late Nantuo is of moraine formation. In the early and late periods of the Late Nantuo, the Area experienced two glacial events and thus

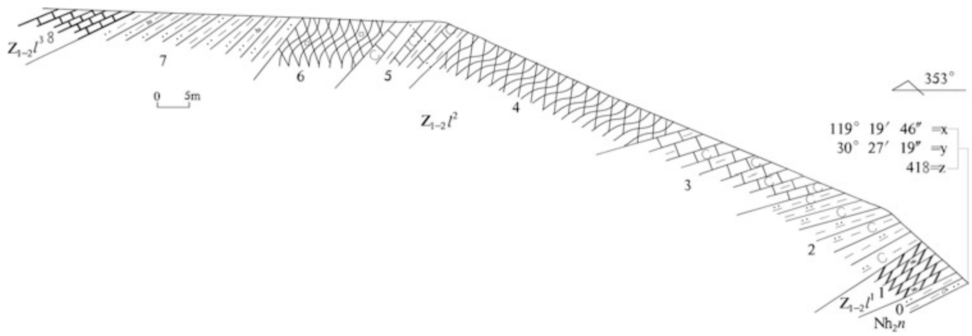


Fig. 2.5 First member ($Z_{1\text{-}2}l^1$)–second member ($Z_{1\text{-}2}l^2$) profile of Lantian Formation in Yeshanwu, Xianxia Town, Ningguo City, Anhui Province

can be divided into two glacial periods and one interglacial period. As a result, two different types of sedimentary rocks were deposited. The sedimentary rocks of the early and late periods were a set of caesious thick laminated and blocky formation of mudstone-bearing moraine conglomerate. With complex components as well as poor sorting and rounding, the conglomerate in the formation is the product of composite sedimentation formed when the moraine fell into the ocean due to the melting of the ice rafting or glaciers. This reflects a sedimentary environment of nearshore neritic transitional zone with weak hydrodynamic force. In the middle period of the Late Nantuo, the grayish silty-fine sandstone formation was deposited, indicating that the climate got warm, the glaciers melted, and the neritic deep shelf sedimentary environment had started.

2.2 Sinian System

The Sinian in the Area is mainly exposed in the west and distributed in the surrounding areas of Tangshe complex as well as the northern part of Xianxia complex including Zhangli, Shimen, Baishawu, Pingtoushan, and Kongfuguan–Taoshuwan–Waijianzi area. The outcrop area is about 29.49 km^2, accounting for 2% of the bedrock area. The middle and lower parts of the Sinian are classified under Lantian Formation ($Z_{1\text{-}2}l$), which is further divided into four members according to the lithologic association. The upper part of the Sinian is classified as Piyuancun Formation (Z_2p).

2.2.1 Lantian Formation ($Z_{1\text{-}2}l$)

The name Lantian Formation was created by Ding (1935) in Lantian Village, Xiuning County, Anhui Province, to mean a set of clastic and carbonate rock association below Shangchangyuan limestone (silicalite in Piyuan Village), which is above moraine layer. The Sinian in Zhejiang Province was highly researched in the 1950s. Xinfu Sheng established the Xifengsi Siliceous Shale in 1959, and Liu Hongyun and Sha Qing'an plotted the profile of the shale and named it Xifengsi Series in the same year. In 1965, Xifengsi Series was renamed Xifengsi Formation by Zhejiang Regional Geological Survey Team. In 1982, the Precambrian System Special Group of Zhejiang Regional Geological Survey Team introduced Dengying Formation and Doushantuo Formation, which were widely used in South China. In 1996, the Sinian in Jiangshan–Lin'an stratigraphic subregion was divided into Lantian Formation and Piyuancun Formation in *Lithostratigraphy of Zhejiang Province*. In this Project, the division scheme of Lantian Formation as described in *Lithostratigraphy of Zhejiang Province* was still adopted according to the characteristics of lithologic association of Nanchewu profile (PM010) of Hanggai map sheet, Dalingtou profile (PM037), Ligu'an profile (PM039), and Yeshanwu profile (PM031) in Xianxia map sheet, and the geological observation traverse within the Area.

2.2.1.1 Lithostratigraphy

The Lantian Formation in the Area mainly outcrops in the surrounding areas of Tangshe complex in the southwest corner of Hanggai map sheet and in the northwest part of Xianxia map sheet including Zhangli Village, Baishawu, Ligu'an, and Damiao–Zhaojia area discontinuously. It is distributed in "U" shape with an SW-trending opening in general. The outcrop area is about 29.49 km^2, accounting for 1.69% of the bedrock area.

The first Member of Lantian Formation ($Z_{1\text{-}2}l^1$): grayish black medium laminated argillaceous dolomitic limestone-bearing manganese and carbon. The rocks are heavily weathered and become brown wadite. The thickness of the member is 9.02 m.

The second member Lantian Formation ($Z_{1\text{-}2}l^2$): gray and dark gray thin–medium laminated argillaceous siltstone and silty mudstone, interbedded with thin–medium laminated and lenstoid carbonaceous limestone in the middle and lower parts. The thickness of the carbonaceous limestone layer varies greatly. In the silty mudstone, a small amount of fine-grained pyrite and horizontal bedding developed. The thickness of this member is 84.34–104.51 m.

The third member of Lantian Formation ($Z_{1\text{-}2}l^3$): The lower part is the interbed of grayish–off-white thin–medium laminated dolomite and gray argillaceous limestone, locally interbedded with medium laminated micrite. The medium part is gray and dark gray medium–thick laminated carbonaceous siliceous limestone and argillaceous limestone interbedded with black thin–medium laminated carbonaceous argillaceous silicalite. The upper part is gray–dark gray medium–thick laminated limy dolomite and dolomitic limestone interbedded with a small amount of dark gray thin laminated siliceous mudstone, and sandy dolomite can be observed occasionally. The thickness of the member is 103.94–234.64 m.

The fourth member of Lantian Formation ($Z_{1\text{-}2}l^4$): gray–dark gray thin laminated siliceous mudstone and carbonaceous siliceous mudstone, generally 2–10 cm and occasionally 20–30 cm thick per layer. Horizontal bedding develops. The thickness of this member is 14.34 m.

1. **Stratigraphic section**

The characters of the lithology and lithologic association of the first member and the second member of Lantian Formation are described by taking the example of the first member ($Z_{1\text{-}2}l^1$)–the second member ($Z_{1\text{-}2}l^2$) profile (Fig. 2.5) of Lantian Formation in Yeshanwu, Xianxia Town, Ningguo City, Anhui Province. The details are as follows:

The third member of Lantian Formation ($Z_{1\text{-}2}l^3$) Total thickness: >7.45 m

8. Off-white thin–medium laminated marbleized dolomitic limestone, very thin horizontal bedding developing, the thickness of single rock layer: 5–20 cm. 7.45 m

——— Conformable contact ———

The second member of Lantian Formation ($Z_{1\text{-}2}l^2$) Total thickness: 84.34 m

7. Dark gray hornfelsic silty mudstone containing fine-grained disseminated pyrite (1%–3%). They become speckled hornfels due to thermal alteration. 21.79 m

6. Off-white thin–medium laminated silty mudstone, containing fine-grained disseminated pyrite (5%–8%). They become speckled hornfels due to thermal alteration. 9.00 m

5. Interbed consisting of dark gray medium laminated siliceous mudstone and off-white carbonaceous limestone. The siliceous limestone contains a small amount of disseminated pyrit 8.27 m

4. Dark gray–grayish-black thin–medium laminated carbonaceous siliceous mudstone. They become speckled hornfels due to thermal alteration. 18.57 m

3. Grayish–off-white thin–medium laminated argillaceous limestone, containing sparse disseminated pyrite. Weakly tremolitized alteration occurs due to thermal action. The thickness of a single rock layer: 5–30 cm. 11.27 m

2. Dark gray–grayish black thin–medium laminated carbonaceous siliceous mudstone, containing a small amount of sparse fine-grained pyrite. 15.44 m

——— Conformable contact ———

The first member of Lantian Formation ($Z_{1\text{-}2}l^1$) 9.02 m

1. Grayish black medium laminated manganese-bearing dolomitic limestone, mainly containing calcite and some dolomite. A small amount of white net-veined quartz stringer of later period developed. A small amount of brown earthy weathered materials, i.e. wadite, are visible on the ground surface. 9.02 m

- - - - - Parallel unconformable contact - - - - -

Nantuo Formation of Later Nanhuan Epoch (Nh_2n) Total thickness: > 1.02 m

0. Gray, blocky-laminated conglomerate-bearing silty mudstone, mainly consisting of mud (70%), some silt (20%–25%) and gravel (5%–10%). The size of the conglomerates varies greatly, with grain size of 2–150 mm. The conglomerates are angular and sub-rounded and are unevenly distributed. 1.02 m

The characters of the lithology and lithologic association of the third member and the fourth member of Lantian Formation are described by taking the example of the third member ($Z_{1\text{-}2}l^3$)–the fourth member ($Z_{1\text{-}2}l^4$) profile (Fig. 2.6) of Lantian Formation of Hanggai map sheet in Nanchewu, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Piyuancun Formation (Z_2p) Total thickness: > 1.28 m

26. Dark gray and grayish-black thick laminated–blocky argillaceous silicalite. 1.28 m

——— Conformable contact ———

The fourth member of Lantian Formation ($Z_{1\text{-}2}l^4$) Total thickness: 56.21 m

25. Gray thin laminated carbonaceous siliceous mudstone, locally interbedded with medium laminated silicalite. 1.78 m

24. Grayish black medium–thick laminated carbonaceous argillaceous silty silicalite. 7.81 m

23. Gray thin–medium-thickness silty silicalite. 19.54 m

22. Dark gray and grayish-black thin laminated carbonaceous silicalite. 15.76 m

21. Grayish black medium–thin laminated carbonaceous siliceous mudstone, interbedded with a layer of argillaceous limestone with the thickness of about 0.5m thick in the lower part. 11.32 m

——— Conformable contact ———

The third member of Lantian Formation ($Z_{1\text{-}2}l^3$) Total thickness: 234.64 m

20. Dark gray medium laminated limy dolomite. The thickness of a single layer is generally 10–30 cm. 17.94 m

19. Interbed consisting of gray medium laminated dolomitic limestone and thin laminated marlstone. 7.97 m

18. Dark gray medium laminated micrite dolomite. 13.89 m

17. Dark gray thick laminated blocky micrite dolomite interbedded with micro-thin laminated sandy dolomite. 9.77 m

16. Dark gray medium–thick laminated very thin grained dolomite. 8.42 m

15. Gray micro-thin laminated siliceous mudstone. 4.52 m

14. Dark gray medium–thick laminated argillaceous siliceous limestone interbedded with medium laminated limy dolomite. Horizontal bedding developed in all rock layers. 5.56 m

13. Dark gray thick laminated–blocky dolomite. 13.01 m

12. Interbeds constituting of gray thin laminated limy siliceous mudstone and micro-thin laminated dolomitic limestone. 1.97 m

11. Dark gray medium laminated carbonaceous marlstone. The thickness of a single rock layer is generally 20–40 cm. 2.10 m

10. Dark gray and grayish-black medium–thin laminated carbonaceous silicalite, interbedded with limestone lens in the middle part. The thickness of a single layer of carbonaceous silicalite is generally 5–30 cm. Micro horizontal bedding developed locally. 4.19 m

9. Gray and dark gray thick laminated–blocky carbonaceous sandy marlstone. 1.11 m

8. Grayish black medium–thin laminated carbonaceous silicalite, interbedded with a small amount of carbonaceous limestone lens. The thickness of a single rock layer is 5–30 cm. 16.85 m

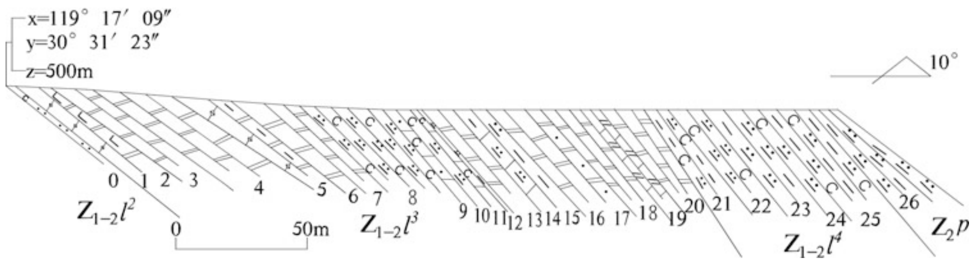


Fig. 2.6 Third member ($Z_{1\text{-}2}l^3$)–fourth member ($Z_{1\text{-}2}l^4$) profile of Lantian Formation in Nanchewu, Hanggai Town, Anji County, Zhejiang Province

7. Dark gray thick laminated silty–fine-crystalline dolomite. The thickness of a single rock layer is generally 50–100 cm. The middle part is medium laminated rocks. 11.73 m

6. Dark gray medium laminated fine-crystalline dolomite. The thickness of each layer is generally 15–30cm. 3.82 m

5. Interbed consisting of grayish medium–thin laminated micrite and micro-thin laminated argillaceous dolomite. 1.47 m

4. Dark gray and grayish-black thick laminated–blocky fine-crystalline dolomite. 44.98 m

3. Off-white thin laminated fine-crystalline dolomite. The thickness of each layer is generally 1–5 cm. 20.36 m

2. Interbed consisting of gray and off-white thin–medium laminated limy dolomite and micro-thin laminated argillaceous limestone. 5.91 m

1. Light off-white thin laminated micritic limestone. The thickness of each layer is generally 2–6 cm. 9.07 m

———Conformable contact———

Underlying strata: dark gray carbonaceous siltstone and silty mudstone of the second member of Lantian Formation.

2. **Lithological Characteristics**

The lithology of the first member of Lantian Formation ($Z_{1\text{-}2}l^1$) is mainly characterized by argillaceous dolomitic limestone-bearing manganese and carbon. The major component is cryptocrystalline calcite, accounting for 65–70%, and the grain size of it is about 0.01 mm. The argillaceous matter accounts for 20–25%. Amorphous carbonaceous matter accounts for 10% and is evenly distributed.

The main lithology of the second member of Lantian Formation ($Z_{1\text{-}2}l^2$) is characterized by carbonaceous siliceous mudstone, silty mudstone, and carbonaceous argillaceous limestone.

(1) Carbonaceous siliceous mudstone: composition: argillaceous matter (70%), cryptocrystalline siliceous matter (25%), and amorphous carbonaceous (5–10%). The argillaceous matter: fine scaly, unevenly distributed and concentrating locally; the cryptocrystalline siliceous matter: evenly distributed; amorphous carbonaceous: unevenly distributed and slightly concentrating locally.
(2) Silty mudstone: composition: argillaceous matter (75%), feldspar and quartz silt (20%), and carbonaceous matter (5%). The argillaceous matter becomes scaly mica partly due to thermal induced metamorphic recrystallization; the feldspar and quartz silt: grain size: 0.02–0.04 mm; the carbonaceous matter: unevenly distributed and concentrating locally.
(3) Carbon-bearing argillaceous limestone: composition: calcite (70%), argillaceous matter (20%), and amorphous carbonaceous matter (5–7%). The calcite:

particle size: 0.01–0.05 mm; the argillaceous matter: unevenly distributed and slightly concentrating locally; the amorphous carbonaceous matter: unevenly distributed and slightly concentrating locally; quartz sands: sparsely visible; particle size: 0.1–0.2 mm.

The lithology of the third member of Lantian Formation ($Z_{1\text{-}2}l^3$) is characterized by various types of rocks, mainly including dolomite, micrite, carbonaceous siliceous limestone, argillaceous limestone, argillaceous carbonaceous silicalite, limy dolomite, siliceous mudstone, and sandy dolomite.

(1) The dolomite: gray–dark gray; composition: dolomite (90–95%) and a small amount of calcite. The dolomite: granular or idiomorphic crystal generally; particle size: 0.1–0.2 mm; the calcite: cryptocrystalline generally and visible locally.
(2) The micrite: gray; composition: calcite (90%), argillaceous matter (< 10%), and occasionally visible silt. The calcite: particle size: < 0.01 mm, cryptocrystalline generally; the argillaceous matter: earthy.
(3) The carbonaceous siliceous limestone: gray–dark gray, composed of calcite (60–65%), siliceous matter (25%), and argillaceous matter (10–15%); grain size of the calcite: < 0.01 mm; the siliceous matter: cryptocrystalline, evenly distributed; the argillaceous matter: earthy.
(4) The argillaceous limestone: composition: calcite (60–65%), argillaceous matter (20–25%), and carbonaceous matter (5–10%). The calcite: particle size: < 0.01 mm; the argillaceous matter: earthy generally; the carbonaceous matter: black amorphous, concentrating locally.
(5) The argillaceous carbonaceous silicalite: black; composition: siliceous matter (45–50%), carbonaceous matter (25–30%), and argillaceous matter (25%). The siliceous matter: cryptocrystalline generally; the carbonaceous matter: black amorphous, evenly distributed; the argillaceous matter: horizontal bedding developing.
(6) The limy dolomite: gray–dark gray, composition: dolomite (75–80%) and calcite (20–25%). The dolomite: granular; particle size: 0.1–0.2 mm; the calcite: fine granular generally, unevenly distributed.
(7) The siliceous mudstone: dark gray; composition: argillaceous matter (60–75%), siliceous matter (25–30%), and silt (5–10%). The argillaceous matter: earthy generally; the siliceous matter: cryptocrystalline generally, evenly distributed; the silt: particle size: 0.01–0.03 mm, composed of quartz, etc.
(8) The sandy dolomite: composition: dolomite (85–90%) and sand grains (10–15%). The dolomite: particle size: 0.05–0.1 generally mm or > 0.1 mm occasionally, fine granular generally; the sand grains: composed of quartz, sub-well rounded; particle size: 0.2–0.25 mm, slightly unevenly distributed.

The main lithology of the fourth member of Lantian Formation Member ($Z_{1\text{-}2}l^4$) is characterized by siliceous mudstone and carbonaceous siliceous mudstone.

(1) The siliceous mudstone: composition: siliceous matter (60–70%) and argillaceous (35–40%). The siliceous matter: cryptocrystalline generally; the argillaceous matter: earthy.
(2) The carbonaceous siliceous mudstone: composition: argillaceous matter (50–65%), siliceous matter (25–30%), and carbonaceous matter (10%). The argillaceous matter: earthy generally; the siliceous matter: cryptocrystalline generally; the carbonaceous matter: black amorphous, unevenly distributed and concentrating locally.

3. **Basic Sequences**

There are eight types of basic sequences developing in the Lantian Formation, including one in the first member, three in the second member, three in the third member, and one in the fourth member (Fig. 2.7).

Basic sequences of type A: located in the first member of Lantian Formation ($Z_{1\text{-}2}l^1$), composed of single grayish black medium laminated argillaceous dolomitic limestone-bearing manganese and carbon, horizontal bedding developing. The basic sequences of this type belong to the sedimentation of platform facies and are of monotonous non-cyclic basic sequence.

Basic sequences of type B: located in the lower part of the second member of Lantian Formation ($Z_{1\text{-}2}l^2$), composed of gray–dark gray thin–medium laminated carbonaceous siliceous mudstone, containing a small amount of synsedimentary fine-grained pyrite, horizontal bedding developing. The basic sequences of this type belong to the sedimentation of bathyal basin facies and are of monotonous non-cyclic basic sequence.

Basic sequences of type C: located in the middle part of the second member of Lantian Formation ($Z_{1\text{-}2}l^2$), composed of ① grayish thin–medium laminated carbonaceous limestone and ② gray–dark gray thin–medium laminated carbonaceous siliceous mudstone. The carbonaceous limestone: 8–30 cm thick per layer, lensoid locally. The carbonaceous siliceous mudstone: 5–30 cm thick per layer, containing a small amount of synsedimentary fine-grained pyrite which concentrates along the bedding generally, horizontal bedding developing in the rock layers. The ratio between the two components is nearly 1:1. The carbonaceous siliceous mudstone is of deep shelf–bathyal basin facies (major) and

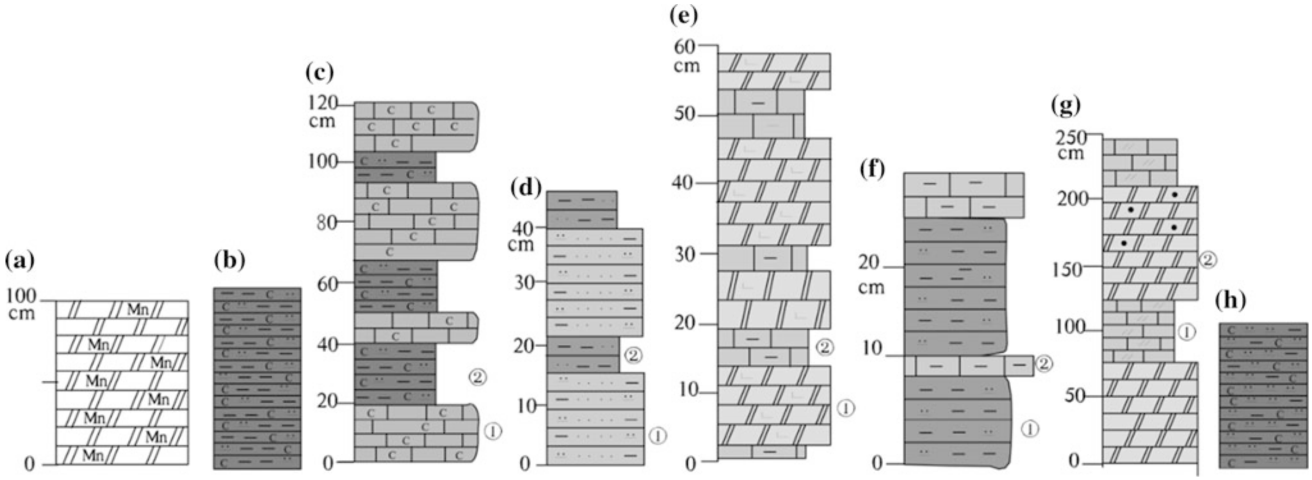


Fig. 2.7 Basic sequences of Lantian Formation ($Z_{1\text{-}2}l$)

the carbonaceous limestone is of shallow shelf facies (minor). The basic sequences of this type belong to non-cyclic basic sequence.

Basic sequences of type D: located in the upper part of the second member of Lantian Formation ($Z_{1\text{-}2}l^2$), composed of ① gray–dark thin–medium laminated silicon-bearing argillaceous siltstone and ② gray thin laminated silty mudstone. For the two components, the mineral composition is similar while the components vary greatly. Horizontal bedding developed in all the rock layers. Thus, the basic sequences of this type belong to shallow shelf–bathyal basin facies and are of non-cyclic basic sequence.

Lithologically, the second member of Lantian Formation gradually becomes carbonates and terrigenous silt from bottom to top, indicating that the sea level gradually rose.

Basic sequences of type E: located in the lower part of the third member of Lantian Formation ($Z_{1\text{-}2}l^3$); composed of ① grayish thin–medium laminated limy dolomite with no bedding developing and ② gray micro-thin laminated argillaceous limestone with horizontal bedding developing; belonging to shallow shelf–platform facies.

Basic sequences of type F: located in the middle part of the third member of Lantian Formation ($Z_{1\text{-}2}l^3$), composed of ① dark gray thin–medium laminated argillaceous silicalite and ② gray micro-thin laminated argillaceous limestone; micro-texture horizontal bedding developing; belonging to bathyal facies.

Basic sequences of type G: located in the upper part of the third member of Lantian Formation ($Z_{1\text{-}2}l^3$), composed of rhythm interbeds of ① gray–dark gray medium–thick laminated dolomitic limestone and ② gray–dark gray medium–thick laminated dolomite, with sandy dolomite visible occasionally; thick laminated structures visible in most dolomite; horizontal bedding developing in all rock layers; belonging to platform facies.

Lithologically, the third member of Lantian Formation has evolved from carbonate to carbonate-bearing argillaceous and siliceous matter, then to sand-bearing carbonate from bottom to top, reflecting that the sea level vibrated between rise and falling with rise as general trend.

Basic sequences of type H: located in the fourth member of Lantian Formation ($Z_{1\text{-}2}l^4$), composed of rhythmite of dark gray thin laminated and thin–medium laminated carbonaceous siliceous mudstone or dark gray thin laminated argillaceous silicalite, micro-texture horizontal bedding developing in rock layers. Thus, the basic sequences of this type belong to deep shelf–bathyal basin facies and are of monotonous non-cyclic basic sequence.

2.2.1.2 Sequence Stratigraphy

According to the characteristics of the lithology, lithofacies association, and sequence boundary of the profiles of Yeshangwu and Dalingtou of Xianxia map sheet, as well as Nanchewu profile of Hanggai map sheet, there is one second-order sequence SS3 in the first member–the second member of Lantian Formation, there is one second-order sequence SS4 in the third member of Lantian Formation, and there is one second-order sequence SS5 in the fourth member of Lantian Formation–Cambrian Dachenling Formation. Among these sequences, SS4 is further divided into four third-order sequences, i.e., Sq1–Sq4 (Fig. 2.8). The characteristics and internal composition of all these sequences from bottom to up are briefly described as follows:

Second-order sequence SS3

It is located in the first member–the second member of Lantian Formation. The bottom of it is a parallel unconformity interface between the argillaceous dolomitic

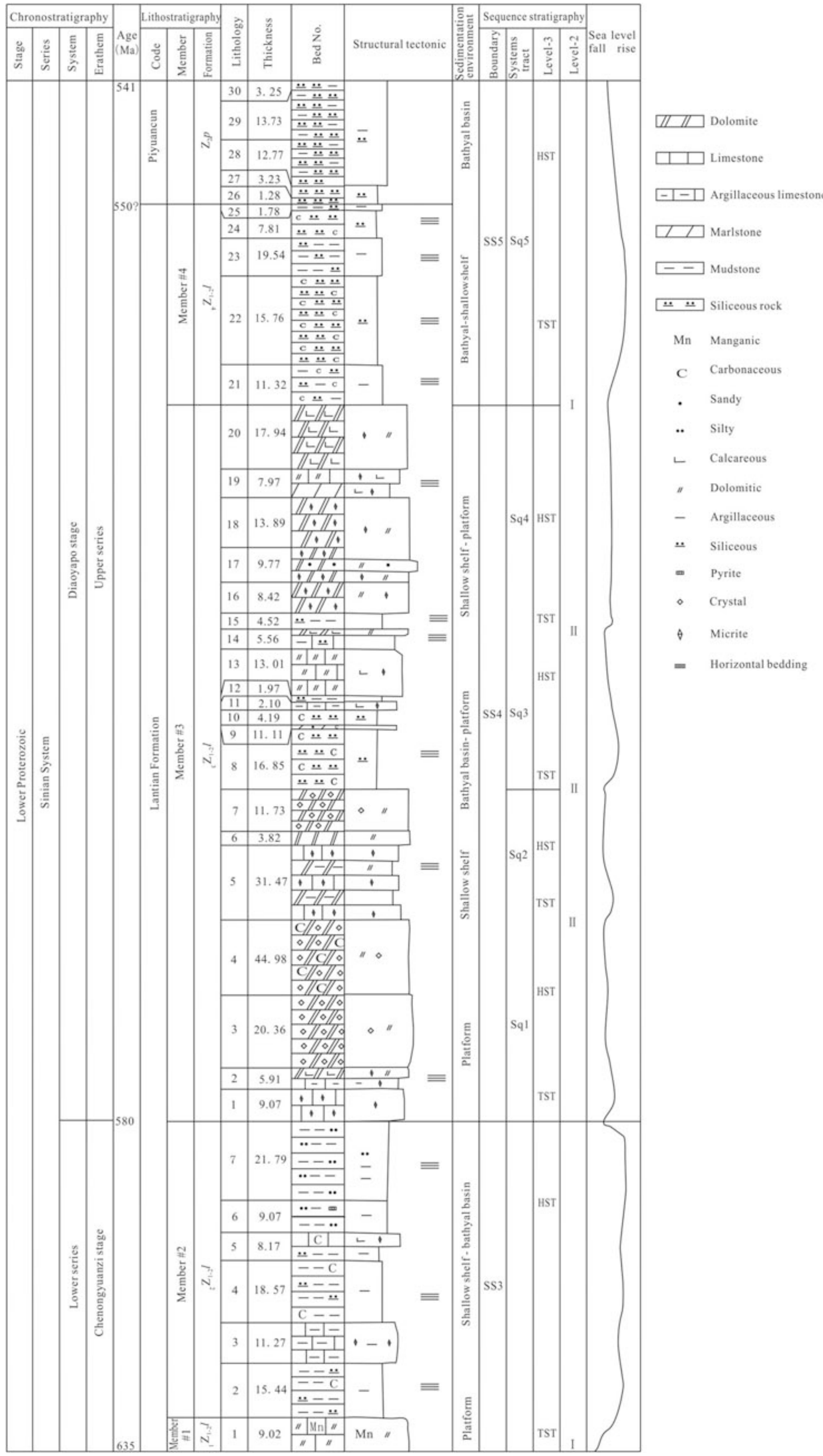


Fig. 2.8 Sequence stratigraphic framework of the Sinian in the area

limestone-bearing manganese and carbon in the first member of Lantian Formation and the silty mudstone-bearing moraine conglomerate in the underlying Nantuo Formation. It is of type-I sequence boundary. The top of SS3 is a conformity interface between the silty mudstone in the second member of Lantian Formation and the limestone in the overlying third member of Lantian Formation. It is of type-II sequence boundary. The sediments in the first member and the lower part of the second member mainly consist of calcium–magnesium carbonate rocks and argillaceous rocks bearing carbon and silicon, with horizontal bedding developing. Therefore, these sediments belong to shallow shelf facies–bathyal basin facies. The sediments in the upper part of the second member of Lantian Formation are silty mudstone and calcium–magnesium carbonate rocks, belonging to shallow shelf facies–platform facies and reflecting the process that sea level gradually fell after reaching the maximum value in the lower part of the second member of Lantian Formation. The lower part of SS3 is of retrogradation type, and the middle and upper parts of SS3 are of aggradation and progradation types, respectively. The age range of SS3 is 63–580 Ma, spanning 55 Ma.

Second-order sequence SS4

Third-order sequence Sq1: located in the lower and middle parts of the third member of Lantian Formation, including transgressive systems tract (TST) and highstand systems tract (HST). The bottom is of type-II sequence boundary. The top of it is the conformity interface between the dolomite in the lower part of the third member of Lantian Formation and the overlying carbonaceous siliceous shale; thus, the top is of type-II sequence boundary. Thin–medium laminated calcareous and dolomitic sediments are mainly distributed in TST, with horizontal bedding developing in rock layers, thus indicating shallow shelf facies. The thick blocky-laminated dolomitic sediments and a small amount of calcareous sediments are distributed in HST, indicating shallow shelf–platform facies. HST accounts for the overwhelming majority of Sq1. The siliceous-argillaceous sediments are interbedded and crossed with calcareous and dolomitic sediments in HST, reflecting the sea level rose in general. Thus, HST is of progradation–aggradation type.

Third-order sequence Sq2: located in the lower-middle part of the third member of Lantian Formation, including TST and HST. The top and bottom of it are both of type-II sequence boundaries. The carbonaceous siliceous sediments are mainly distributed in TST, with micro-texture horizontal bedding developing, thus indicating bathyal basin facies. Calcareous sediments (major), as well as argillaceous sediments and terrigenous quartz sands (minor), are distributed in HST, indicating shallow shelf–platform facies. Representing the regression process of seawater in general, Sq2 is a sequence of retrogradation type.

Third-order sequence Sq3: located in the upper-middle part of the third member of Lantian Formation, including TST and HST. The top and bottom are both of type-II sequence boundaries. Thin–medium laminated siliceous argillaceous sediments are mainly distributed in TST, thus indicating the bathyal basin facies. Medium–thick laminated calcareous and dolomitic sediments, as well as a small amount of thin–medium laminated siliceous argillaceous sediments, are distributed in HST, thus belonging to the bathyal basin–neritic platform facies. HST accounts for an overwhelming majority of Sq3. The siliceous-argillaceous sediments are interbedded and crossed with calcareous and dolomitic sediments in HST, reflecting that the sea level alternately rose and fell frequently and thus belonging to aggradation type.

Third-order sequence Sq4: located at the upper part of the third member of Lantian Formation, including TST and HST. The top and bottom of it are both of type-II sequence boundaries. Thin laminated siliceous argillaceous sediments are mainly distributed in TST besides a small amount of carbonaceous sediments, with micro-texture horizontal bedding developing in rock layers. Therefore, TST is of bathyal basin facies. Dominant medium–thick laminated dolomitic sediments, minor calcareous carbonate, and a small amount of terrigenous quartz sands are distributed in HST, indicating shallow shelf–platform facies. HST accounts for the overwhelming majority of Sq4, representing the process that sea level continually fell and thus belonging to progradation–aggradation type.

The age range of the sequences Sq1–Sq4 is 580–560 Ma, spanning 20 Ma. Each single third-order sequence spans 5 Ma on average.

2.2.1.3 Biostratigraphy and Chronostratigraphy

The renowned Lantian Biota is situated in Lantian area, Xiuning County, south Anhui. The fossils are preserved in the shale of the second member of Lantian Formation in the form of carbonaceous films. After the fossil biota was reported by Xing et al. (1989) for the first time, a number of articles on description and research of the macrofossils in the Area were published successively. Yan et al. (1992) described macro-algae fossils of 12 genera and 18 species and called this biotic association "Lantian Flora". Tang et al. (1997) mainly discussed a category of disk-shaped and ellipsoidal fossils in the fossil biota and considered them as the macrofossils evidence of sexual differentiation in metaphyte. In 1994–1999, Yuan et al. carried out systematic field collection and detailed research of the specimens of the biota and classified the 50 genera and species described previously under 12–15 species. Yuan et al. (2012) further researched the Lantian Flora that was discovered in 40-m-thick black shale of the second member of Lantian Formation and concluded that Lantian Flora was the earliest macrobiota with a highly rich species and complex biological structure so far. Therefore, they put forward the concept of Lantian Biota, which was mainly composed of multicellular macro-algae fossils and might contain some fossils related to metazoans.

Little survey and research have been conducted on paleontology of the Lantian Formation in Zhejiang. Previous survey and research on Sinian System in the northwest Zhejiang mainly focused on the areas near the Jiangshan–Shaoxing fracture zone in the south, and much effort was paid to the profiles of Doushantuo Formation and Dengying Formation in Wujialing, Jiangshan City, the profiles of Doushantuo Formation and Dengying Formation in Shaojiashan, Zhuji City, the profile of Banqiaoshan Formation in Zhongjiazhuang, Fuyang City, and the profiles of Lantian Formation and Piyuancun Formation in Qiuyuan, Chun'an County. All of the profiles are contemporaneous heteropical sedimentation. In Doushantuo Formation and Dengying Formation of the Sinian in which rich palaeobios were obtained, the biota was mainly composed of microfossil plants, chitinozoans-like organism, and micro-vermes. The early Sinian biotic association was composed of microfossil plants. As for the biotic association of the Later Sinian, there were many stromatolites, chitinozoans-like animals, and micro-vermes besides massively flourishing microfossil plants. In addition to recurring microfossil plants, there were plenty of stromatolites, chitinozoans-like animals, and micro-vermes.

As a period when great changes happened in the biological world, the Sinian is an important stage of fauna origination. In the Dengying Formation of the Sinian, not only a lot of microfossil plants and stromatolites but also vermes and chitinozoans-like animals developed. The later species consist of the oldest marine fauna, which can be comparable to Ediacaran mollusk and trace fossil fauna. Some individuals of fauna are also found in similar strata in the USA, Sweden, UK, and southwest Africa. This fauna developed after the glacial period at the end of Proterozoic Era, and its age range is about 680–543 Ma. It provided an important biological basis for disintegration of the former Sinian in South China, which was then divided into then Nanhuan System and the Sinian System (Fig. 2.8).

2.2.1.4 Analysis of Sedimentary Environment

In the Early Sinian, with glacier melting and the sea level rising, the Lantian Formation in the Area experienced the following sedimentary environment. For the first member, about 8–10-cm-thick gray manganese-bearing dolomite was deposited, representing the carbonate sedimentation formation in the environment of an arid hot restricted marine platform facies. The second member of Lantian Formation mainly consists of dark gray–grayish black carbonaceous siliceous argillaceous sediments and a small amount of silty sediments, interbedded with a small amount of argillaceous carbonate rocks. Horizontal bedding developed in rock layers. Therefore, the second member represents a deep standing-water environment. Therefore, the second member belongs to the carbonate-bearing siliceous-argillaceous formation of shallow shelf outer margin–bathyal basin facies. For the third member of Lantian Formation, the sediments mainly consist of dark gray dolomite-bearing carbonate, interbedded with a small amount of carbonaceous siliceous sediments. The dolomite carbonate contains a large amount of terrigenous quartz sand grains locally. This indicates that this member was generally in an oxidization neritic environment and occasionally in a deep standing-water oxidation–reduction environment due to the sharp rise of the sea level. Therefore, the main part of the third member is a set of siliceous-argillaceous carbonate formation of shallow shelf–open platform facies. For the fourth member, dark gray–grayish black carbonaceous siliceous argillaceous sediments are dominant in the member and the silty sediments are available occasionally. Horizontal bedding developed in the rock layers. Therefore, the fourth member belongs to siliceous-argillaceous formation in the deep standing-water environment. As a result, Lantian Formation generally went through the change of the sedimentary environment, i.e., platform → bathyal basin → shallow shelf → open platform → bathyal basin successively.

As for the sedimentary environment of the black shale in Lantian Formation, very thin bedding structures developed in the shale where Lantian Biota fossils are preserved, and there are no signs of sedimentary structures and fossil transportation reflecting strong hydrodynamic environment. Thus, it is suggested that these macro-organisms should be buried in situ and they should live under the maximum wave

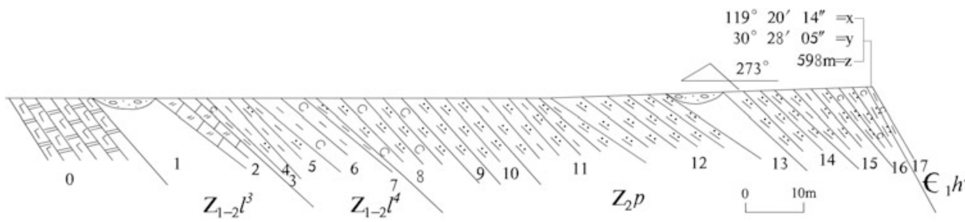


Fig. 2.9 Fourth member of Sinian Lantian Formation ($Z_{1\text{-}2}l^4$)–Piyuancun Formation (Z_2p) profile in Ligu'an, Zhangcun Town, Anji County, Zhejiang Province

base and in the euphotic zone. According to the paleogeography back then and by reference to the standards on modern marine environment, the Lantian Biota should largely live in the margin of platform or local standing water of platform, with water depth ranging from 50 to 200 m. Preserved on shale surface in the form of carbonaceous film, the fossils are complete in morphology and sessile equipment is available for most species, suggesting that Lantian Biota is a complex benthic sessile macrobiota. This is very probably related to the intermittent anoxic event that happened universally in oceans during that period.

The Lantian Biota is a critical link in the evolvement of simple or micro-eukaryote into the organisms with complex physical conformation and diverse morphology, suggesting that the origination and early evolution of multicellular macro-organisms probably occurred in a deep standing-water environment. Regionally, the four lithological members of Lantian Formation vary slightly in lithologic association and stratum thickness, reflecting they were in the same stable sedimentary terrain within the Area. In Xianlin area, Yuhang, about 80 km to the south of the Area, the stratigraphic facies becomes the interbeds consisting of sandy dolomite and dolomite sandstones of Banqiaoshan Formation and the sedimentary environment is transitioned to neritic platform–tidal flat facies.

2.2.1.5 Trace Elements in Strata (Ore-Bearing)

Three rock spectra of Lantian Formation were systematically collected from the Nanchewu profile (PM010) of Hanggai map sheet. According to spectral analysis, the members of Lantian Formation vary slightly in terms of trace element enrichment. The first member is enriched in Sb, Bi, and Ag, and poor in Au, Be, Cu, Pb, Zn, W, Mo, Sn, and S. The second member is enriched in Sb, Bi, Ag, F, and S, and poor in Au, Be, Zn, and Mo. The third member is enriched in Sb, Bi, W, Mo, Ag, and S, and poor in Au, Be, Cu, Zn, and TFe. The fourth member of Lantian Formation is enriched in Au, Sb, Bi Pb, W, Mo, and Ag, and poor in Be and TFe. Therefore, all the members are enriched in Sb, Bi, and Ag, and poor in Au, Be, Cu, Zn, and Mo. Furthermore, the concentration coefficients of Au, Ag, Sb, and Bi of the fourth member are 10–25 times higher than those of other members. The trace element enrichment is related to rock type. The silicon-bearing carbonaceous mudstone is enriched in many types of trace elements with high concentration coefficients. The limestone ranks the second, and silicalite ranks the last in terms of trace element enrichment.

2.2.2 Piyuancun Formation (Z_2p)

The name Piyuancun Formation was created by Li and Li (1930) in Piyuancun Village, Lantian Town, Xiuning Country, Anhui Province. Qian et al. (1964) determined its meaning again and used it to refer to a set of silicalite in black and white between the parts under the Early Cambrian phosphorous and carbonaceous shale and Lantian Formation, with the horizon lying in the Sinian. Zhejiang Regional Geological Team (1990) introduced the Piyuancun Formation to Changhua–Anji area, and its horizon belonged to the Sinian. However, the horizon of the stratum in Kaihua–Lin'an and Jiangshan–Shaoxing areas which is equivalent to Piyuancun Formation was still located in the lower part of Hetang Formation. In this Project, the Piyuancun Formation stated in the list of *Lithostratigraphy of Zhejiang Province* was still adopted according to characteristics of lithologic association of Nanchewu (PM010) profile of Hanggai map sheet, the profiles of Xianxia map sheets including Meijiata (PM035), Dalingtou (PM0036), and Ligu'an (PM039), and the geological observation traverse in the Area.

2.2.2.1 Lithostratigraphy

The outcrops of Piyuancun Formation in the Area are largely associated with Lantian Formation and are mainly distributed in the surrounding areas of Tangshe complex in the southwest corner of Hanggai map sheet and in the northwestern part of Xianxia map sheet including Zhanglicun, Baishawu, Ligu'an, and Damiao–Zhaojia area discontinuously. Thus, the distribution in "U" shape is formed with SW-trending opening in general. The outcrop area is about 8.05 km^2, accounting for 0.63% of the bedrock area.

Lithologically, Piyuancun Formation (Z_2p) consists of thin–thick laminated silicalite and argillaceous silicalite, with very thin horizontal bedding developing in rock layers. Silicalite is distributed in the shape of a band in black and white locally. Compared with the overlying Hetang Formation, Piyuancun Formation is characterized by the rocks of lighter color and lower content of carbonaceous argillaceous sediments. The thickness of Piyuancun Formation is 22.47–57.98 m.

1. **Stratigraphic section**

The lithological characters of Piyuancun Formation are described by taking the example of the fourth member of Sinian Lantian Formation ($Z_{1\text{-}2}l^4$)–Piyuancun Formation (Z_2p) profile (Fig. 2.9) of Xianxia map sheet in Ligu'an, Zhangcun Town, Anji County, Xianxia, Zhejiang Province. The details are as follows:

The first member of Hetang Formation Total thickness: > 0.66 m

17. Dark gray thin–medium laminated carbonaceous siliceous mudstone, 3–15 cm thick per layer, with well-developed bedding, micro-folds visible in rocks. 0.66 m

——— Conformable contact ———

Piyuancun Formation Total thickness: 57.98 m

16. Gray medium laminated argillaceous silicalite, about 20 cm thick per layer, with bedding developing. 4.63 m

15. Gray thick laminated argillaceous silicalite, 50–100 cm thick per layer. 5.67 m

14. Gray thin laminated argillaceous silicalite, 2–10 cm thick per layer, with very thin horizontal bedding developing. 5.67 m

13. Covering. 6.31 m

12. Grayish black thin–medium laminated argillaceous silicalite, 3–25 cm thick per layer, with well-developed very thin horizontal bedding. 9.73 m

11. Hoary medium–thick laminated silicalite in black and white, 20–50 cm thick per layer, very thin horizontal bedding in black and white developing. 7.39 m

10. Dark gray blocky–laminated argillaceous silicalite, the thickness of a single layer: > 1m generally. 4.97 m

9. Hoary thin laminated silicalite, 2–10 cm thick per layer, with well-developed bedding. 2.84 m

8. Dark gray medium–thick laminated argillaceous silicalite, 20–70 cm thick per layer, with well-developed bedding. 10.77 m

——— Conformable contact ———

The fourth member of Lantian Formation Member Total thickness: > 7.05 m

7. Hoary medium laminated carbonaceous siliceous mudstone, 20–40 cm thick per layer, with well-developed bedding. 1.33 m

6. Black thin laminated carbonaceous mudstone, 2–5 cm thick per layer, with well-developed bedding. 5.72 m

2. **Lithological Characteristics**

The rocks in Piyuancun Formation (Z_2p) are mainly of two types: silicalite and argillaceous silicalite.

Silicalite: dark gray, in black and white locally; cryptocrystalline texture; consisting of cryptocrystalline siliceous sediments (85–95%) and a small amount of argillaceous sediments (< 10%); medium–thick laminated generally and thin laminated partly; generally distributed at the lower part.

Argillaceous silicalite: gray and dark gray; cryptocrystalline texture; mainly consisting of cryptocrystalline siliceous sediment (50–75%); argillaceous sediment contained (10–25%, up to 30% locally), generally earthy; black non-crystalline carbonaceous sediment visible occasionally (< 10%), concentrated locally; generally thin laminated and partly medium laminated; generally distributed in the upper part.

3. **Basic Sequences**

There are two types of basic sequences developing in Piyuancun Formation according to rock association (Fig. 2.10).

Basic sequences of type A: distributed in the middle and lower parts of Piyuancun Formation, composed of dark gray, light gray–white cryptocrystalline silicalite, 0.2–2 mm thick, silicalite in sharply changed dark color and light color constituting very thin horizontal bedding, belonging to monotonous basic sequence.

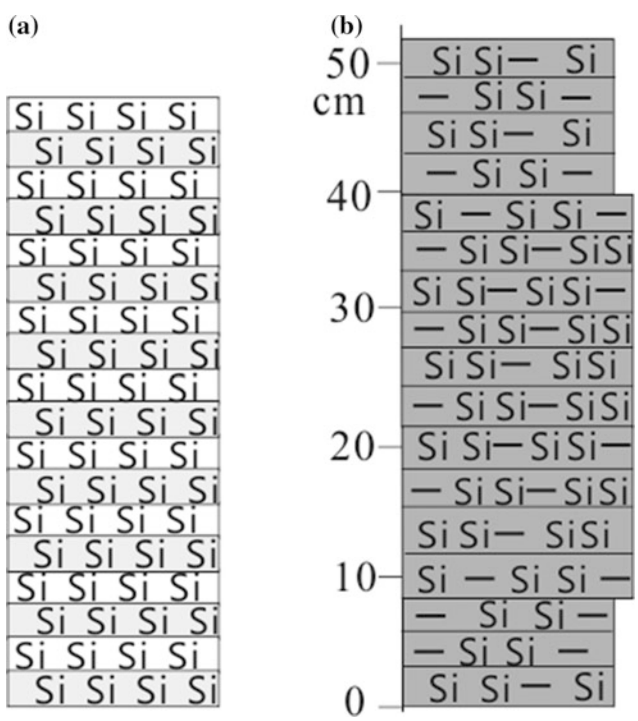


Fig. 2.10 Piyuancun Formation (Z_2p) basic sequence

Basic sequences of type B: distributed in the upper part of Piyuancun Formation, composed of thin–thick laminated argillaceous silicalite, very thin horizontal bedding developing in rock layers, belonging to monotonous basic sequence.

2.2.2.2 Sequence Stratigraphy

Piyuancun Formation is simple in terms of lithology and lithologic association. It is in conformable contact with its overlying and underlying strata, making it difficult to be further divided in terms of sequence stratigraphy and systems tract separately. According to the features of the lithology, lithofacies association, and sequence boundary of the profiles of Xianxia map sheet including Yeshanwu, Dalingtou, and Ligu'an as well as Nanchewu profile of Hanggai map sheet, there is one second-order sequence SS5 from the fourth member of Lantian Formation to Cambrian Dachenling Formation (Fig. 2.8), and there is one third-order sequence Sq5 from the fourth member of Lantian Formation to Piyuancun Formation.

Third-order sequence Sq5: located from the fourth member of Lantian Formation to Piyuancun Formation, including TST and HST. Its bottom and top belong to type-I and type-II sequence boundaries, respectively. TST is located in the fourth member of Lantian Formation, with argillaceous–siliceous sediment as well as a small amount of carbonaceous sediment constituting the sediments. Horizontal bedding developed in rock layers. Therefore, TST belongs to standing-water basin facies in bathyal weak reduction environment. HST is located in the upper part of Piyuancun Formation, and the sediments mainly consist of argillaceous–siliceous matter. Very thin horizontal bedding developed here. However, during the Piyuancun Formation period, Ediacaran Biota developed, which indicated oxidization environment and thus reflected that the sedimentary environment transitioned to bathyal–neritic weak oxidization environment. Therefore, from bottom to up, the sedimentary environment of Sq5 changed from bathyal basin facies to bathyal–neritic shelf facies, and is of progradational–aggradational type.

2.2.2.3 Biostratigraphy and Chronostratigraphy

Compared with adjacent southern Anhui area, less research has been carried out on palaeontology in Piyuancun Formation of Zhejiang Province. Dong et al. (2012) discovered Ediacaran fossils, macrofossils, unnamed fusiform fossils, and spherical fossils in the Piyuancun Formation of Lantian profile of Xiuning County, indicating that the silicalite of Piyuancun Formation was the sediment of Ediacaran Period. Among these fossils, *Palaeopaschnus* is distributed at the middle and upper parts of the silicalite in Piyuancun Formation and the distribution of *Horodyqkia* extends until near the boundary of Piyuancun Formation and Hetang

Formation, indicating the boundary between the Ediacaran and the Cambrian which is divided based on biostratigraphy largely coincides with the boundary between Piyuancun Formation and Hetang Formation in southern Anhui.

2.2.2.4 Analysis of Sedimentary Environment

The sediments of Piyuancun Formation mainly include gray–dark gray cryptocrystalline siliceous, with very thin horizontal bedding developing, indicating quiet water. There are very little carbon and sulfide in the sediment, suggesting weak oxidization environment. Compared with Lantian Formation, the Ediacaran biota and macro-algae indicate similar paleoclimate condition; however, the existence of metazoans indicates that oxygen was more sufficient in water.

In conclusion, the sedimentary environment of Piyuancun Formation is of shallow shelf facies. The boundary between the Sinian and the Cambrian is a very important turning point in geological history, since it represents a transformation from micro-bios-dominated Precambrian biosphere to animal-dominated Phanerozoic Eon biosphere and meanwhile reveals the beginning of oxygen-enriched surface environment (Anbar and Knoll 2002; Marshall 2006).

2.2.2.5 Trace Elements in Strata (Ore-Bearing)

Four rock spectra were collected from Piyuancun Formation in Nanchewu profile (PM010) of Hanggai map sheet. Piyuancun Formation is enriched in Sb, Bi, Mo, and Ag, and poor in Au, Be, Cu, Pb, Zn, W, F, S, and TFe. Compared with the four members of Lantian Formation, the content of Ag, Sb, and Bi is normal while the content of all other trace elements is all very lower.

2.2.3 Comparison of Regional Stratigraphy

The Sinian in Zhejiang Province is mainly distributed in the northwest of Jiangshan–Shaoxing fracture zone. With the change of paleotopography, rock layers of different thicknesses were deposited from northwest to southeast. According to the information on the Area and previous stratigraphic profiles, the northwest of Zhejiang can be divided into three zones of sedimentary facies, which include Hanggai–Kaihua hollow zone, Yuhang–Tonglu uplift zone, and Xiaoshan (Zhuji)–Jiangshan low-lying zone from northwest to southeast.

The Sinian in Zhejiang Province mainly consists of carbonate formation and siliceous argillaceous formation, followed by the formation of terrigenous clastic sedimentary rocks. In the Project, typical profiles in Hanggai area (the Area), Dashuping of Fuyang, Yuhang, and Fudun of Xiaoshan are selected for comparison of regional strata (Fig. 2.11).

The worldwide glacial period ended at the end of the Nanhuan. In the early period of the Early Sinian, a layer of carbonate rocks started to be deposited on tillite, which is called carbonatite cap. During this period, the strata of Hanggai area were about 9-m-thick manganese-bearing dolomite of the first member of Lantian Formation on the bottom of Sinian System, the strata of Fuyang area of Yuhang were about 28-m-thick dolomite of the first member of Doushantuo Formation, and the strata of Xiaoshan area were about 5-m-thick manganese-bearing dolomite of the first member of Doushantuo Formation.

In the middle and later period of the Early Sinian, the strata of Hanggai area consisted of carbonaceous siliceous silty mudstone of bathyal basin facies interbedded with a small amount of carbonaceous limestone of shallow shelf facies in the second member of Lantian Formation, and the thickness is about 85 m; the strata of Yuhang area consisted of dolomitic limestone interbedded with argillaceous limestone and a small amount of mudstone and dolomite in Doushantuo Formation; the strata of Xiaoshan area gradually changed from the interbed of caesious argillaceous dolomite and silty mudstone to the dolomite and amaranthine potassium-bearing siltstone of the second member of Doushantuo Formation from bottom to top, with terrigenous clasts increasing, indicating strong oxidization and high-energy environment.

In the early period of the Later Sinian, the strata of Hanggai area mainly consisted of the third member of Lantian Formation of shallow shelf facies. It changed from the interbed of thin laminated dolomite and argillaceous limestone to the thick laminated dolomite interbedded with a small amount of sand dolomite from bottom to top, and a thickness is 235 m; the strata of Yuhang area mainly consisted of dolomite and a small amount of carbonaceous calcareous mudstone, silty dolomite, and dolomitic quartz sandstone of the first member of Banqiaoshan Formation with terrigenous clasts increasing evidently, belonging to neritic platform facies; the strata of Xiaoshan region consisted of dolomite, siltstone, and potassic siltstone of the second member of Doushantuo Formation from bottom to

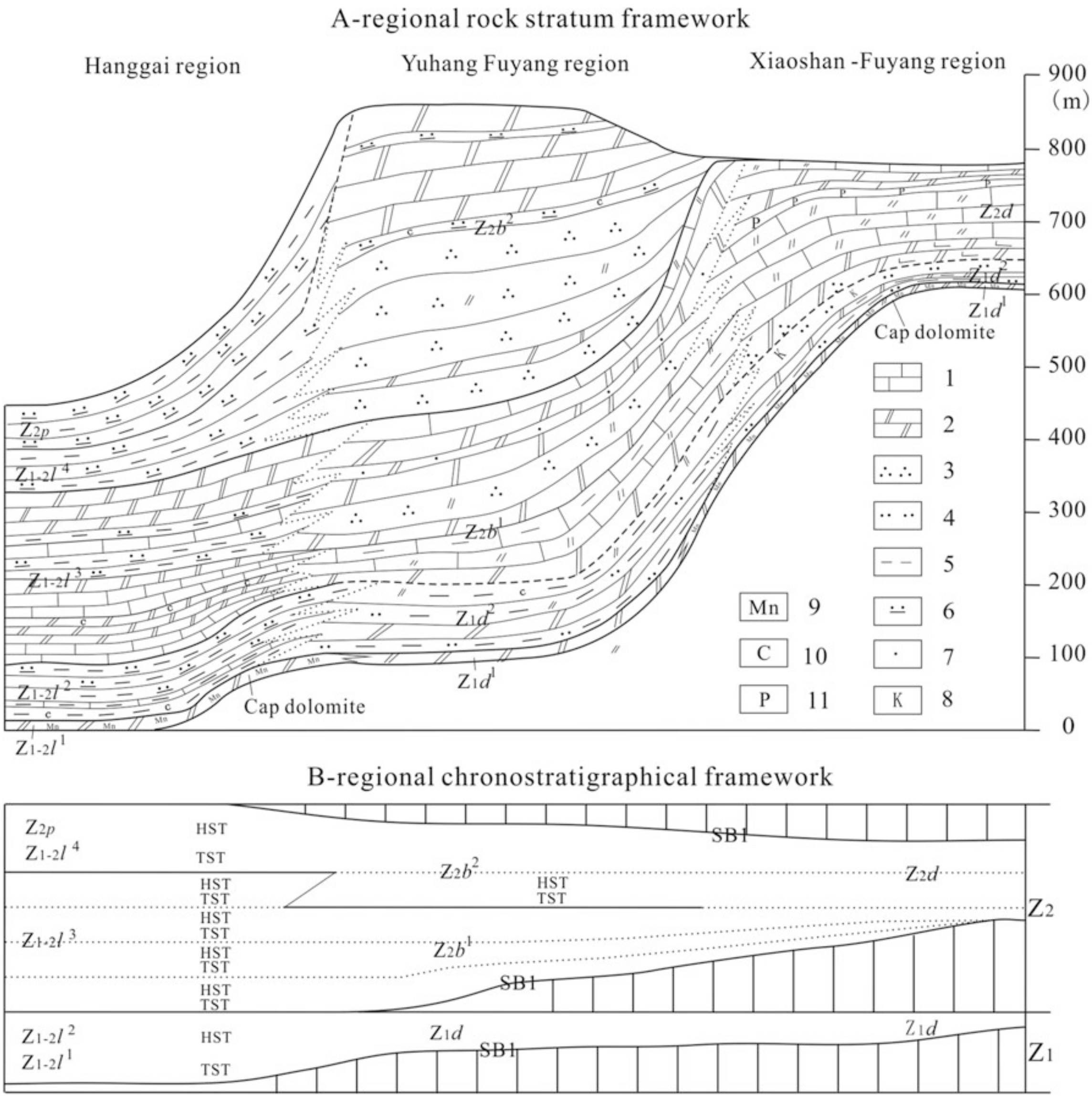


Fig. 2.11 Regional stratigraphic framework in Hanggai–Fuyang, Yuhang–Zhuji, Xiaoshang area of Sinian Period: 1. limestone; 2. dolomite; 3. quartz sandstone; 4. siltstone; 5. mudstone; 6. silicalite; 7. sandy sediment; 8. potassium-bearing sediment; 9. manganese-bearing sediment; 10. carbonaceous sediment; 11. collophanite; $Z_{1\text{-}2}l^1$—the first member of Lantian Formation; $Z_{1\text{-}2}l^2$—the second member of Lantian Formation; $Z_{1\text{-}2}l^3$—the third member of Lantian Formation; $Z_{1\text{-}2}l^4$—the fourth member of Lantian Formation; Z_2p—Piyuancun Formation; Z_2dy—Dengying Formation; Z_2b—Banqiaoshan Formation; Z_1d—Doushantuo Formation; SB1–type-I unconformity interface; TST—transgressive systems tract; HST—highstand systems tract

top. The dominated rocks of the strata in these areas were gradually changed from carbonate rocks to terrigenous clastic sedimentary rocks from northwest to southeast.

In the late period of the Later Sinian, the strata of Hanggai area consisted of the siliceous mudstone of bathyal–abyssal facies in the fourth member of Lantian Formation and the silicalite of Piyuancun Formation, and the thickness is about 110 m; the strata of Yuhang area mainly consisted of dolomitic sandstone and a small amount of gravel–clastic dolomite of platform facies in Banqiaoshan Formation, about 423 m thick, equivalent to neritic sandbank; the strata of Xiaoshan region consisted of dolomite, dolomite-bearing conglomerate clastic, and collophanite of neritic platform facies in Dengying Formation, about 135 m thick.

In conclusion, northwest Zhejiang in the Sinian consisted of a hollow basin in the northwest, uplift zone in the middle, and relatively low-lying areas in its southwest from northwest to southeast. The dominated rocks of northwest Zhejiang were gradually changed from carbonate rocks to terrigenous clastic sedimentary rocks from northwest to southeast.

2.3 Cambrian System

The Cambrian is widely distributed in the Area. It mainly outcrops in the southwestern part and the southeast corner of Hanggai map sheet as well as the western part and the southeast corner of Xianxia map sheet. Besides, it is sporadically distributed in the northeast and south of Chuancun map sheet. The total outcrop area is 170.60 km^2, accounting for 13.42% of the bedrock area. The Cambrian features complete and continuous outcrops and is divided into five formations from bottom to top, i.e., Hetang Formation ($Є_1h$), Dachenling Formation ($Є_2y$), Yangliugang Formation ($Є_2y$), Huayansi Formation ($Є_3h$), and Xiyangshan Formation ($ЄOx$). The adjacent formations are in conformable contact. According to the lithological association, Hetang Formation ($Є_1h$) and Yangliugang Formation ($Є_2y$) are, respectively, divided into two members, and Xiyangshan Formation is divided into three members.

2.3.1 Hetang Formation ($Є_1h$)

The name Hetang Formation was created by Lu et al. (1955) in Hetang Village, northeast of Dachen, Jiangshan City, Zhejiang Province. It was used to refer to black carbonaceous shale (stone coal layer) by Sheng (1951) and was subsequently used up to now by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature, which includes *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). In this Project, Hetang Formation was still adopted according to the lithological characteristics of the Nanche profile (PM010) of Hanggai map sheet, profiles of Xianxia map sheet including the Meijiata (PM035) and Ligu'an (PM040), and survey traverse in the Area.

2.3.1.1 Lithostratigraphy

The Hetang Formation in the Area mainly outcrops in the Gaocun forest farm–Tongcun forest farm–Tangkengwu area in the southwest of Hanggai map sheet and the Zhangli Village–Baishawu–Ligu'an–Damiao–Zhaojia area in the northwest of Xianxia map sheet. Hetang Formation is associated with Lantian Formation and Piyuancun Formation. Thus, the distribution in "U" shape is formed with SW-trending opening in general. Besides, it is sporadically distributed in Chenjiatang and the east of Tianhuangping in the northeast of Chuancun map sheet. The total outcrop area is about 49.18 km^2, accounting for 3.87% of the bedrock area.

The first member of Hetang Formation ($Є_1h^1$): The lithology is mainly characterized by the dark gray and grayish black thin laminated carbonaceous silicalite, the argillaceous silicalite, and the siliceous mudstone interbedded with carbonaceous mudstone. The lower-middle part is interbedded with medium laminated stone coal layer and multiple thin–medium laminated phosphate nodule layers. The thickness of the member is 146.50–445.99 m^2.

The second member of Hetang Formation ($Є_1h^2$): The lithology is mainly characterized by the dark gray and grayish black thin–medium laminated pyrite-bearing argillaceous carbonaceous silicalite, carbonaceous siliceous mudstone, interbedded with carbonaceous mudstone and partly with pyrite layers or pyrite nodule layers. The thickness of the member is 155.56–201.35 m.

1. **Stratigraphic section**

The lithology Hetang Formation is described by taking the example of the Cambrian Hetang Formation ($Є_1h$)–Dachenling Formation ($Є_1d$) profile (Fig. 2.12) of Hanggai map sheet in Nanchewu, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Dachenling Formation Total thickness: >0.96 m

46. Gray medium–thin laminated argillaceous limestone, the thickness of a single layer: 5–20 cm generally. 0.96 m

Conformable contact

The second member of Hetang Formation Total thickness: 55. 56 m

45. Grayish black medium laminated carbonaceous silicalite, the thickness of a single layer: 20–60 cm. 1.57 m

44. Dark gray and gray medium laminated argillaceous carbonaceous silicalite, the thickness of a single layer: 20-40 cm. 16.25 m

43. Grayish black thin laminated carbonaceous argillaceous silicalite, the thickness of a single layer: 1–5 cm. 100.88 m

42. Grayish black thin laminated argillaceous carbonaceous silicalite, the thickness of a single layer: 3–10 cm. 15.16 m

41. Dark gray thin laminated silty mudstone. 11.60 m

40. Grayish black medium–thin laminated carbonaceous argillaceous silicalite. 1.54 m

39. Gray thin laminated carbonaceous silicalite, with the thickness of a single layer of 0.5 - 5 cm. 8.56m

Conformable contact

The first member of Hetang Formation Total thickness: 113.53 m

38. Gray medium laminated carbonaceous argillaceous silicalite, the thickness of a single layer: 20–50 cm. 15.78 m

37. Gray medium–thin laminated siliceous mudstone, very thin horizontal bedding developing. 10.35 m

36. Dark gray medium laminated siliceous mudstone. 10.77 m

35. Gray thin laminated carbonaceous argillaceous silicalite, the thickness of a single layer: 0.5–5 cm, very thin horizontal bedding developing. 45.59 m

34. Grayish black thin laminated argillaceous silicalite, the thickness of a single layer: 0.5–10 cm, very thin horizontal bedding developing. 6.06 m

33. Dark gray medium–thin laminated silicalite, the thickness of a single layer: 5–15 cm. 10.85 m

32. Grayish black thin laminated carbonaceous silicalite, the thickness of a single layer: 0.2–6 cm. 5.45 m

31. Dark gray and greyish-black thin laminated argillaceous silicalite, the thickness of a single layer: 2–8 cm, very thin horizontal bedding developing locally. 8.68 m

Conformable contact

Piyuancun Formation Total thickness: >3.25 m

30. Light gray thick laminated argillaceous silicalite, bands in black and white developing in the layer. 3.25m

The lithology Hetang Formation is described as follows by taking the sample of Hetang Formation ($Є_1h$)–Dachenling Formation ($Є_1h$) profile of the Cambrian of Xianxia map sheet in Meijiata, Xianxia Town, Ningguo City, Anhui Province (Fig. 2.13). The details are as follows:

Dachenling Formation Total thickness: >12.09 m

53. Black thick laminated micrite, the thickness of a single layer: 50–150 cm, very thin horizontal bedding developing. 12.09m

Conformable contact

The second member of Hetang Formation 201.35 m

52. Black thick laminated carbonaceous mudstone, the thickness of a single layer: 50–80 cm, very thin horizontal bedding developing. 22.93 m

51. Black medium laminated carbonaceous siliceous mudstone, the thickness of a single layer: 20–30 cm, horizontal bedding developing. 7.49 m

50. Black thin–medium laminated siliceous carbonaceous mudstone, the thickness of a single layer: 8–25 cm thick. 3.57 m

49. Black thin laminated carbonaceous siliceous mudstone interbedded with medium laminated carbonaceous siliceous mudstone, the thickness of a single-layer carbonaceous siliceous mudstone: 2–8 cm; very thin horizontal bedding developing, flaky; the thickness of a single layer of the carbonaceous mudstone: 15–30 cm. 8.10 m

48. Black medium laminated carbonaceous siliceous mudstone, the thickness of a single layer: 10–20 cm. 7.46 m

47. Black thin laminated carbonaceous siliceous mudstone interbedded with medium laminated siliceous mudstone; the thickness of a single layer of the carbonaceous siliceous mudstone: 4–8 cm, very thin horizontal bedding developing, flaky. 3.57 m

46. Black thin laminated carbonaceous siliceous mudstone, the thickness of a single-layer: 8–9 cm, horizontal bedding developing. 3.21 m

45. Black thin laminated carbonaceous siliceous mudstone, the thickness of a single-layer: 5–9 cm generally and >10cm partly. 5.00 m

44. Black medium laminated carbonaceous siliceous mudstone, micro-fine grained pyrite visible occasionally, the thickness of a single layer: 15–30 cm, horizontal bedding developing. 4.56 m

43. Black thin–medium laminated carbonaceous siliceous mudstone, the thickness of a single-layer: 6–11 cm, horizontal bedding developing. 23.93 m

42. Black thin laminated siliceous carbonaceous mudstone, the thickness of a single layer: 5–8 cm generally and >10 cm partly, very thin horizontal bedding developing. 9.68 m

41. Black medium laminated siliceous carbonaceous mudstone containing sparse micro-fine grained pyrite, the thickness of a single layer: 15–30 cm, very thin horizontal bedding developing. 5.58 m

40. Black thin laminated carbonaceous siliceous mudstone, disseminated pyrite sparsely distributed in the mudstone and concentrating locally and discontinuously along the bedding, the grain size of the pyrite: 0.1–0.5 mm, the thickness of a single layer: 5–9 cm generally and 10–12 cm partly. 7.93 m

39. Black medium laminated silicon-bearing carbonaceous mudstone interbedded with carbonaceous mudstone. The micro-fine vein consisting of aggregates of pyrite with a grain size of 0.1–1 mm is visible in the siliceous carbonaceous mudstone. The middle part of this bed is interbedded with the two layers of 3–5 cm thick carbonaceous mudstone. The thickness of a single layer of siliceous carbonaceous mudstone: 10–20 cm. 19.07 m

38. Black thin laminated siliceous carbonaceous mudstone, micro-fine grained pyrite developing along the bedding, the thickness of a single layer: 1–3 cm. 1.23 m

37. Black medium laminated carbonaceous siliceous mudstone containing disseminated pyrite with a grain size of 0.1–1 mm, the thickness of a single layer thickness: 10–30 cm, horizontal bedding developing. 4.12 m

36. Black thin laminated siliceous carbonaceous mudstone with pyrite being distributed occasionally, the thickness of a single-layer: 1–5 cm. 15.06 m

35. Black medium laminated carbonaceous silicalite containing disseminated pyrite, the thickness of a single layer: 10–30 cm, horizontal bedding developing. 0.67 m

34. Black thin laminated carbonaceous silicalite, micro-layer (disseminated) pyrite developing along the layers, the thickness of a single layer: 2–7 cm, very thin horizontal bedding developing; three layers of disseminated–densely disseminated pyrite visible. 4.53 m

33. Black medium laminated carbonaceous siliceous mudstone, micro-layer pyrite with a grain size of 0.1–0.2 mm visible in the layers, the micro-vein association consisting of 2 mm×5 mm pyrite nodule partly visible. 3.87 m

32. Dark gray–black thin laminated carbonaceous silicalite interbedded with medium laminated siliceous mudstone, the thickness of single-layer carbonaceous silicalite: 2–7 cm, the thickness of single-layer siliceous mudstone: 15–20 cm, the ratio of the carbonaceous silicalite to the siliceous mudstone: (2–5):1. 4.13 m

31. Dark gray medium laminated carbonaceous silicalite, the thickness of a single-layer: 10–20 cm, horizontal bedding developing. 4.54 m

30. Black thin laminated carbonaceous silicalite, the thickness of a single layer: 3–6 cm; aggregation of micro-fine grained pyrite visible along the bedding, micro interbedded, the thickness of single layer: 0.1–0.3 mm; 20 cm thick carbonaceous mudstone constitutes the top. 3.27 m

29. Black medium laminated carbonaceous silicalite; aggregation of micro-fine grained pyrite concentrating along the layers, forming the densely disseminated pyrite layer with a thickness of 0.1–1 mm; 3×10 cm pyrite nodule visible occasionally; the thickness of a single layer: 10–12 cm. 7.75 m

28. Black thin laminated carbonaceous silicalite; fine line consisting of 5% micro-fine grained pyrite visible along the layer; 3–4 layers of 1–3 cm × 3–7 cm pyrite nodules visible, with the major axis extending along the layers discontinuously. 10.10 m

——————— Conformable contact ———————

The first member of Hetang Formation Total thickness: 445.99 m

27. Black medium laminated carbonaceous silicalite, a small amount of micro-fine grained pyrite visible in the rock, the thickness of a single layer: 10–30 cm. 2.24 m

26. Black thin laminated siliceous carbonaceous mudstone, the micro-fine grained pyrite distributed along the bedding, interbedded with a layer of 1 cm thick pyrite. 2.18 m

25. Black medium laminated siliceous carbonaceous mudstone; the thickness of a single layer: 10–20 cm; the top: off-white clay layer, 0.1–2 cm thick, discontinuously distributed along the layers. 16.96 m

24. Covering. 31.23 m

23. Dark gray thin–medium laminated carbonaceous siliceous mudstone, the thickness of a single layer: 6–15 cm. 58.74 m

22. Covering. 30.76 m

21. Black medium laminated carbonaceous silicalite, the micro-fine grained disseminated pyrite visible occasionally in the rocks, the thickness of a single layer: 20–30 cm. 25.05 m

20. Black medium laminated carbonaceous silicalite, the thickness of a single layer: 10–20 cm, horizontal bedding developing, containing a small amount of disseminated pyrite. 6.21 m

19. Black thin laminated carbonaceous siliceous mudstone, containing a small amount of disseminated pyrite, the thickness of a single layer: 2–6 cm. 7.65 m

18. Black medium laminated carbonaceous siliceous mudstone, the micro-fine grained pyrite layer distributed along the bedding, 1 cm × 3 cm ellipsoid pyrite nodule partly visible, the covellite occasionally visible in cracks, the thickness of a single layer: 10–30 cm. 17.18 m

17. Covering. 22.46 m

16. Dark gray thin–medium laminated carbonaceous siliceous mudstone interbedded with micro–thin laminated carbonaceous mudstone, the thickness of a single layer of carbonaceous siliceous mudstone: 8–15 cm, horizontal bedding developing; the thickness of a single layer of carbonaceous mudstone: 0.5–1 cm, a small amount of micro-fine grained pyrite visible in the rocks. 7.72 m

15. Black medium laminated carbonaceous siliceous shale; the thickness of a single layer: 20–30 cm; horizontal bedding developing; interbedded with a layer of phosphate nodules with thickness of 30–40 cm near the upper part, the size of a single nodule: 1–3 cm, ellipsoid. 20.63 m

14. Black medium laminated carbonaceous mudstone, micro-fine grained disseminated pyrite concentrating along the bedding, the thickness of a single layer: 10–25 cm. 56.63 m

13. Dark gray thin laminated carbonaceous silicalite, the thickness of a single layer: 3–8 cm, horizontal bedding developing. 10.92 m

12. Dark gray thin–medium laminated siliceous carbonaceous mudstone interbedded with micro laminated carbonaceous mudstone, the thickness of a single layer of siliceous carbonaceous mudstone: 8–20 cm, very thin horizontal bedding developing; the thickness of a single layer of carbonaceous mudstone: 1cm. The ratio of the siliceous carbonaceous mudstone to the carbonaceous mudstone: (10–20):1. 21.72 m

11. Dark gray thin laminated carbonaceous mudstone, the thickness of a single layer: 1–8 cm, flaky. 17.46 m

10. Covering. 6.31 m

9. Dark gray thin laminated carbonaceous siliceous mudstone, the thickness of a single layer: 3–8 cm or partly up to 10cm. micro-fine grained pyrite visible locally. 14.48 m

8. Dark gray thin–medium laminated carbonaceous siliceous mudstone interbedded with micro laminated carbonaceous shale, horizontal bedding developing in carbonaceous siliceous mudstone, the thickness of a single layer: 8–20 cm, the thickness of a single layer of carbonaceous shale: 1–2 cm. 7.18 m

7. Dark gray thin laminated carbonaceous silicalite, the thickness of a single layer: 1–3 cm, horizontal bedding developing, prone to thin plate rocks after weathering. 3.85 m

6. Black medium laminated carbonaceous siliceous mudstone, a small amount of micro-fine grained pyrite distributed in the rocks in disseminated manner, the pyrite nodule with a grain size of 1–3 mm discontinuously distributed along the layers locally, the thickness of a single layer: 20–40 cm, very thin horizontal bedding developing. 4.67 m

5. Dark gray thin siliceous carbonaceous mudstone interbedded with thick laminated carbonaceous mudstone, the thickness of a single layer siliceous carbonaceous mudstone: 1–5 cm, horizontal bedding developing, the thickness of a single layer of carbonaceous mudstone: 0.5–1.5 cm, the ratio of the siliceous carbonaceous mudstone to the carbonaceous mudstone: (2–4):1. 21.60 m

4. Interbed consisting of dark gray medium laminated carbonaceous siliceous mudstone and thin siliceous mudstone, the thickness of a single layer of carbonaceous siliceous mudstone: 10–20 cm, the thickness of a single layer of siliceous mudstone: 1–3 cm. The ratio of carbonaceous siliceous mudstone to the siliceous mudstone: (2–4):1. 7.55 m

3. Dark gray medium laminated carbonaceous silicalite, very thin horizontal bedding in black and white developing, the thickness of a single layer: 30–45 cm. 1.32 m

2. Dark gray medium laminated carbonaceous silicalite, very thin horizontal bedding developing, flaky, the thickness of a single layer: 10–25 cm. 6.19 m

1. Dark gray thin laminated siliceous mudstone, the thickness of a single layer: 1–5 cm, very thin horizontal bedding developing. 17.1 m

———— Conformable contact ————

Piyuancun Formation (Z_2p) Total thickness:>13.16 m

0. Silicalite in black and white, very thin horizontal bedding developing, the thickness of a single layer of bedding: 1–3 mm. 13.16 m

2. **Lithological Characteristics**

The lithology of the first member of Hetang Formation is mainly characterized by carbonaceous silicalite, argillaceous silicalite, siliceous mudstone, carbonaceous mudstone, and phosphate nodule layer.

(1) The carbonaceous silicalite: dark gray–black, composited of cryptocrystalline siliceous matter (80–90%) and the amorphous carbonaceous matter (5–15%), horizontal bedding developing generally in the layers.
(2) The argillaceous silicalite: dark gray, argillaceous cryptocrystalline texture; mainly composed of cryptocrystalline siliceous matter (45–65%), argillaceous matter

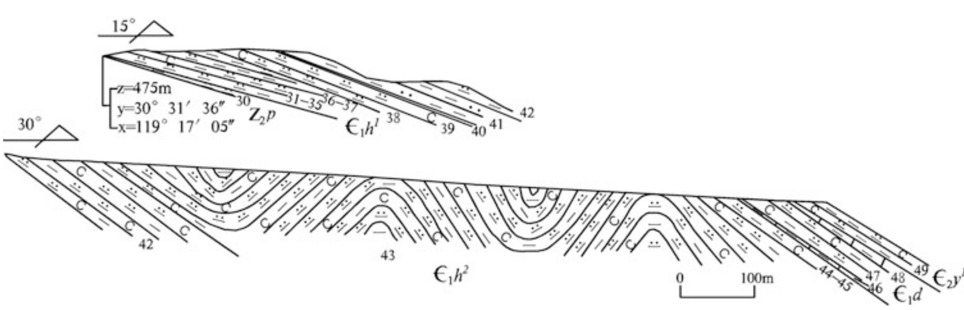


Fig. 2.12 Hetang Formation (Є$_1h$)–Dachenling Formation (Є$_1d$) profile of Cambrian System in Nanchewu, Hanggai Town, Anji County, Zhejiang Province

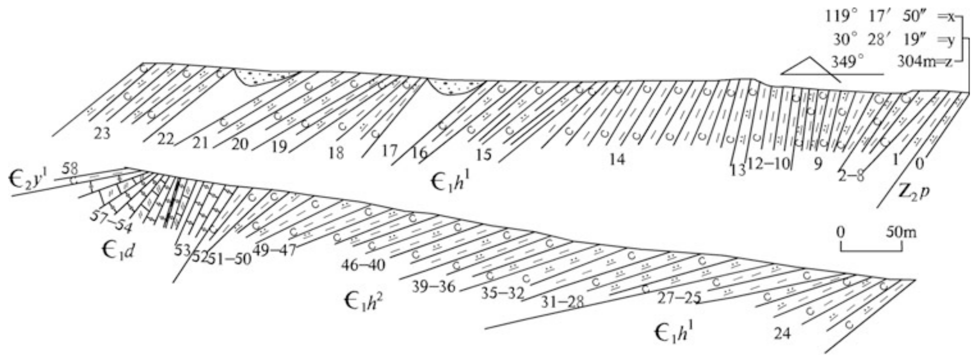


Fig. 2.13 Hetang Formation (Є$_1h$)–Dachenling Formation (Є$_1d$) profile of Cambrian Period in Meijiata, Xianxia Town, Ningguo City, Anhui Province

(20–35%), and amorphous carbonaceous (10–15%); micro-fine-grained pyrite visible occasionally.

(3) The siliceous mudstone: gray–dark gray, composition: argillaceous matter (65–75%) (major), siliceous (25–35%) (minor), micro-fine-grained pyrite visible occasionally, very thin horizontal bedding developing in the rock.

(4) The carbonaceous mudstone: black, mainly composed of carbonaceous matter (30–60%) and argillaceous (40–70%) matter, pyrite visible occasionally.

(5) The phosphate nodule layer: dark gray, in colloform texture, composited of black phosphorite-bearing siliceous spherulite of circularly shaped structure, nodule size: 2–30 mm, partly containing the small shelly fossils.

The lithology of the second member of Hetang Formation is mainly characterized by pyrite-bearing carbonaceous argillaceous silicalite and carbonaceous siliceous mudstone, interbedded with carbonaceous mudstone, a small amount of pyrite layer or pyrite nodule layer visible.

(1) The pyrite-bearing carbonaceous silicalite: dark gray; major component: cryptocrystalline siliceous matter (55–70%); minor components: amorphous carbonaceous matter (10–20%), argillaceous matter (15–25%), and pyrite (5–10%); silt visible occasionally (< 5%); aggregation of micro-fine-grained pyrite concentrating along the layers.

(2) The carbonaceous siliceous mudstone: grayish black; mainly composed of the argillaceous matter (45–65%), cryptocrystalline siliceous matter (15–25%), amorphous carbonaceous matter (10–15%), and pyrite (< 5%); micro-fine-grained pyrite concentrating along the layers.

(3) The carbonaceous mudstone: black, micro-laminated with the thickness of less than 2 cm generally, composed of carbonaceous (10–20%) and argillaceous (80–90%), pyrite visible occasionally.

(4) The pyrite layer or pyrite nodule layer, main component: micro-fine-grained pyrite (45–75%) with a grain size of less than 0.2 mm; minor component: argillaceous matter (15–25%), carbonaceous matter visible occasionally, disseminated pyrite concentrating along the layers, pyrite nodule with a size of 2–20 cm appearing locally; the thickness of the lithological layer formed: less than 3 cm.

3. **Basic Sequences**

There are three types of basic sequences developing in Hetang Formation (Є$_1h$), including three in the first member of Hetang Formation (Є$_1h^1$) and two in the second member of Hetang Formation (Є$_1h^2$). The two members share two same types of basic sequences (Fig. 2.14).

Basic sequences of type A: located in the lower parts of the first member and the second member, composed of ① grayish black thin–medium laminated carbonaceous argillaceous silicalite and ② black micro-laminated carbonaceous mudstone. For the first component: small pyrite lens commonly visible, micro-fine-grained pyrite distributed along the layers, horizontal bedding developing, spongy spicules as a result of pyrite metallization visible occasionally, thickness: 5–18 cm. For the second component: mainly

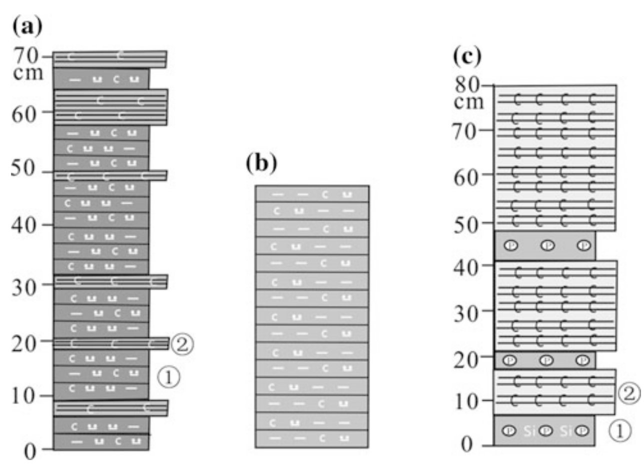


Fig. 2.14 Basic sequence map of Hetang Formation (Є$_1h$)

composed of carbonaceous matter, 2–20 mm thick, prone to deformation under compression and becoming graphitization films. The basic sequences of this type are composed of argillaceous–siliceous rocks and contain carbon and sulfide in reduction environment. Therefore, they belong to argillaceous–siliceous facies of abyssal basin and are of non-cyclic basic sequence.

Basic sequences of type B: located in the upper parts of the first member and the second member, composed of the dark gray thin–medium laminated carbonaceous siliceous mudstone with argillaceous matter as major component and siliceous matter as minor component, micro-fine-grained pyrite concentrating along the bedding. Therefore, they belong to the siliceous-argillaceous facies of abyssal standing-water reduction environment and are of monotonous basic sequence.

Basic sequences of type C: located in the lower part of the first member of Hetang Formation, composed of ① black thin laminated phosphorite-bearing siliceous spherulite and ② black thin laminated carbonaceous mudstone or stone coal layer. The siliceous spherulite in the phosphorite is of a circularly shaped structure, indicating high-energy water body. In the carbonaceous mudstone, there are high content of argillaceous matter (60–80%), as well as high content of carbonaceous and organic matter, indicating that the sedimentation is closely related to paleontological activities. The basic sequences of this type are of non-cyclic basic sequence.

2.3.1.2 Sequence Stratigraphy

According to the characteristics of lithologic association of the Cambrian as well as the types of tops and bottoms, there is a second-order sequence SS4 from the fourth member of Lantian Formation of the Late Sinian to the Dachenling Formation of the Early Cambrian, and there is a second-order sequence SS5 from the first member of Yangliugang Formation of the Middle Cambrian to the Huayansi Formation of the Late Cambrian. According to the changes in sedimentary facies of the second-order sequences, SS4 is further divided into seven third-order sequences (Sq5–Sq11), and SS5 is further divided into four third-order sequences (Sq12–Sq15).

There are a few types of rocks in Hetang Formation in the Area, and the main component is argillaceous–siliceous matter. Besides, there is a small amount of carbonaceous matter. This indicates monotonous standing-water reduction environment. The relative change in the content of argillaceous–siliceous matter reflects slight rise and falling of the sea level. Based on these, as well as the carbon and sulfide contained in the rocks of various periods, the transgression, the maximum flooding surface, and the regression are identified. Meanwhile, the division of Hetang Formation in terms of the transgressive systems tract (TST), the starved section, and the highstand systems tract (HST) is determined. According to the lithology, the petrofacies association, and the characteristics of sequence boundary of the Meijiata profile of Xianxia map sheet and Nanchewu profile of Hanggai map sheet, the first member of Hetang Formation ($Є_1h^1$) is divided into four third-order sequences (Sq6–Sq9) and the second member of Hetang Formation is divided into one third-order sequence. All of these third-order sequences are the parts of the second-order sequence SS5 (Fig. 2.15).

Third-order sequence Sq6: Located at the bottom of the first member of Hetang Formation, it includes TST and HST. The bottom of it is the conformity interface between the dark gray thin laminated siliceous mudstone and the silicalite or argillaceous silicalite of Piyuancun Formation. It is in regional parallel unconformable contact with Jiangshan–Changshan–Yushan area in the southwest. The top of it is the internal conformity interface of the first member of Hetang Formation. The top and the bottom are both of type-II sequence boundaries. TST is located in Bed 1–Bed 3, and the major and minor sediments in TST are siliceous matter and argillaceous matter, respectively. Owing to the very thin horizontal bedding developing partly, TST belongs to argillaceous–siliceous facies of abyssal basin. Located in Bed 4–Bed 6, HST contains the carbonaceous siliceous argillaceous matter bearing much micro-fine-grained pyrite as the main sediments. Furthermore, the horizontal bedding developed. Therefore, HST belongs to siliceous-argillaceous facies of bathyal basin. Therefore, the sedimentary environment in this sequence varies from abyssal basin facies to bathyal basin facies from bottom to top and this sequence is of progradation–aggradation type.

Third-order sequence Sq7: Located in the lower-middle part of the first member of Hetang Formation, it includes TST and HST, with the top and the bottom of type-II sequence boundary. TST is located in Bed 7–Bed 13. The sediments of it mainly include argillaceous–siliceous matter. Besides, there is a small amount of amorphous carbonaceous matter and associated synsedimentary micro-fine-grained sulfide locally. It can be indicated that the sedimentary environment of TST is standing-water reduction condition under wave base and TST belongs to abyssal siliceous-argillaceous facies. HST is located in Bed 14, and the major and minor sediments are the argillaceous and carbonaceous matters, respectively, associated with pyrite deposited. Thus, HST belongs to bathyal mudstone facies. Therefore, the sedimentary environment of this sequence gradually varies from the abyssal basin facies to the bathyal basin facies from bottom to top, and this sequence is of progradation–aggradation type.

Third-order sequence Sq8: Located in the upper-middle part of the first member of Hetang Formation, it includes TST and HST, with the top and the bottom of type-II sequence boundary. TST is located in Bed 15–Bed 16. The

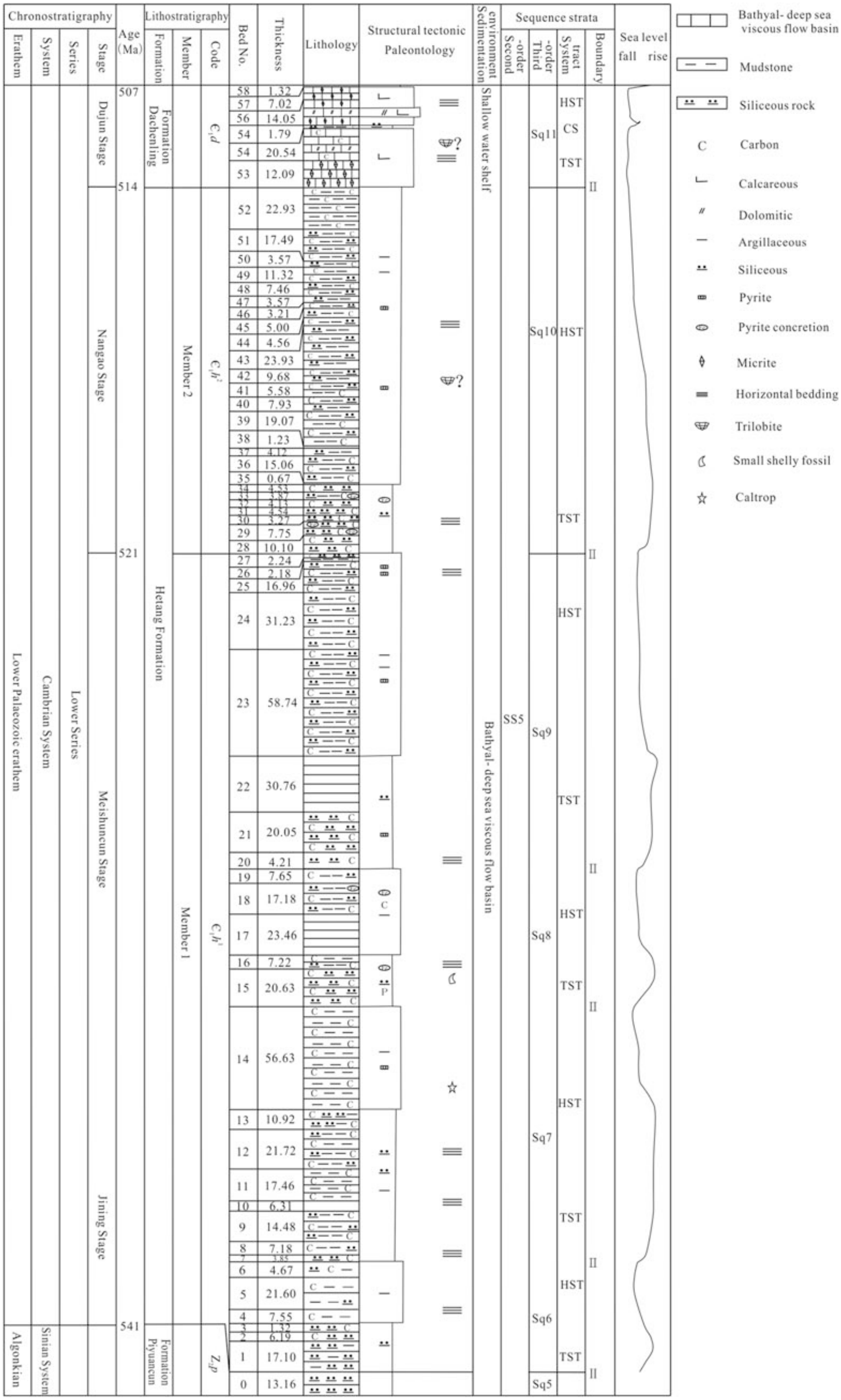


Fig. 2.15 Sequence stratigraphic framework of Hetang Formation–Dachenling Formation of Cambrian Period in the area

major and minor sediments of it are siliceous and argillaceous matters, respectively. Besides, there is a small amount of amorphous carbonaceous matter and associated micro-fine-grained sulfide deposited. Thus, TST belongs to abyssal argillaceous–siliceous facies in standing-water reduction environment under wave base. HST is located in Bed 17–Bed 19. The major and minor sediments of it are argillaceous and siliceous matters, respectively, with amorphous carbonaceous matter and pyrite commonly visible. Thus, HST belongs to bathyal mudstone facies under strong reduction environment. Therefore, the sedimentary environment in this sequence varies from the abyssal basin facies into the bathyal basin facies from bottom to top, and this sequence is of progradation–aggradation type.

Third-order sequence Sq9: Located in the upper part of the first member of Hetang Formation, it includes TST and HST, with the top and the bottom of type-II sequence boundary. TST is located in Bed 20–Bed 22. The major and minor sediments of it are siliceous and argillaceous matters, respectively. Besides, there is a small amount of amorphous carbonaceous matter and associated much micro-fine-grained sulfide deposited. Thus, TST belongs to abyssal argillaceous–siliceous facies in standing-water reduction environment under wave base. HST is located in Bed 23–Bed 27. The main and minor sediments of it are argillaceous and siliceous matters, respectively, with micro-layers of amorphous carbonaceous matter and pyrite commonly visible. Thus, TST belongs to bathyal mudstone facies under the strong reduction environment. Therefore, the sedimentary environment in this sequence varies from the abyssal basin facies into bathyal basin facies from bottom to top, and this sequence is of the progradation–aggradation type.

Third-order sequence Sq10: Located in the upper part of the second member of Hetang Formation, it includes TST and HST, with the top and the bottom of type-II sequence boundary. TST is located in Sq28–Sq34. The main sediment of it is siliceous matter. Besides, there is a small amount of argillaceous and amorphous carbonaceous matter as well as associated micro-fine-grained sulfide and nodules. Thus, TST belongs to abyssal argillaceous–siliceous facies in standing-water strong reduction environment under wave base. HST is located in Sq35–Sq52. The major and minor sediments are argillaceous and siliceous matters, respectively. Besides, there is a small amount of crystalline carbonaceous matter. There are commonly micro-fine-grained pyrite layers. Thus, HST belongs to bathyal mudstone facies under strong reduction environment. The sedimentary environment in this sequence changed from the abyssal basin facies into bathyal basin facies from bottom to top, and this sequence is of progradational–aggradational type.

The age range of the third-order sequences Sq6–Sq10 is 541–514 Ma, spanning 27 Ma. Each of the third-order sequences spans 5.4 Ma on average.

2.3.1.3 Biostratigraphy and Chronostratigraphy

No fossils were obtained in Hetang Formation of the Area in the Project. Ju (1983) reported that the fossils of *Hupeidiscus orientalis* (*Chang*) were discovered in Hetang Formation of Hanggai Town, Anji County. Much research on the palaeontology of Hetang Formation in Zhejiang Province was conducted in the areas such as Shangwan and Sanxikou of Fuyang, Hetang of Jiangshan, Duibian and Wujialing of Jiangshan, and Fenshui of Tonglu. Wanshi and Wuxi of Fuyang produced trilobite and peduncle, the first member of Hetang Formation in Duibian and Wujialing of Jiangshan, Dongxi of Tonglu, Shangwan of Fuyang, and Xinqiaotou of Xiaoshan produced small shelly animals, the second member of Hetang Formation in Duibian and Hetang of Jiangshan, Shangwan and Sanxikou of Fuyang, Xiayuqiao of Lin'an, and Fenshui of Tonglu produced trilobite and spongy caltrop.

The aforesaid organisms are the earliest metazoans since the Phanerozoic. Among these organisms, *Hupeidiscus orientalis* (*Chang*) is the earliest trilobite discovered in Zhejiang Province. According to *Stratigraphic Chart of China* (2014) of All China Commission of Stratigraphy, the small shelly animals in the first member of Hetang Formation belong to the Meishucunian, and the geological age range of them is the early–middle period of the Early Cambrian. The trilobites in the second member of Hetang Formation are parts of Hupeidiscus–Sinodiscus biozone. They belong to the Nangao, and the geological age range of them is the middle–late period of the Early Cambrian.

2.3.1.4 Analysis of Sedimentary Environment

The sediments of the Early Cambrian mainly consist of siliceous and argillaceous matter followed by carbonaceous matter. Besides, there is a small amount of terrigenous silt and sulfide. Regionally, a large amount of the literature indicates, based on the analysis of sediments, stable isotopes, and fossils, that the sedimentary environment of the Hetang Formation mainly is of deepwater basin–deepwater shelf facies, and the stone coal layer is mainly developed in the sagging part of the slope of the stagnant basin.

The composition of the sediment in Hetang Formation in the Area is evidently different from bottom to up. The content change of the pyrite, organic carbonaceous matter, and prehistoric fossils with facies significance indicates the change of the sedimentary environment from the weak oxidation environment to the reduction environment.

The sediments in the lower part of the first member of Hetang Formation mainly consist of major siliceous matter. Besides, there is a small amount of organic carbon and pyrite visible occasionally. The spongy spicules were well reserved in the rocks. All these indicate that the sedimentary environment in the lower part is still standing-water weak oxidation environment with weak hydrodynamic force. The stone coal layer in the middle part the first member of Hetang Formation mainly consists of organic carbon and contains multiple layers of phosphate nodules. Besides, most small shelly animals and the earliest trilobites were produced here. In this period, the highest content of oxygen in the water was beneficial to organism survival, and the first life explosion in earth history occurred during this period. The sediment in the upper part of the first member is mainly composed of the siliceous carbonaceous shale. However, it contains much sedimentary micro-fine-grained pyrite and pyrite layer with a thickness of 1–2 cm appears locally, indicating that the sedimentary environment was changed into a deep standing-water reduction environment.

The sediments of the second member of Hetang Formation mainly consist of argillaceous matter followed by carbonaceous and the siliceous matter. Horizontal bedding developed. Pyrite is generally distributed in the sediments, and the content of it is higher than that in the first member. Compared with the first member, the second member features more and evidently thicker (1–5 cm) pyrite interbeds. All these indicate a standing-water reduction environment.

Therefore, the sediments of the first member of Hetang Formation mainly include pelagic siliceous matter followed by a small amount of sulfide in the upper part. Therefore, the first member belongs to deepwater shelf–bathyal basin facies in weak oxidation–reduction environment with relatively scare terrigenous sediment sources. The main sediment in the second member of Hetang Formation is the siliceous argillaceous matter, containing much sulfide. Therefore, the second member belongs to bathyal–abyssal basin facies in standing-water reduction environment with scare terrigenous sediment sources.

Regionally, southwestward to Xianxia area of Anhui Province from the Area, the thickness of Hetang Formation increases gradually from nearly 300 to 650 m. It is inferred that the sedimentary basin became deeper accordingly. About 70 km southeastward to Yuhang area from the Area, the lithofacies of Hetang Formation changes into black carbonaceous dolomitic mudstone without silicalite, stone coal layer, and phosphorite, and the thickness is 25 m. This indicates a neritic platform environment.

2.3.1.5 Trace Elements in Strata (Ore-Bearing)

Eighteen rock spectra of the first member ($Є_1h^1$) and the second member ($Є_1h^2$) of Hetang Formation were systematically collected from the Nanchewu profile (PM010) of Hanggai map sheet in Hanggai Town, Anji County, Zhejiang Province. According to spectral analysis, the enriched elements of the first member of Hetang Formation are basically similar to those of the second member. The first member is enriched in Sb, Bi, Cu, Zn, Mo, and Ag, and poor in Au, Be, W, F, and the second member is enriched in Sb, Bi, Zn, Mo, and Ag, and poor in Au. These enriched and poor elements are related to rock type. The argillaceous rock bearing carbon and silicon are enriched in many types of trace elements with high concentration coefficients. The siliceous rock ranks the second.

According to the report of geological investigation of Lin'an map sheet on a scale of 1:200,000 (Zhejiang Bureau of Geology 1967), there are 4–15 layers of phosphate nodule or phosphorite in the first member of Hetang Formation. The thickness is 0.1–2.5 m, and the nodule size is 2–5 cm generally or even up to 10 cm × 25 cm. The content of P_2O_5 is 1–30%. The phosphate nodule layers mostly concentrate nearby stone coal bed. The first member of Hetang Formation in the Area is interbedded with 1–2 layers of stone coal. The ash content is 80–90%, and the thickness is 2–50 m. In the stone coal layers and the phosphate nodule layers, the content of vanadium is 0.3–2% or even up to 6% and content of Mo is 0.004–0.025%. Besides, the content of U and Ni is high, reaching the lowest production grade locally.

2.3.2 Dachenling Formation ($Є_1d$)

The name Dachenling Formation was created by Li and Yu (1965) in Dachenling Village in the southeast of Dachen Town, Jiangshan City, Zhejiang Province, when they discovered *Arthricocephalus* in the bottom of the former Yangliugang Formation. It is still used up to now by the preparation group of the regional stratigraphic table of Zhejiang Province (1979) as well as in the literature such as *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). In this Project, the name Dachenling Formation is still adopted according to the characteristics of Wenguan profile (PM003), Yekengwu profile (PM043), and Nanche profile (PM010) of Hanggai map sheet, Meijiata profile (PM035) of Xianxia map sheet, and the lithology along the survey traverse.

2.3.2.1 Lithostratigraphy

The distribution of the Dachenling Formation in the Area is basically the same as that of Hetang Formation. The outcrop area of Dachenling Formation is about 7.64 km^2, accounting for 0.60% of the bedrock area. The characteristics of the lithology and the lithologic association are as follows. The lower part of the formation consists of the interbeds of the gray–dark gray medium laminated dolomitic limestone and the micro-laminated calcareous dolomite. The middle part of the formation consists of the dark gray–black carbonaceous argillaceous or silty silicalite interbedded with dolomitic limestone. The upper part of the formation consists of the interbeds of dark gray thin–medium laminated micrite or dolomitic limestone and thick laminated marlstone or dolomitic limestone. This formation is in conformable contact with underlying Hetang Formation and overlying Yangliugang Formation. The thickness of Dachenling Formation is 52.94–76.20 m.

1. **Stratigraphic section**

The lithology of Dachenling Formation is described by taking the example of Cambrian Hetang Formation ($\epsilon_1 h$)–Dachenling Formation ($\epsilon_1 d$) profile (Fig. 2.13) of Xianxia map sheet in Meijiata, Xianxia Town, Ningguo City. The details are as follows:

The first member of Yangliugang Formation Total thickness: >1.32 m

58. Dark gray thin–medium laminated carbonaceous mudstone, the thickness of a single layer: 6–20 cm, very thin horizontal bedding developing. 1.32 m

———— Conformable contact ————

Dachenling Formation Total thickness: 55.48 m

57. Gray medium laminated micrite interbedded with micro laminated dolomitic limestone; the micrite: the thickness of a single layer: 10–25 cm, very thin horizontal bedding developing, pyrite nodules with a size of 1 cm visible occasionally; the dolomitic limestone: micro banded, fawn after weathering, the thickness of a single layer: 1–3cm; the ratio of the micrite to the dolomitic limestone is (3–8):1; the karst micro-landform with lithological difference is costate. 7.02 m

56. Gray thick laminated micrite interbedded with thick laminated dolomitic limestone; the micrite: the thickness of a single layer: 50–60 cm, very thin horizontal bedding developing; dolomitic limestone: the thickness of a single layer: 1–3cm, a part of the layers distributed in a banded and discontinuous manner; the ratio of the micrite to dolomitic limestone: (30–40):1. 14.05 m

55. Dark gray medium–thick laminated carbonaceous siliceous mudstone, the thickness of a single layer: 30–40 cm, very thin horizontal bedding developing. 1.79 m

54. Gray thick laminated carbonaceous micrite interbedded with the thick laminated dolomitic limestone; the thickness of a single layer of the carbonaceous micrite: 50–80 cm; the thickness of a single layer of the dolomitic limestone: 0.5–2 m; very thin horizontal bedding visible in the layers of both the carbonaceous micrite and the dolomitic limestone. 20.54 m

53. Black thick laminated micrite, the thickness of a single layer: 50–150 cm, very thin horizontal bedding developing. 12.09 m

———— Conformable contact ————

The second member of Hetang Formation Total thickness: >40.42 m

52. Black thick laminated carbonaceous mudstone, the thickness of a single layer: 50–80 cm, very thin horizontal bedding developing. 22.93 m

51. Black medium laminated carbonaceous siliceous mudstone, the thickness of a single layer: 20–30 cm, horizontal bedding developing. 17.49 m

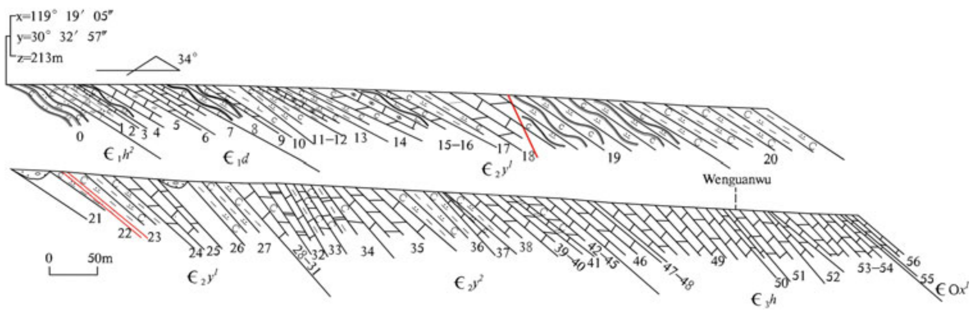


Fig. 2.16 Cambrian Dachenling Formation ($Є_1d$)–Huayansi Formation ($Є_3h$) profile in Wenguan Village, Hanggai Town, Anji County, Zhejiang Province

The lithology of Dachenling Formation is described by taking the example of Dachenling Formation ($Є_1d$)–Huayansi Formation ($Є_3h$) profile (Fig. 2.16) of Hanggai map sheet in Wenguan Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

The first member of Yangliugang Formation Total thickness: >24.51 m

8. The middle part: poor and discontinuous outcrops, lithology: dark gray thin–medium laminated siliceous carbonaceous silt mudstone; the thickness of a single layer: 8–20 cm; very thin horizontal bedding developing; the upper part: thin laminated marlstone with a thickness of 2 cm. 24.51 m

———— Conformable contact ————

Dachenling Formation Total thickness: 64.09 m

7. Interbed of dark gray thin micrite and argillaceous limestone; very thin horizontal bedding developing; the thickness of the micrite layers is not stable, and thickness of thick layers is even double that of thin layers. 6.4 m

6. Dark gray medium laminated marlstone, the thickness of a single layer: 15–30 cm, very thin horizontal bedding developing, prone to flake off along the bedding into 1–3 mm schistose. The upper part is interbedded with a small amount of medium laminated dolomitic limestone with the thickness of 10–15 cm. 4.13 m

5. Dark gray thin laminated micrite interbedded with thick laminated argillaceous limestone, very thin horizontal bedding developing in both the micrite and the argillaceous limestone. 25.45 m

4. Dark thin laminated carbonaceous silty siliceous mudstone, flaky. 10.60 m

3. Dark gray medium laminated dolomitic limestone, the thickness of a single layer: 15–30 cm, very thin horizontal bedding developing, spheroid partially due to weathering. 1.99 m

2. Black carbonaceous argillaceous silicalite, with a small amount of disseminated micro-grained pyrite (<1 mm), pyrite concentrating along the bedding locally. 10.21 m

1. Dark gray medium laminated dolomitic limestone, interbedded with carbonaceous siliceous mudstone with the thickness of 20 cm in the middle part; very thin horizontal bedding developing in the dolomitic limestone. 5.31 m

———— Conformable contact ————

The second member of Hetang Formation Total thickness: >11. 36 m

0. Black carbonaceous silty siliceous mudstone, with a small amount of micro-fine grained pyrite concentrating along the bedding; the pyrite: content: <5%, grain size: <1 mm. 11.36 m

2. **Lithological Characteristics**

The lithology of Dachenling Formation is mainly characterized by dark gray dolomitic limestone, dark gray–black carbonaceous argillaceous silicalite, dark gray micrite, thick laminated argillaceous limestone, and a small amount of dark gray marlstone.

(1) The dolomitic limestone: dark gray, microcrystalline structure; composition: microcrystalline calcite (75–85%), dolomite (5–20%), amorphous carbonaceous matter (5–8%). The analysis results of the chemical samples obtained by chip-channel method from Yekengwu profile are provided in *Report on the Survey and Evaluation Results of Cambrian Limestone Resources of Zhejiang Province* (2007). According to the results, the content of CaO and MgO in the dolomitic limestone of Dachenling Formation is 45–49% and 2.8–4%, respectively.
(2) The carbonaceous argillaceous silicalite and pyrite-bearing carbonaceous silicalite: dark gray–black; composition: cryptocrystalline siliceous matter (55–70%), amorphous carbonaceous matter (10–20%), argillaceous matter (15–45%), and pyrite (5–10%); silt visible occasionally (< 5%); the pyrite: micro-fine-grained, concentrating along the layers.
(3) The micrite: dark gray, microcrystalline structure; main components: microcrystalline calcite (80–95%) and argillaceous matter, the respective content of CaO and MgO in the rock: 40–49% and < 1%.
(4) The argillaceous limestone: dark gray; microcrystalline structure; main components: microcrystalline calcite (70–80%), argillaceous matter (10–15%), and dolomite (5%); containing a small amount of carbonaceous; the content of CaO and MgO in the rock is 36–42% and 0.5–1.5%.
(5) The marlstone: dark gray, microcrystalline structure; composition: microcrystalline calcite (45–55%), argillaceous matter (25–30%), dolomite (5–10%), carbonaceous (5–10%), and micro-fine-grained pyrite (2–3%); the pyrite concentrating along the layer; the respective content of CaO and MgO in the marlstone: 36–38% and 2–5.8%.

3. **Basic sequences**

There are three kinds of basic sequences developing in Dachenling Formation (Є$_1$*d*) (Fig. 2.17).

Basic sequences of type A: Located in the lower part generally, the lithology is characterized by: ① dark gray thin laminar dolomitic limestone: the thickness of a single layer: 0.5–2 cm generally or 3–5 cm occasionally, very thin horizontal bedding developing; and ② dark gray thin–medium laminated microcrystalline limestone: the thickness of a single layer: 2–10 cm, horizontal bedding developing. Since horizontal bedding is visible in both the dolomitic limestone and the microcrystalline limestone and the sediments are mainly composed of microcrystalline calcite, the basic sequences of this kind belong to carbonate facies of shallow shelf under standing-water sedimentary environment and are of non-cyclic basic sequence.

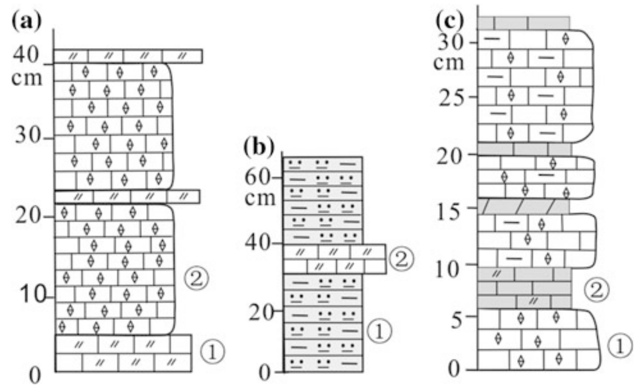


Fig. 2.17 Basic sequences of Dachenling Formation

Basic sequences of type B: Located in the middle part, the lithology is mainly characterized by dark gray–dark thin laminated carbonaceous argillaceous or silt silicalite; gray medium laminated dolomitic limestone is visible occasionally. The silicalite is mainly composed of cryptocrystalline siliceous matter, containing organic carbonaceous matter and pyrite. Therefore, the basic sequences of this kind belong to argillaceous–siliceous facies under bathyal–abyssal reduction environment. They consist of monotonous rocks; therefore, they are of monotonous basic sequence.

Basic sequences of type C: Located in the upper part, they are composed of the interbed of two kinds of rocks: ① dark gray thin laminated argillaceous micrite or micrite: mainly composed of microcrystalline calcite, with a small amount of dolomite of banded distribution, the thickness of a single layer: 2–13 cm, inconspicuous horizontal bedding developing; and ② dark gray micro-laminated limestone or dolomitic limestone: composed of microcrystalline calcite (major), argillaceous matter (minor), and dolomite (a small amount), the thickness of a single layer: 0.5–2 cm generally, very thin horizontal bedding developing. Stylolitic structures often developed between the two kinds of rocks. Compared with the basic sequences of type A, the basic sequences of type B contain more calcareous and argillaceous matter and feature evidently thicker rock layers, indicating that the water is relatively deeper and the basic sequences of type B belong to carbonate facies of the margin of shallow shelf.

According to the analysis of the lithology and sedimentary structure of the basic sequences in Dachenling Formation, the lower part is mainly composed of calcareous dolomite matter, indicating shallow sedimentary water; the middle part mainly consists of argillaceous–siliceous matter, indicating deep sedimentary water; the upper part mainly includes calcareous argillaceous matter, indicating that the water became shallower. Therefore, the sedimentary environment of Dachenling Formation can be described as: shallow-water weak oxidation → deepwater reduction → shallow-water weak oxidation.

2.3.2.2 Sequence Stratigraphy

According to the lithology and lithofacies association and the characteristics of sequence boundary of Meijiata Profile of Xianxia map sheet and Nanchewu profile of Hanggai map sheet, there is one third-order sequence Sq11 in Dachenling Formation. Sq11 belongs to the second-order sequence SS5 and is described as follows.

Third-order sequence Sq11 contains the transgressive systems tract (TST), starved section (CS), and the highstand systems tract (HST). The top and the bottom are conformity interfaces and belong to type-II sequence boundary. TST is located in the lower part of the sequence. The major and minor sediments of TST are calcareous matter and dolomitic matter, respectively. Besides, there is a small amount of argillaceous matter. Therefore, TST belongs to the sedimentary environment of the inner margin of shallow shelf. CS is located in the middle part of the sequence. The main sediment in CS is argillaceous–siliceous matter, resulting from scare chemical sedimentation of the precipitates under pelagic deepwater environment during the maximum marine flooding surface. HST is located in the upper part of the sequence. The major and minor sediments in it are calcareous matter and argillaceous matter, respectively. Besides, there is a small amount of dolomitic matter. Compared with the lower part of the sequence, HST contains more argillaceous matter; thus, HST belongs to oxidation–reduction sedimentary environment of the outer margin of shallow shelf. Therefore, the sedimentary environment in this sequence can be described as: shallow water → deepwater → shallow water. The water became deeper generally, and Sq11 is of aggradational–retrogradational type.

The age range of Sq11 is 514–507 Ma, spanning 7 Ma.

2.3.2.3 Biostratigraphy and Chronostratigraphy

No fossils were obtained in Dachenling Formation in the Project. Much research on the palaeontology of Hetang Formation in Zhejiang Province has been conducted in the areas such as Shangwan and Sanxikou of Fuyang, Hetang of Jiangshan, Duibian and Wujialing of Jiangshan, and Fenshui of Tonglu. According to the research, these areas produced trilobites, brachiopoda, hyoliths, worms, and paleopaly, which are parts of the Arthricocephalus biozone and belong to the Duyun according to *Stratigraphic Chart of China* (2014) prepared by All China Commission of Stratigraphy.

2.3.2.4 Characteristics of Stable Isotopes

As for the limestone of normal marine facies, the $\delta^{13}C$ value is $0 \pm 2‰$ and $\delta^{18}O$ value is from −13.0‰ to −1.30‰, with the average value of −9.76‰ (Zheng and Chen 2000); the $\delta^{34}S$ value is relatively stable in the Precambrian; the $\delta^{34}S$ value was the highest in the Early Paleozoic with the value of 26.0–35‰; $\delta^{34}S$ fluctuated in the Devonian, dropped to the lowest in the Permian, and increased to about 20‰ of the modern value irregularly after the Cretaceous Period $\delta^{34}S$ (Fig. 2.18).

Two samples were collected from the limestone of Dachenling Formation of Wenguan profile (PM003) for stable isotope analysis of $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$. The $\delta^{13}C$ values of the two limestone samples are −1.04 and 0.17‰, respectively, and the average is −0.44‰. The $\delta^{18}O$ values of the limestone samples are −16.66‰ and −14.55, respectively, and the average value is −15.61‰. The $\delta^{34}S$ values of the two samples are 23.1 and 35.3‰, respectively, and the average value is 29.2‰. Compared with the limestone of normal marine facies, the two limestone samples feature weak negative excursion of $\delta^{13}C$ and $\delta^{18}O$. This is consistent with the negative anomaly of $\delta^{13}C$ in the bottom of Dachenling Formation in Lin'an and Fuyang areas. The possible reason is the regional sea level rise in the

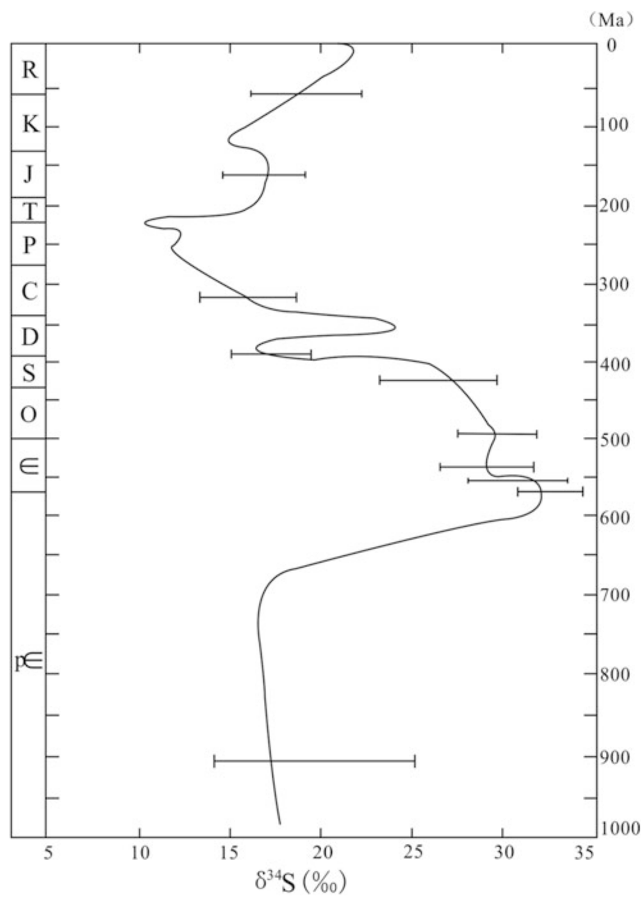


Fig. 2.18 Seawater sulfate $\delta^{34}S$ value change curve in the geological time (modified from Claypool et al. 1980)

Early Cambrian. Besides, this can prove that the Dachenling Formation in the Area belongs to the shallow shelf sedimentary environment with comparative deepwater. The $\delta^{34}S$ value is consistent with high $\delta^{34}S$ content range in the sulfate in the seawater of the Early Cambrian. The possible reason is as follows. With the organism explosion in the Early Cambrian, the sulfate-reducing bacteria reduced the sulfate, causing the fractionation of sulfur isotope. This further reflects that it is the shallow shelf environment with shallow water, moderate environment, and the rich nutrients that provided the condition for organism explosion in the Early Cambrian Period.

2.3.2.5 Analysis of Sedimentary Environment

The main lithology of the Dachenling Formation is characterized by limestone and argillaceous silicalite. As for the limestone, the major and minor components are microcrystalline calcite and dolomite, respectively; trilobites were produced in this formation and horizontal bedding developed, showing weak hydrodynamic force and shallow shelf environment with high oxygen content. There are 2–3 beds of argillaceous–siliceous sediment in the middle part of Dachenling Formation, with micro-fine horizontal bedding developing, indicating deep shelf–bathyal basin facies in a standing-water weak oxidation–reduction environment with scarce terrigenous sediment sources. Marl is absent due to the transition between the limestone and the argillaceous–siliceous sediment. Therefore, it can be inferred that the sea level once experienced a sharp rising and falling, and the sea level in the Dachenling Formation of the Area should experience 2–3 large-scale processes of rising and falling. Regionally, in Jiangshan–Zhuji area near Shaoxing–Jiangshan junction zone, a layer of micro-thin laminated carbonaceous mudstone can be identified in the middle part of the Dachenling Formation, indicating an inconspicuous sea level rise; in the Kaihua–Wangfu of Chun'an area, the Dachenling Formation is interbedded with 3–4 beds of argillaceous silicalite, indicating that sea level experienced four processes of rising and falling in this area.

2.3.2.6 Trace Elements in Strata (Ore-Bearing)

1. **Characteristics of trace elements in strata**

Ten rock spectra were collected in Dachenling Formation of Nanchewu profile (PM010) and Wenguan profile (PM003). According to spectral analysis, there is a big difference in trace element enrichment among a different lithology of Dachenling Formation. The argillaceous silicalite is enriched in Sb, Bi, Mo, Ag, and S, and poor in Au, Be, Zn, and TFe, while the limestone is enriched in Bi and Mo, and poor in Au, Be, Cu, Pb, Zn, W, and TFe. Therefore, argillaceous silicalite is obviously more enriched in trace elements than limestone. Furthermore, for the trace elements enriched in both argillaceous silicalite and limestone, the concentration coefficients in argillaceous silicalite are more than 5 times higher than those in limestone.

2. **CaO and MgO in main limestone and marl**

According to the *Report on the Survey and Evaluation Results of Cambrian Limestone Resources of Zhejiang Province* (2007), sampling by channel method and analysis was conducted for two beds of limestone in Dachenling Formation of Yekengwu profile, which is located in Hanggai Town, Anji County. According to the analysis results, the average content of CaO and MgO in the lower limestone (thickness: 23.05 m) is 47.56% and 2.04%, respectively. The average content of CaO and MgO in the upper limestone (thickness: 5.32 m) is 45.53% and 3.90%, respectively (Zhejiang Institute of Geological Survey 2007).

2.3.3 Yangliugang Formation ($\epsilon_2 y$)

The name Yangliugang Formation was created by Lu et al. (1955) in Yangliugang Village that is about 3.5 km to the northeast of Dachen, Jiangshan City, Zhejiang Province. According to the stratigraphic site conference data of western Zhejiang in 1963, Lu et al. (1955) believed that the Yangliugang Formation contained a part of Huayansi Formation and the stratum with the fossils of *Lejopyge* and *Oidalagnostus* constituted the top of Yangliugang Formation. Li and Yu (1965) divided the *Arthricocephalus* horizon from the bottom of the Yangliugang Formation and established Dachenling Formation accordingly. Since then, Yangliugang Formation is a part of the Middle Cambrian Series and thus the lithostratigraphy of it is consistent with its chronostratigraphy. Yangliugang Formation has been subsequently used up to now by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). In this Project, Yangliugang Formation was still adopted according to the lithological characteristics of Wenguancun profile (PM003) and Yekengwu profile (PM043) of Hanggai map sheet, Shiling profile (PM024) and Yutang profile (PM038) of Xianxia map sheet, and survey geological observation traverse in the Area.

2.3.3.1 Lithostratigraphy

The vast majority of the Yangliugang Formation ($\epsilon_2 y$) in the Area is distributed basically in the same way with Hetang Formation and Dachenling Formation. However, Yangliugang Formation features more extensive outcrops. The outcrop area is about 63.72 km^2, accounting for 5.01% of the bedrock area. In addition, Yangliugang Formation is distributed in a sporadic manner in Nanheling Village in the south of Xianxia intrusion in the southwest corner of Xianxia map sheet, Gaoling Village in the southeast corner of Xianxia map sheet, and Langling Village in the southern part of the Chuancun map sheet.

According to the characteristics of the lithology and lithologic association, Yangliugang Formation ($Є_2y$) can be divided into the first member of Yangliugang Formation ($Є_2y^1$)) and the second member of Yangliugang Formation ($Є_2y^2$).

The first member of Yangliugang Formation ($Є_2y^1$): grayish black thin laminated siliceous mudstone and silicalite, interbedded with argillaceous limestone; large lenticular limestone commonly visible; siliceous matter decreasing and calcareous argillaceous matter increasing upward; the bottom, consisting of thin laminated siliceous mudstone, in conformable contact with the dolomitic limestone of underlying Dachenling Formation; thickness: 118.05–279.13 m.

The second member of Yangliugang Formation ($Є_2y^2$): The lower part consists of dark gray thin–medium laminated marl, interbedded with banded–thin laminated microcrystalline limestone generally and pie-strip shaped microcrystalline limestone locally; the upper part is composed of the interbed of dark gray thin–medium laminated marl and banded–thin laminated microcrystalline limestone; from bottom to up, argillaceous matter decreases, calcareous matter increases, marl gradually decreases, microcrystalline limestone gradually increases; the thickness of the member ranges 134.40–247.60 m.

1. **Stratigraphic section**

The lithology of Yangliugang Formation is described by taking the example of Dachenling Formation ($Є_1d$)–Huayansi Formation ($Є_3h$) profile (Fig. 2.16) of Hanggai map sheet in Wenguan Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Huayansi Formation Total thickness: >15.76 m

46. Rhythm interbed of dark gray thin–medium laminated microcrystalline limestone and micro laminated marl. 15.76 m

———— Conformable contact ————

Yangliugang Formation Total thickness: 522.02 m

The second member of Yangliugang Formation Total thickness: 242.89 m

45. The lower part: interbed of dark gray banded microcrystalline limestone and thin laminated marl, the ratio between the two components: 1:1; the upper part: medium laminated marl interbedded with thin laminated microcrystalline limestone, the thickness of a single layer of the marl: 10–30 cm, the thickness of a single layer of microcrystalline limestone: 3–5 cm; the lower part: thinner marl with the thickness of a single layer of 8–15 cm, the microcrystalline limestone remaining the same compared with the middle part; very thin horizontal bedding visible in all rocks. 14.94 m

44. Dark gray medium laminated marl interbedded with medium laminated microcrystalline limestone; the marl: very thin horizontal bedding developing, prone to become thin laminated owing to weathering; the microcrystalline limestone: horizontal bedding developing, blocky owing to weathering, three layers in total, the thickness of a single layer: 30–35 cm. 2.74 m

43. Interbed of dark gray thin banded microcrystalline limestone and argillaceous limestone; the thickness of a single layer of the two components: 1–3 cm thick and 1–4 cm respectively. 5.42 m

42. Dark gray thin–medium laminated carbonaceous marl interbedded with a small amount of pie-strip shaped microcrystalline limestone; the thickness of a single layer of the carbonaceous marl: 8–15 cm; the size of a pie strip: (10–30) cm× (5–8) cm (length × width). 2.96 m

41. Interbed of dark gray thin banded microcrystalline limestone and dolomitic limestone; the banded microcrystalline limestone: 30–120 cm (length), very thin horizontal bedding developing; the thickness of the

single bed: 2–4 cm; the thickness of a single layer of limestone: 0.1–0.2 cm. 4.17 m

40. Dark gray thin–medium laminated argillaceous microcrystalline limestone, the thickness of a single layer: 8–20 cm, very thin horizontal bedding developing. 5.27 m

39. Interbed of dark gray thin laminated microcrystalline limestone and thick laminated marl; the thickness of a single layer of the two components: 4–8 cm and 1–3 mm respectively. 7.78 m

38. Interbed of dark gray thick laminated carbonaceous siliceous mudstone and rhythmic bed of thin laminated microcrystalline limestone and marl; the carbonaceous siliceous mudstone: very thin horizontal bedding developing, interbedded with a small amount of (5–10) cm × (5–30) cm microcrystalline limestone ellipsoid, the thickness of a single layer: 65–70 cm; the thin laminated microcrystalline limestone: very thin horizontal bedding developing, the thickness of a single layer: 2–8 cm; the thickness of a single layer of thin laminated marl: 1–3 cm. 20.08 m

37. Dark gray medium laminated microcrystalline limestone interbedded with black carbonaceous mudstone. For the microcrystalline limestone, the thickness of a single layer is 25–45 cm and gradually becomes 8–25 cm upwards. 5.26 m

36. Dark gray thin–medium laminated carbonaceous siliceous mudstone, interbedded with a small amount of microcrystalline limestone ellipsoid bed; the carbonaceous siliceous mudstone: very thin horizontal bedding developing, the thickness of a single layer: 6–15 cm; the size of microcrystalline limestone ellipsoid: 45 cm × 25 cm. 30.96 m

35. Interbed of dark gray thin–medium laminated marl and microcrystalline limestone; unclear horizontal bedding developing in the microcrystalline limestone; the marl: very thin horizontal bedding developing extremely, the thickness of a single layer: 8–20 cm; the ratio between the two components: about 1:1; the microcrystalline limestone gradually decreasing upwards. 43.09 m

34. Interbed of dark gray medium laminated carbonaceous marl and medium laminated argillaceous dolomite; the limestone: gradually decreasing upwards, the marl: very thin horizontal bedding developing extremely; the argillaceous dolomite: horizontal bedding developing, the thickness of a single layer: 20–45 cm, 4–5 layers in the lower part, the ratio to the argillaceous dolomite: 2:1 and 1:2 upwards, ellipsoid in the top. 25.77 m

33. Dark gray medium laminated argillaceous microcrystalline limestone, interbedded with black micro-thin bedded carbonaceous marl; the argillaceous microcrystalline limestone: unclear horizontal bedding developing, the thickness of a single layer: 12–70 cm; the carbonaceous marl: very thin horizontal bedding developing extremely, the thickness of a single layer: 1–8 cm generally and 30 cm locally. 13.75 m

32. Interbed of dark gray medium laminated carbonaceous dolomite and microcrystalline limestone; the microcrystalline limestone: vertical joints developing, thin segmented after being squeezed; the thickness of a single layer: 10–40 cm; the carbonaceous dolomite: the thickness of a single layer: 17–40 cm, the ratio to microcrystalline limestone: 2:1. 19.63 m

31. Dark gray medium–thick laminated carbonaceous marl, interbedded with five layers of microcrystalline limestone ellipsoid; the carbonaceous marl: containing micro-fine grained impregnated pyrite (<5%) that concentrate along the layers, the thickness of a single layer: 1–2 mm; the ellipsoid: (40–30) cm × (20–15) cm in size, micro horizontal bedding developing inside. 7.97 m

30. Interbed of dark gray thin–medium laminated microcrystalline limestone and marl; the thickness of a

single layer of microcrystalline limestone: 6–15 cm generally and 25–34 cm locally; the thickness of a single layer of marl: 2–13 cm. 11.81 m

29. Dark gray medium laminated carbonaceous argillaceous dolomite, the thickness of a single layer: 15–30 cm; very thin horizontal bedding developing extremely. 5.85 m

28. Interbed of dark gray medium laminated microcrystalline limestone and thin laminated carbonaceous marl; the microcrystalline limestone: very thin horizontal bedding developing, the thickness of a single layer: 15–20 cm; the ratio between the two components: about 1:1. 4.75 m

——— Conformable contact ———

The first member of Yangliugang Formation Total thickness: 79.13 m

27. Dark gray thin–medium laminated carbonaceous siliceous mudstone, interbedded with 10 layer of microcrystalline limestone ellipsoid, very thin horizontal bedding developing. 33.26 m

26. Covering. 13.10 m

25. Dark gray thin laminated microcrystalline limestone, interbedded with micro laminated marl; the microcrystalline limestone: very thin horizontal bedding developing, the thickness of a single layer: 2–5 cm generally and 25 cm locally; the thickness of the single bed of marl: 0.1–5 cm generally. 12.10 m

24. Dark gray medium laminated carbonaceous marl, interbedded with carbonaceous siliceous mudstone: the carbonaceous marl: finely disseminated pyrite visible occasionally, horizontal bedding developing, the thickness of a single layer: 20–30 cm. 8.47 m

23. Dark gray carbonaceous siliceous mudstone, fine-grained disseminated pyrite (<3%) visible. 19.16 m

22. Dark gray thin–medium laminated carbonaceous siliceous mudstone, very fine horizontal bedding developing, prone to flake off into flaky rocks with a thickness of 1–3 mm, a small amount of micro-fine disseminated pyrite (5%) visible in the mudstone that concentrates along the beds. 2.93 m

21. Covering. 8.60 m

20. Dark gray thin–medium laminated carbonaceous siliceous mudstone, horizontal bedding developing, occasionally interbedded with the limestone ellipsoid. 35.91 m

19. Dark gray thin–medium laminated carbonaceous siliceous mudstone, very thin horizontal bedding developing. 36.58 m

18. Dark gray medium laminated marl, interbedded with medium laminated microcrystalline limestone and thin laminated argillaceous dolomite; the marl: very thin horizontal bedding developing, the thickness of a single layer: 10–30 cm; the microcrystalline limestone: vertical joints developing, the thickness of a single layer: 10–30 cm, ellipsoidal after deformation; the thickness of a single layer of the argillaceous dolomite: 3–6 cm. 42.28 m

17. Dark gray thin laminated carbonaceous siliceous mudstone, interbedded with a microcrystalline limestone ellipsoid beds; the carbonaceous mudstone: very thin horizontal bedding extremely developing; the microcrystalline limestone ellipsoid: very thin horizontal bedding developing, size: 10–30 × 20–120 cm. 11.67 m

16. Dark gray medium laminated argillaceous limestone, very thin horizontal bedding developing. 0.50 m

15. Dark gray thick laminated carbonaceous limestone, interbedded with thin laminated calcareous mudstone and microcrystalline limestone ellipsoid; the thickness of a single layer of the carbonaceous limestone: 50–100 cm; the calcareous mudstone: prone to be platy, the thickness of a single layer: 3–5 cm; the microcrystalline limestone ellipsoid: 20 cm × 30 cm in size, horizontal bedding developing, long-axis parallel

bedding discontinuously distributed along the beds. 21.72 m

14. Dark gray medium laminated carbonaceous siliceous mudstone, interbedded with two layers of marl with the thickness of 25cm near the top; the siliceous mudstone: very thin horizontal bedding developing, the thickness of a single layer: 20–30 cm. 6.19 m

13. Dark gray medium laminated carbonaceous argillaceous silicalite, interbedded with three layers of microcrystalline limestone ellipsoids; the thickness of a single layer of carbonaceous argillaceous silicalite: 20–35 cm; the microcrystalline limestone ellipsoid: size (length × width): (20–120) × (15–50) cm approximately, long-axis parallel bedding developing; very thin horizontal bedding developing in all the layers and passing through the ellipsoid. 11.84 m

12. Covering. 7.02 m

11. Dark gray thin laminated carbonaceous argillaceous silicalite, the thickness of a single layer: 3–10 cm, very thin horizontal bedding developing, prone to flake off into platy rocks with a thickness of 3–5 mm. 5.74 m

10. Dark gray medium laminated carbonaceous calcareous mudstone, the thickness of a single layer: 10–40 cm, very thin horizontal bedding developing in all beds, microcrystalline limestone ellipsoid with a size of 10–30 cm × 20–50 cm visible locally along the beds; the long axis of the ellipsoid parallel to the bedding; the bedding in the mudstone parallel to the middle part of the ellipsoid; the bedding surrounding both sides of the ellipsoid visible. 14.38 m

9. Dark gray medium laminated carbonaceous marl, very thin horizontal bedding developing along the beds. 4.45 m

8. Dark gray thin–medium laminated silicon-bearing carbonaceous silty mudstone; the thickness of a single layer: 8–20 cm, very thin horizontal bedding developing. 20.03 m

——— Conformable contact ———

Dachenling Formation Total thickness: >2.84 m

7. Rhythm interbed of dark gray thin laminated microcrystalline limestone and micro laminated argillaceous limestone. 2.84m

2. **Lithological characteristics**

The lithology of Yangliugang Formation ($Є_2y$) is mainly characterized by microcrystalline limestone, marl, siliceous mudstone, or argillaceous silicalite. Besides, there are a small amount of dolomitic limestone and carbonaceous dolomite. In the first member, siliceous mudstone or argillaceous silicalite is common in the lower part, and microcrystalline limestone and marl are more common in the upper part. In the second member of Yangliugang Formation ($Є_2y^2$), microcrystalline limestone and marl are common, and the lower part is commonly interbedded with multilayers of dolomitic limestone and carbonaceous dolomite. Furthermore, a small amount of siliceous mudstone or argillaceous silicalite is interspersed in the dolomitic limestone and carbonaceous dolomite.

(1) The carbonaceous siliceous mudstone and silicalite: dark gray–black, argillaceous structure, mainly composed of argillaceous matter (10–25%), siliceous matter (60–75%), and silt (5–10%), additionally containing a small amount of carbon (5–10%).
(2) The dolomitic limestone: gray, micro-argillaceous phanerocrystalline structure, mainly composed of calcite (40–60%), dolomite (3–5%), and terrigenous clastic (such as quartz and sericite) (10–30%), the content of CaO and MgO: 30–40% and 1–9%, respectively.
(3) The marlstone: dark gray, micro-argillaceous phanerocrystalline, mainly composed of calcite (45–75%), argillaceous matter (25–30%), dolomite (5–18%), and carbonaceous (2–5%), the content of CaO and MgO: 29–35% and 1–4%, respectively.

(4) The micrite: gray, micro-argillaceous phanerocrystalline, composed of calcite (85–90%) and a small amount of argillaceous matter (10%), the content of CaO and MgO: 38–45% and 1–5%.
(5) The carbonaceous dolomite: gray, mainly composed of dolomite (75%), argillaceous matter (10–15%), and amorphous carbonaceous matter (5–10%).

3. **Basic sequences**

According to the rock types, association relationship, and sedimentary structure, there are five types of basic sequences developing in the Yangliugang Formation ($Є_2y$) from bottom to top (Fig. 2.19).

Basic sequences of type A: mainly distributed in the middle and lower parts of the first member, and consisting of thin–medium laminated siliceous mudstone. The components of the mudstone mainly include siliceous argillaceous matter besides a small amount of carbonaceous matter, silty matter, and pyrite. Therefore, the basic sequences of this type are of eupelagic siliceous argillaceous facies and belong to monotonic basic sequence.

Basic sequences of type B: distributed in the middle part and the lower part of the first member and the middle part of the second member, and consisting of ① the thin–medium laminated siliceous mudstone and ② ellipsoidal microcrystalline limestone. The siliceous mudstone: major component of the basic sequences of this type, the thickness of a single layer: 5–13 cm generally, fine horizontal bedding developing, containing a small amount of fine-grained pyrite, thus belonging to eupelagic argillaceous silicon facies. The microcrystalline limestone: ellipsoidal with a size of (5–15) cm × (20–50) cm, horizontal bedding developing, distributed discontinuously along the beds, therefore, belonging to carbonaceous facies of deep shelf. Since the limestone ellipsoid increases upward, the basic sequences of this type are of the basic sequence with carbonate rock increasing upward.

Basic sequences of type C: mainly distributed in the upper parts of the first member and the second member, and consisting of ① thin–medium laminated marl and ② microcrystalline limestone. The lower part of the basic sequences of this type is mainly composed of marl. The middle part is the marl-bearing microcrystalline limestone lenses, which gradually increase upward and become the main body of this type of basic sequences. The ratio of marl to microcrystalline limestone is about 1:1. Therefore, the basic sequences of this type are of the cyclic basic sequence with calcareous matter increasing and argillaceous matter decreasing gradually upward.

Basic sequences of type D: distributed in the lower part of the second member, consisting of ① medium laminated marl and ② the thin–medium laminated argillaceous dolomite or rhythmic layers of microcrystalline limestone. The main lithology is characterized by marl. The dolomite gradually decreases upward. Micro-fine horizontal bedding developed in the beds. This indicates that the sediment formed on a standing-water shallow shelf. Therefore, the

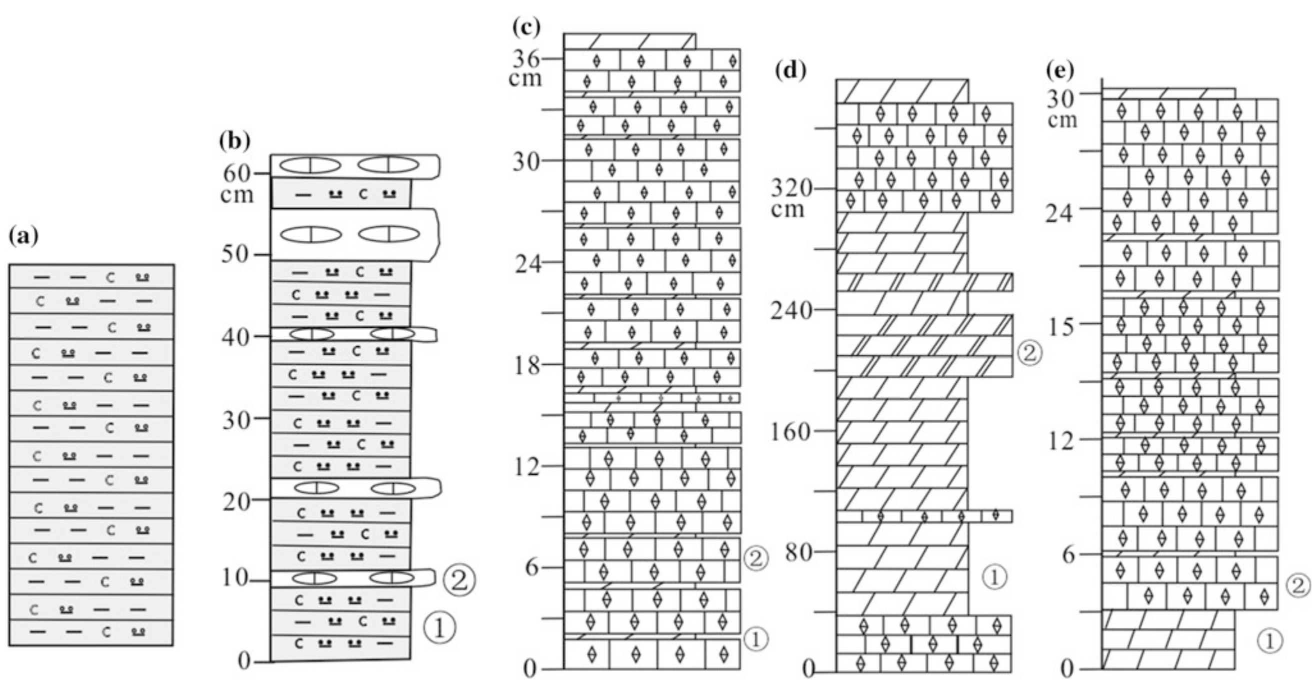


Fig. 2.19 Basic sequences of Yangliugang Formation ($Є_2y$)

basic sequences of this type are of a carbonate rock facies of shallow shelf. According to the relative changes of calcareous and magnesium carbonate, the basic sequences of this type are of the basic sequence with calcareous matter increasing and dolomite decreasing upward, generally reflecting the rise of the sea level.

Basic sequences of type E: distributed in the lower part and the middle-upper part of the second member, and consisting of ① medium laminated marl and ② thin–medium laminated argillaceous limestone or rhythmic layers of microcrystalline limestone. The marl constitutes the main lithology, and the amount of it is about 2–5 times that of microcrystalline limestone. Micro-fine horizontal bedding developed in the beds, indicating that the sediment formed on a relatively shallow shelf. Therefore, the basic sequences of this type are of carbonate rock facies of shallow shelf and belong to the basic sequence with calcareous matter increasing and argillaceous matter decreasing upward, reflecting the falling of the overall sea level.

In terms of the basic sequence association, the first member of the Yangliugang Formation mainly consists of the basic sequences of types A, B, and D from bottom to top, thus constituting a higher-order cyclic sequence. The second member of Yangliugang Formation is composed of the basic sequences of types D, B, and E from bottom to top, thus also constituting a higher-order cyclic sequence. Therefore, two progradational–aggradational sequences that become thicker upward are divided from Yangliugang Formation.

2.3.3.2 Sequence Stratigraphy

According to the association of lithology and lithofacies and the characteristics of sequence boundary of Wenguan profile of Hanggai map sheet, there is two third-order sequences (Sq12–Sq13) in the first member of Yangliugang Formation ($\epsilon_2 y^1$) and one third-order sequence (Sq14) in the second member of Yangliugang Formation ($\epsilon_2 y^2$) (Fig. 2.20). All of these sequences belong to the second-order sequence SS6.

Third-order sequence Sq12: Located in the lower part of the Yangliugang Formation, it contains TST and HST. The bottom of Sq12 is the parallel unconformity interface between the siliceous argillaceous facies in bathyal basin sedimentary environment of Yangliugang Formation and the carbonate facies in shallow shelf sedimentary environment of Dachenling Formation. The sedimentation of intermediate transitional environment is missing. Therefore, the bottom is of type-I sequence boundary. The top of Sq12 is a conformity interface between the siliceous argillaceous facies in bathyal basin sedimentary environment and the argillaceous carbonate facies in deep shelf sedimentary environment, belonging to type-II sequence boundary. TST is located in Bed 8–Bed 14. The main sediment of TST is thin–medium laminated siliceous argillaceous matter. The upper part of TST is occasionally interbedded with microcrystalline limestone ellipsoid; thus, TST is of bathyal siliceous argillaceous facies in weak reduction sedimentary environment under wave base, in which sediment is lacking. HST is located in Bed 15–Bed 18. The sediment of it is calcareous carbonate mainly besides a small amount of pyrite-bearing siliceous and argillaceous matter. Horizontal bedding developed in HST. Therefore, HST belongs to the carbonate facies in the shallow shelf sedimentary environment. Since siliceous matter decreases and argillaceous calcareous matter increases from bottom to top in this sequence, Sq12 is a sequence of progradational–aggradational type with the sea level gradually falling.

Third-order sequence Sq13: Located in the upper part of the Yangliugang Formation, it contains TST and HST. The top and bottom of Sq13 are of type-II sequence boundary. The TST is located in Bed 19–Bed 23. The sediment of TST is mainly siliceous argillaceous matter or argillaceous–siliceous matter, associated with sulfide and amorphous carbonaceous matter. Micro-fine horizontal bedding developed in TST. Therefore, TST is of bathyal siliceous argillaceous facies in reduction deep standing-water environment. HST is located in Bed 24–Bed 28. The sediment in HST is mainly calcareous carbonates and siliceous argillaceous matter, belonging to the facies of siliceous argillaceous matter-bearing carbonatite under deep shelf environment. Since siliceous argillaceous matter gradually decreases and carbonatite gradually increases from bottom to up in this sequence, Sq13 is of progradational–aggradational sequence with the sea level gradually falling.

Third-order sequence Sq14: Located in the second member of Yangliugang Formation, it includes TST, CS, and HST. The bottom of Sq14 is of type-I sequence boundary, and the top is of type-II sequence boundary. The TST is located on the Bed 29–Bed 35. The sediment in the bottom of TST is mainly dolomitic matter, and therefore, it is inferred that brief uplift and exposure once occurred. The sediment in the upper part of TST is mainly calcareous carbonate followed by argillaceous matter and dolomitic matter, belonging to the argillaceous carbonate rock facies under oxidization zone environment near wave base in the inner edge of shallow shelf. CS is located in Bed 36, and the sediment in it is siliceous argillaceous matter, belonging to bathyal siliceous argillaceous facies. HST is located in Bed 37–Bed 40, and the sediment in it is mainly calcareous carbonate, belonging to shallow shelf facies. Therefore, from

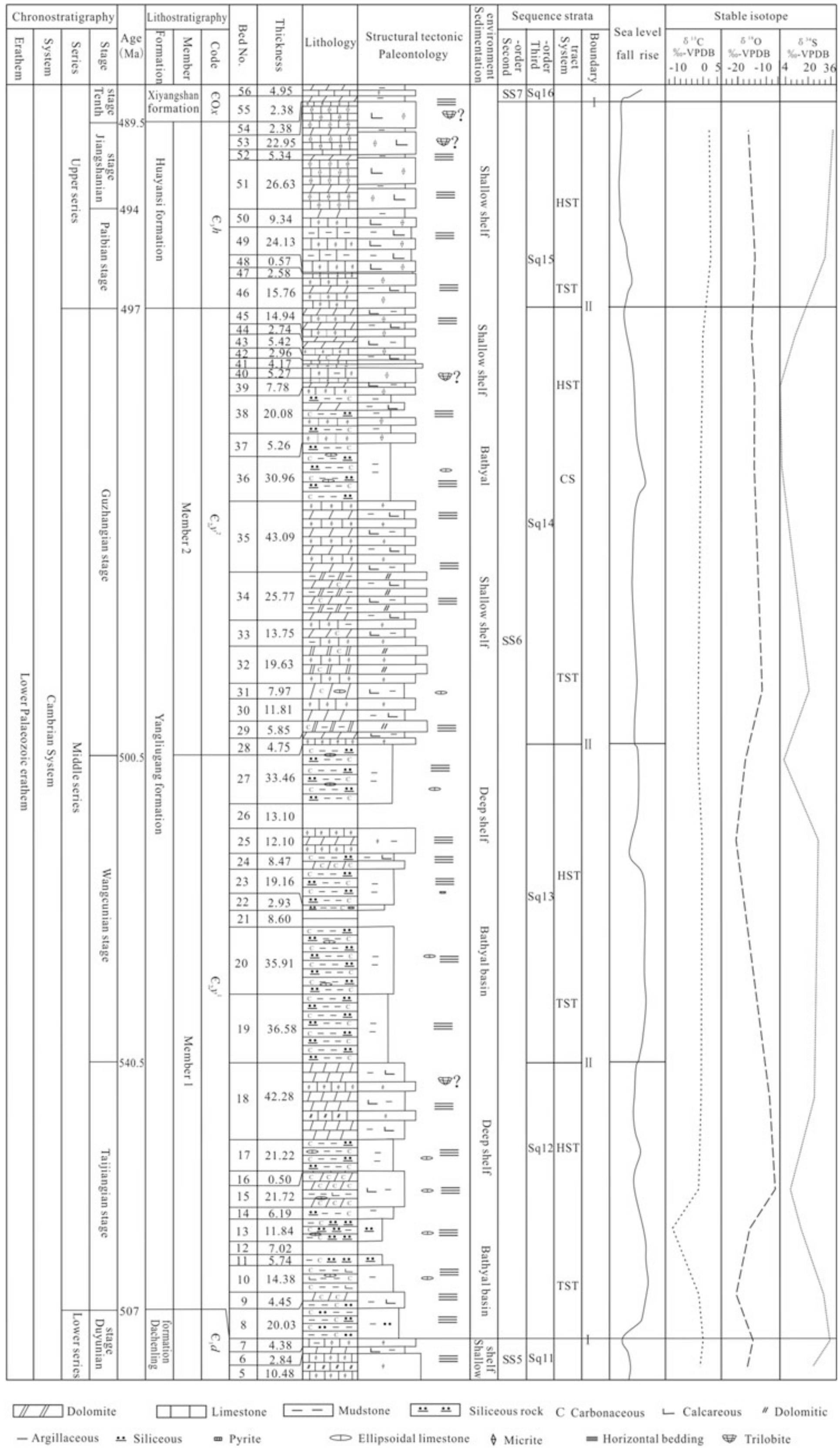


Fig. 2.20 Sequence stratigraphic framework of Yangliugang Formation–Huayansi Formation of the Cambrian Period in the area

bottom to top, the sediment in Sq14 is calcareous argillaceous matter, siliceous argillaceous mater, and argillaceous calcareous matter successively, indicating that the sea level experienced rise and falling successively. Therefore, Sq14 belongs to the sequence of progradation–retrogradation type.

In terms of time, the age range of Sq12, Sq13, and Sq14 sequences is 507 → 504.5 → 500.5 → 497 Ma, respectively. Therefore, the three sequences span 10 Ma in total. In detail, Sq12, Sq13, and Sq14 span 2.5 Ma, 4 Ma, and 3.5 Ma, respectively.

2.3.3.3 Biostratigraphy and Chronostratigraphy

In this Project, no fossils were obtained in Yangliugang Formation in the Area. Lu and Lin (1983) and Ju (1983) conducted detailed research on the palaeontology of Cambrian Period. In August 2011, Peng Shanchi et al. carried out systematic stratigraphic research on Dadoushan profile in Duibian, Jiangshan City, Zhejiang Province, and improved the materials obtained by Lu and Lin (1983). According to the improvement, five fossil zones are divided from the Yangliugang Formation from bottom to up, which are the fossil zones of *Ptychagnostus gibbus, Ptychagnostus atavus, Pseudophalacroma ovale, Lejopygelaevigata armata,* and *Proagnostus bulbus*, respectively, from bottom to up. Furthermore, according to the *Stratigraphic Chart of China* (2014), Yangliugang Formation belongs to the Taijiangian Stage, Wangcunian Stage, and Guzhangian Stage. In detail, the first member of Yangliugang Formation belongs to Taijiangian Stage and Wangcunian Stage, and the second member of Yangliugang Formation belongs to Guzhangian Stage.

2.3.3.4 Characteristics of Stable Isotopes

Five whole-rock stable isotope samples of $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$ of limestone were, respectively, collected from the first member and the second member of Yangliugang Formation in Wenguan profile (PM003).

As for the first member of Yangliugang Formation, the $\delta^{13}C$ value is from −10.69 to −0.39‰, with an average of −3.00‰; the $\delta^{18}O$ value is from −20.56 to −6.94‰ with an average of −14.48‰. As for the second member of Yangliugang Formation, the $\delta^{13}C$ value ranges from −1.84 to −0.02‰, with an average of –0.90‰; the $\delta^{18}O$ value is from −17.47 to −11.49‰, with an average of −14.48‰. Compared to the limestone of normal marine facies ($\delta^{13}C$ value: 0 ± 2‰, $\delta^{18}O$: from 13.0 to −1.30‰), the ten limestone samples experienced significant negative excursion of $\delta^{13}C$ value and $\delta^{18}O$ value. Consequently, it can be inferred that the sea level continued to rise after the period of Dachenling Formation and the Yangliugang Formation entered into the sedimentary environment such as bathyal basin and deep shelf. As a result, a large amount of organic matter with a large amount of $\delta^{13}C$ and $\delta^{18}O$ in the sediment were quickly buried, thus causing a negative excursion of $\delta^{13}C$ and $\delta^{18}O$ in the limestone.

The $\delta^{34}S$ value of the first member of Yangliugang Formation is 8.3–31.3‰, with an average of 21.34‰; the $\delta^{34}S$ value of the second member of Yangliugang Formation is 0.5–20.09‰, with an average of 7.46‰. The change of the $\delta^{34}S$ value is consistent with the variation range of $\delta^{34}S$ in the Cambrian Period. However, the $\delta^{34}S$ value tends to gradually decrease during the period of Dachenling Formation → the first member of Yangliugang Formation → the second member of Yangliugang Formation, indicating that after the organism explosion in Early Cambrian Period (premature), the degree of organism thriving gradually weakened, reducing the sulfur isotope fractionation of reducing bacteria.

2.3.3.5 Analysis of Sedimentary Environment

The sediment of the Yangliugang Formation in the Area is mainly siliceous argillaceous matter and argillaceous carbonate. There is a very little amount of terrestrial silt present. This is quite different from the Yangliugang Formation near the Jiangshan–Shaoxing fracture zone to the southeast and the Yangliugang Formation in Yuhang area, indicating a different palaeogeographic environment.

In the lower part of the first member of Yangliugang Formation, the sediment is mainly composed of siliceous argillaceous matter. Besides, a small amount of the synsedimentary micro-fine-grained pyrite is visible generally in the sediment. Horizontal bedding developed in the beds of the lower part. This indicates weak hydrodynamic force and that the sedimentary environment is the reproduction of the bathyal basin anoxic reduction environment in the Early and Late Cambrian Epoch. In the middle-lower part of the first member of Yangliugang Formation, the silicon argillaceous matter gradually decreases and the mud increases upward. The silicon argillaceous matter is interbedded with some carbonate layers or lens and becomes medium laminated marl upward in which micro-fine horizontal bedding developed. This indicates that the sedimentary environment had become standing-water deep shelf facies with weak oxidation after nearly 300 million years. The lithology and lithologic association of the middle-upper and the upper parts of the first member of Yangliugang Formation are similar to those of the lower-middle and lower parts of the first member of Yangliugang Formation, and the sedimentary environment change of the middle-upper and the upper parts also seems to be the reproduction of previous sedimentary environment.

In the second member of Yangliugang Formation, the main sediment is carbonated-bearing argillaceous matter interbedded with a small amount of siliceous argillaceous matter in the middle part. Micro-fine horizontal bedding developed in all sedimentary beds. This indicates a standing-water, low-energy, and deepwater body. There are small amounts of organic carbon and sulfide, indicating weak oxidation deep shelf sedimentary environment. The siliceous argillaceous matter means pelagic bathyal basin environment, reflecting the sea level experienced a large-scale rise and falling process in the Late Middle Cambrian Epoch.

Regionally, in the Yangliugang Formation of Yuhang area, which is 60–70 km away to the southeast of the Area and the Yangliugang Formation in the areas near Jiangshan–Shaoxing fracture zone including Zhuji, Quzhou, Jiangshan, and Changshan, the sediments are all limestone and marl, there is no siliceous matter, and very rare synsedimentary sulfides exist. This indicates that the sedimentary environment becomes shallow shelf facies.

2.3.3.6 Trace Elements in Strata (Ore-Bearing)

1. **Characteristics of Trace Elements in Strata**

Thirty-nine rock spectra were collected in Yangliugang Formation of Wenguan profile (PM003). The first member of Yangliugang Formation ($Є_2y^1$) and the second member of Yangliugang Formation ($Є_2y^2$) are similar in enriched elements. Argillaceous silicalite features the concentration coefficients of Sb, Bi, Mo, and Ag about two times those in limestone. The concentration coefficients of other trace elements in argillaceous silicalite are closely similar to those in the limestone.

2. **CaO and MgO in Main Limestone and Marl**

According to the *Report on the Survey and Evaluation Results of Cambrian Limestone Resources of Zhejiang Province* (2007), the average content of CaO and MgO in the limestone and marl with a thickness of 16 m on the top of the second member of Yangliugang Formation in the Yekengwu profile of Hanggai Town, Anji County, is 35.17% and 2.40%, respectively. The content of CaO and MgO in the rocks in other parts of the Yangliugang Formation is 10%–30% and 1%–5%, respectively.

2.3.4 Huayansi Formation ($Є_3h$)

Huayansi Formation, formerly known as Huayansi limestone, was renamed Huayansi Formation by Lu et al. (1955) in Huayan Temple (Tianma Mountain), Changshan County, Zhejiang Province. It was subsequently used up to now by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). In this Project, the name Huayansi Formation was still adopted according to the lithological characteristics of Wenguancun profile (PM003), Yekengwu profile (PM043), and Jinyindong profile (PM042) of Hanggai map sheet, Shiling profile (PM024) and Yutang profile (PM038) of Xianxia map sheet, and geological observation traverse in the Area.

2.3.4.1 Lithostratigraphy

Huayansi Formation ($Є_3h$) in the Area is distributed basically in the same way with Yangliugang Formation. However, Huayansi Formation features more extensive outcrops. The outcrop area is about 11.30 km^2, accounting for 0.89% of the bedrock area.

The lithology and lithologic association of Huayansi Formation ($Є_3h$) are characterized by dark gray thin–medium laminated dolomitic micrite interbedded with micro-laminated marl. Therefore, the lithologic association is monotonous. Besides, horizontal bedding developed and there is no obvious banded structure. Huayansi Formation is in conformable contact with the overlying Xiyangshan Formation and the underlying Yangliugang Formation, with a thickness of 109.68–213.99 m.

1. **Stratigraphic section**

The lithology of Huayansi Formation is described by taking the example of the Cambrian Dachenling Formation ($Є_1d$)–Huayansi Formation ($Є_3h$) profile (Fig. 2.16) of Hanggai

Xiyangshan Formation Total thickness: >2.38 m

55. Interbed consisting of dark gray thin–medium laminated marl and thin–medium laminated micrite. 2.38 m

——————— Conformable contact ———————

Huayansi Formation Total thickness 109.68 m

54. Interbed consisting of dark gray thin–micro laminated argillaceous limestone and thin–medium laminated micrite; the argillaceous limestone: very thin horizontal bedding developing, the thickness of a single layer: 0.1–2 cm; the micrite: horizontal bedding developing, the thickness of a single layer: 5–15 cm. 2.38 m

53. Rhythm interbed consisting of dark gray thin laminated micrite and micro laminated marl; the respective thickness of a single layer of the micrite and the marl: 2–5 cm and 0.1–0.3 cm. 22.95 m

52. Rhythm interbed consisting of dark gray thin–medium laminated micrite and thin laminated marl; the respective thickness of a single layer of the micrite and the marl: 6–36 cm and 1–5 cm. 5.34 m

51. Dark gray thin–medium laminated micrite intercalated with marl; the thickness of a single layer of the micrite and the marl: 7–15 cm and 1–3 cm respectively. 26.63 m

50. Interbed consisting of dark gray thin laminated micrite and marl; the respective thickness of a single layer of the micrite and the marl: 2–6 cm and 1–4 cm. 9.34 m

49. Rhythm interbed consisting of dark gray thin laminated micrite interbedded with micro laminated argillaceous limestone; the respective thickness of a single layer of the micrite and the marl: 3–8 cm and 0.1–0.5 cm. 24.13 m

48. Dark gray thin–medium laminated micrite interbedded with micro laminated dolomitic limestone; the micrite: lotus-root-shaped owing to deform caused by compression; the dolomitic limestone: beige owing to weathering. 0.57 m

47. Rhythm interbed consisting of dark gray thin laminated micrite interbedded with by micro-texture marl; the respective thickness of a single layer of the micrite and the marl: 2–6 cm and 0.1–0.2 cm. 58 m

46. Rhythm interbed consisting of dark gray thin–medium laminated micrite interbedded with micro laminated marl; the micrite: very thin horizontal bedding developing, the thickness of single bed: 4–10 cm; the marl: protrude-shaped owing to weathering, the thickness of a single layer: 0.1–1 cm. 15.76 m

——————— Conformable contact ———————

The second member of Yangliugang Formation ($Є_2y^2$) Total thickness: >14.94 m

45. The lower part: interbed consisting of dark gray banded micrite and thin laminated marl, the ratio between the two components: 1:1; the upper part: medium laminated marl interbedded with thin laminated micrite, the respective thickness of a single layer of the marl and the micrite: 10–30 cm and 3–5 cm; the lower part: thinner marl with thickness of 8–15 cm, the micrite remaining the same, very thin horizontal bedding visible in all layers. 14.94 m

map sheet in Wenguan Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

2. **Lithological characteristics**

The lithology of Huayansi Formation (Є$_3h$) is mainly characterized by dolomitic micrite and marl.

(1) The dolomitic micrite: sand–clastic microcrystalline structure; composition: calcite (80–90%), dolomite (3–10%), and carbonaceous matter (5–8%); the respective content of CaO and MgO: 37–50% and 2–5%, horizontal bedding developing.
(2) The marl: sand–clastic microcrystalline structure; composition: calcite (70–80%), argillaceous matter (10–20%), and amorphous carbonaceous matter (5–8%). The mixture of the argillaceous matter and dolomitic matter is distributed in micro-lamellar matter, with horizontal bedding developing extremely. The respective contents of CaO and MgO are 37–40% and 5–15%.

3. **Basic sequences**

Two types of basic sequences are developed in Huayansi Formation (Є$_3h$) (Fig. 2.21). All of them consist of ① dark gray thin–medium laminated micrite and ② micro-laminated argillaceous limestone. The amount of the micrite is about 5–10 times that of the marl. In the middle part of the sequences, the micrite is mainly medium laminated and accounts for a high proportion, indicating the process of rising and falling of the sea level. The sediments of this formation are mainly microcrystalline calcareous carbonates. The rocks are mostly medium laminated and partly thin laminated, with horizontal bedding developing. The argillaceous limestone appears in the interbed with a general thickness of less than 2–3 cm. Fine horizontal bedding extremely developed. Therefore, argillaceous limestone belongs to the carbonate facies of shallow shelf.

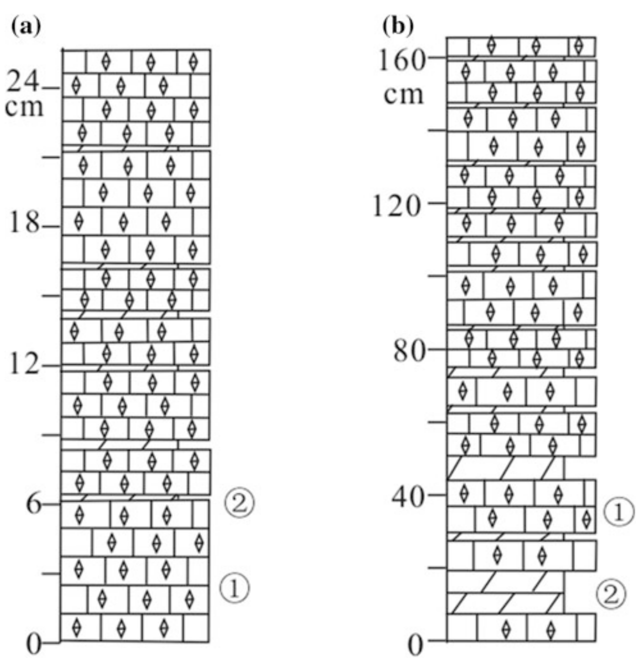


Fig. 2.21 Basic sequences of Huayansi Formation (Є$_3h$)

2.3.4.2 Sequence Stratigraphy

According to the lithology and lithofacies association and the characteristics of sequence boundary of the Wenguan profile of Hanggai map sheet, there is one third-order parasequence set Sq15, which belongs to the second-order sequence SS6 of Huayansi Formation (Є$_3h$).

Third-order parasequence set Sq15

The lithology of the Huayansi Formation is mainly characterized by micrite. Besides, there is a small amount of marl and occasionally visible dolomitic limestone. Among them, micrite accounts for more than 75%, and the thickness (structure) and proportion of it vary from bottom to up, reflecting the rise and falling of the sea level. Owing to this, it can be determined that Huayansi Formation is of transgression–regression sedimentary system, and the top and bottom of Huayansi Formation are both of type-II sequence boundaries. Three third-order parasequences can be identified in the Wenguan profile of Hanggai Town, Anji County. Among them, the first parasequence in the lower part belongs to TST and the second and the third parasequences in the upper belong to HST.

The first-order parasequence is located in Bed 46–Bed 47. The sediment of it is the interbed consisting of thin laminated microcrystalline mud interbedded with micro-laminated calcareous argillaceous matter, thus belonging to TST of argillaceous carbonate facies of shallow shelf sedimentation during transgression period.

The second and the third parasequences are, respectively, located in Bed 49–Bed 52 and Bed 53–Bed 54. The sediment is thin–medium laminated micrite interbedded with micro-laminated dolomitic limestone, with fine horizontal bedding developing in all layers, indicating that HST belongs to shallow shelf carbonate facies after the maximum flooding period.

In summary, the third-order parasequence set Sq15 in the Huayansi Formation reflects a comparatively stable rudimentary environment, in which the sea level experienced slight oscillation of rising and falling in shallow shelf sedimentary basin. Therefore, the third-order parasequence set belongs to the sequence of aggradation type. In terms of time, the age range of Sq15 is 497–489.5 Ma, spanning 8.5 Ma.

2.3.4.3 Biostratigraphy and Chronostratigraphy

In this Project, no fossils were obtained in Huayansi Formation in the Area. Peng (2011) conducted a systematic stratigraphic study on the Dadoushan profile in Duibian, Jiangshan City, Zhejiang Province, divided *Agnostotes orientalis* fossil zone from the profile, and established the "golden spikes" stratotype sections of Jiangshanian Stage. Furthermore, they divided the following seven fossil zones from Huayansi Formation. According to the *Stratigraphic Chart of China* (2014), the *Linguagnostus reconditus* zone belongs to the bottom of the Paibian Stage of early period of the Late Cambrian, the *Glyptagnostus stolidotus* zone belongs to the lower part of the Paibian Stage of the early period of the Late Cambrian, the Glyptagnostus reticulatus zone belongs to the middle part of the Paibian Stage of the early period of the Late Cambrian, the *Agnostus inexpectans* zone belongs to the middle and upper parts of Paibian Stage of the early period of the Late Cambrian, the *Corynexochus plumula* zone belongs to the upper part of Paibian Stage of the early period of the Late Cambrian, the *Agnostotes orientalis* zone belongs to the lower part of Jiangshanian Stage of the middle period of the Late Cambrian, and the *Eolotagnostus* zone belongs to the upper part of the Jiangshanian Stage of the middle period of the Late Cambrian.

2.3.4.4 Characteristics of Stable Isotopes

Two whole-rock stable isotope samples of δ^{13}C, δ^{18}O, and δ^{34}S of limestone were collected from the Huayansi Formation of the Wenguan profile (PM003).

The respective δ^{13}C values of the two samples are 2.66 and 2.09‰, with an average of 2.38‰. Therefore, the values feature slight positive excursion compared to the limestone of normal marine facies, reflecting that the sea level fell after the sedimentation of the Yangliugang Formation and the sedimentary environment is of shallow shelf facies. With the burial of the organic matter in the sediment, the consumption of δ^{13}C decreased, resulting in the positive excursion of the relative enrichment of δ^{13}C in limestone.

The respective δ^{18}O values of the two samples are −14.01 and −16.15‰, with an average of −15.08‰. The respective δ^{34}S values of the two samples are 31.7 and 37.5‰, with an average of 34.6‰. According to the analysis of the Dachenling and Yangliugang formations mentioned above, the δ^{18}O values should also have featured positive excursion but feature slight negative excursion according to the test results. As for the reasons, the δ^{18}O values were very possibly affected by the burial temperature of the sediment and temperature of the seawater (more than by the impact caused by the falling of the sea level) at that time. Qi (2006) believed that when the temperature rises and the seawater evaporates, ^{16}O is prone to escape from seawater into the atmosphere since it is light and highly active, while the fractionation coefficient of the isotope becomes weak with the rise of temperature since it is inversely proportional to temperature. Therefore, the difference in oxygen isotope content between seawater and vapor becomes smaller and the amount of ^{16}O that escapes from the sea decreases. As a result, in the seawater, the amount of ^{16}O and ^{18}O in seawater relatively increases and decreases, respectively (i.e., δ^{18}O decreases). The δ^{18}O values of the Huayansi Formation in the Area feature significant negative excursion compared to the limestone of normal marine facies. The reason may be that, with the continuous falling of the sea level in the shallow sedimentary environment, the burial temperature of the sediment rises. This promotes the short-term thriving of reducing bacteria followed by the increase of fractionation of the sulfur isotope. Consequently, the δ^{34}S value becomes abnormally high (average: 34.6‰) and positive anomaly occurs. However, since there were only two samples collected in this Project, the above results are poorly persuasive. Further efforts are required in the future in order to confirm whether the above explanation is reasonable.

2.3.4.5 Analysis of Sedimentary Environment

Huayansi Formation is the simplest stratum in the lithology and lithologic association of the Cambrian. The main sediment is thin–medium laminated microcrystalline calcite, interbedded with a small amount of micro-laminated mud or dolomitic lime mud occasionally. Fine horizontal bedding developed in the layers, but no obvious organic carbonaceous matter and sulfide are visible. The ancient organisms in Huayansi Formation are mainly planktonic Agnostus. It is indicated that the hydrodynamic force was weak in the environment and the oxygen content in the water was not favorable for the survival of benthic organisms. Therefore, the sedimentary environment of Huayansi Formation belongs to shallow shelf near the oxidation–reduction surface under the wave base.

Regionally, Huayansi Formation features in a similar way as the lithology and stratum thickness of the Area and is the main marker stratum of the regional geological survey of the Cambrian.

2.3.4.6 Trace Elements in Strata (Ore-Bearing)

1. **Characteristics of trace elements in strata**

Twelve rock spectra were collected in Huayansi Formation ($\epsilon_3 h$) of Wenguan profile (PM003). According to the results of the spectral analysis, Huayansi Formation ($\epsilon_3 h$) is enriched in Sb and Bi, and poor in Au, Be, Cu, Pb, Zn, W, Sn, and TFe. Compared with the lower Yangliugang Formation, Dachenling Formation, and Hetang Formation, Huayansi Formation features less enriched trace elements and the enrichment coefficients are 1 times smaller. This is related to the fact that microlithic limestone constitutes the main lithology of this formation.

2. **CaO and MgO content of main limestone and marl**

According to the *Report on the Survey and Evaluation Results of Cambrian Limestone Resources of Zhejiang Province* (2007), the limestone thickness of the Huayansi Formation in the Yekengwu profile of Hanggai Town, Anji County, is 135.95 m. Furthermore, among the 53 samples, the respective average content of CaO and MgO is 44.39% and 3.22%.

2.3.5 Xiyangshan Formation (€O_x)

The name Xiyangshan Formation, formerly known as Xiyangshan shale, was created by Lu et al. (1955) in Xiyang Mountain, which is 1.5 km to south of the town of Changshan County, Zhejiang Province. It belongs to the Late Cambrian and is a biostratigraphic unit. It was successively used in the *Qu County Map Sheet on a Scale of* 1:200,000 (1969), *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), etc. For this formation, the preparation group of regional stratigraphic table of Zhejiang Province (1979) adopted both division proposed by Lu et al. (1955) and lithostratigraphy division, while lithostratigraphy division was adopted in *Lithostratigraphy of Zhejiang Province* (1995). In this Project, Xiyangshan Formation (€O*x*) was still used according to the lithologic characteristics of Kaokengkou profile (PM004), Yekengwu profile (PM043), Jinyindong profile (PM042) in Hanggai map sheet, Shiling profile (PM024) and Yutang profile (PM038) in Xianxia map sheet, and survey traverse.

2.3.5.1 Lithostratigraphy

Xiyangshan Formation (€O*x*) is basically distributed in the same way as Yangliugang Formation in the Area. However, Xiyangshan Formation features more extensive outcrop. The outcrop area is about 38.76 km^2, accounting for 3.05% of the bedrock area.

According to the lithology and lithologic association, the Xiyangshan Formation (€O*x*) is divided into the first member of Xiyangshan Formation (€Ox^1), the second member of Xiyangshan Formation (€Ox^2), and the third member of Xiyangshan Formation (€Ox^3). It is in conformable contact with the overlying Yinzhubu Formation and the underlying Huayansi Formation.

The first member of Xiyangshan Formation (€Ox^1): The lower part is composed of the interbed consisting of deep gray thin–medium laminated marl and thin–medium laminated micrite, which are interbedded with carbonaceous and calcareous siliceous mudstones. Furthermore, the interbed gradually changes into the interbed consisting of dark gray vein-strip shaped, lenticular, and banded micrite and medium laminated argillaceous limestone from bottom to up. The lithologic association is mainly composed of argillaceous marl, followed by micrite. Besides, there is a small amount of siliceous mudstone. Very thin horizontal bedding developed in all layers. The marl is prone to be platy owing to weathering. The thickness of this member is 144.76–427.6 m.

The second member of Xiyangshan Formation (€Ox^2): The middle and lower parts of the member consist of multicycle interbed of dark gray medium–thick laminated marl (micrite or dolomitic limestone locally) and marl-bearing vein-strip shaped micrite → small-vein-strip shaped micrite. The small-vein-strip shaped micrite is 1–2 cm thick and 5–100 cm long. Furthermore, the sparse small-vein-strip shaped micrite gradually becomes dense from bottom to top within the single circle. The upper part of the member is composed of the rhythmic interbed of dark gray medium laminated siliceous mudstone and marl and "vein-strip shaped micrite." Compared with the micrite strips of the first and the third member, the "vein-strip shaped micrite" in this member features a longer cross section and a greater thickness. The thickness of this member is 113.63 m.

The third member of Xiyangshan Formation (€Ox^3): dark gray medium-thickness–thick argillaceous limestone, containing vein-strip shaped and lenticular micritic marl. The multicycle interbed of the vein-strip shaped micrite is mainly composed of argillaceous limestone. The part near the top of the member consists of dark gray medium laminated argillaceous limestone and marl, interbedded with the banded and thin laminated micrite. The thickness of this member is 254.24 m.

1. **Stratigraphic section**

The stratigraphic profile of Xiyangshan Formation is described by taking the example of Cambrian Xiyangshan Formation (€O*x*) profile (Fig. 2.22) of Hanggai map sheet in Kaokengkou Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Yinzhubu Formation Total thickness: >10.99 m

55. Gray medium laminated calcareous argillaceous siltstone. 10.99 m

Conformable contact

Xiyangshan Formation Total thickness 547.60 m

The third member of Xiyangshan Formation Total thickness 244.67 m

54. Two rhythmic interbed consisting of dark gray medium laminated silty mudstone and vein-strip shaped marl. The lower silty mudstone is 40 cm thick with horizontal bedding developing; the thickness of a single layer of upper vein-strip shaped marl is 40–50 cm; the vein-strip is (5–6) × (10–20) cm, accounting for 50%; the marl is 3–5 cm thick per vein-strip and gradually decreases upwards. 1.48 m

53. Interbed consisting of dark gray thin–medium laminated marl and vein-strip shaped micrite with the ratio between the two components of 1:1. As for the marl, the proportion in the lower part, middle part, and upper part of the layer is 100%, 50%, and 5% respectively, and the thickness of a single layer in the lower part, middle part, and upper part of the layer is 15–20 cm, 3–5 cm, and 0.5 cm respectively. As for the micrite, the proportion is contrary to that of the marl, it gradually becomes thin laminated from being vein-strip shaped from bottom to up, and the thickness of a single layer is 2–3 cm→ 6–15 cm from bottom to up. 4.02 m

52. Interbed consisting of dark gray small-vein-strip shaped marl and carbonaceous mudstone. The small-vein-strip shaped marl is 1 cm× (5–10) cm, accounting for 80%. The carbonaceous mudstone is 0.1–0.5 cm thick. 1.06 m

51. Dark gray thin laminated micrite; the thickness of a single layer: 3–10 cm. 1.06 m

50. Interbed consisting of dark gray medium laminated marl and thin laminated micrite. The thickness of a single layer of the marl: 20–30 cm; the thickness of a single layer of the micrite: 8–10 cm; the ratio between the two components: 1.5: 1. 2.47 m

49. Dark gray medium laminated marl, the thickness of a single layer: 20–50 cm. 4.90 m

48. Dark gray medium laminated micrite, the thickness of a single layer: 20–50 cm. 7.17 m

47. Dark gray medium laminated argillaceous limestone, the thickness of a single layer: 20–50 cm, horizontal bedding developing. 26.30 m

46. Dark gray banded micrite-bearing marl, the thickness of a single layer: 3–5 cm, horizontal bedding developing. 2.78 m

45. Dark gray medium –laminated argillaceous limestone bearing vein-strip shaped micrite. The thickness of a single layer of the argillaceous limestone: 40–100 cm; the thickness of a single layer of the vein-strip: (3–5) × (20–30) cm, the content of the vein-strip shaped micrite: <5%. 7.30 m

44. Dark gray medium laminated micrite interbedded with micro laminated argillaceous limestone. The micrite; horizontal bedding developing, the thickness of a single layer: 13–20 cm. The thickness of a single layer of argillaceous limestone: 0.5–1 cm. 2.91 m

43. Dark gray medium laminated carbonaceous marl, generally interbedded with vein-strip shaped micrite and locally interbedded with banded carbonaceous marl. The carbonaceous marl: very thin horizontal bedding developing, prone to flake off along the bedding. The vein-strip shaped micrite is (10–30) × (3–5) cm in size and is mostly visible in a single bed, accounting for 10%–15% of the layer. 46.83 m

42. Dark gray medium–thick laminated carbonaceous marl interbedded with a small amount of vein-strip shaped micrite. The carbonaceous limestone: very thin horizontal bedding developing, the thickness of a single layer: 30–60 cm. The vein-strip of micrite is 3–6 cm thick and 20–50 cm long and mostly visible in 1–3 layers; the micrite accounts for 5% of the layer. 29.70 m

41. Dark gray banded to thin laminated micrite, interbedded with micro-thin laminated marl. The micrite: the thickness of a single layer: 1–5cm, horizontal bedding developing. The marl: very thin horizontal bedding extremely developing, the thickness of a single layer varies greatly with a value of 0.1–1 cm. 2.91 m

40. Dark gray medium laminated marl, the thickness of a single layer: 20–50 cm, horizontal bedding developing. 27.47 m

39. Dark gray thin–medium laminated vein-strip shaped micrite and argillaceous limestone. The vein-strip of micrite is (1–3) × (5–20) cm thick, accounting for 10% of the layer. The argillaceous limestone: the thickness of a single layer: 8–20 cm, horizontal bedding developing. 23.49 m

38. Dark gray medium laminated argillaceous limestone, the thickness of a single layer: 20–50 cm, horizontal bedding developing. 19.39 m

37. Dark gray thin laminated argillaceous limestone bearing vein-strip shaped–banded micrite. The thickness of a single layer of argillaceous limestone is 3–10 cm. The vein-strip shaped or banded micrite is 2–5 cm thick per single bed and varies greatly in length. 23.41 m

36. Dark gray medium laminated argillaceous limestone, the thickness of a single layer: 30–50 cm, occasionally containing a small amount of the small vein-strip shaped micrite. 9.57 m

——— Conformable contact ———

The second member of Xiyangshan Formation Total thickness 101.60 m

35. Interbed consisting of dark gray thin laminated marl and vein-strip shaped, banded, and thin laminated micrite. The thickness of a single layer of the micrite is 1–5 cm. The marl accounts for 60% (in the upper part) and 40% (in the lower part) of the layer. 12.03 m

34. Dark gray thin–medium laminated siliceous mudstone and marl, interbedded with a small amount of vein-strip shaped–banded limestone. The thickness of a single layer of the marl is 5–30 cm; the thickness of a single vein-strip of the siliceous mudstone is similar to that of the marl; the thickness of the vein-strip shaped and banded limestone and vein-strip shaped limestone is 3–8 cm. 13.68 m

33. Interbed of dark gray thin laminated marl and vein-strip shaped–banded micrite. A single bed of the marl is 3–8 cm thick. The thickness of a single layer of the micrite is 1–3 cm. 3.35 m

32. Dark gray vein-strip shaped micrite and banded marl. The micrite is 1–3cm thick. The ratio between the two components is about 1:1. 1.01 m

31. Dark gray medium laminated siliceous mudstone, interbedded with small-vein-strip shaped micrite in the middle part. The single bed of siliceous mudstone is 10–30 cm thick. The size of a single vein-strip shaped micrite is (1–3) × (5–20) cm; the ratio between the two components is 1:1. 2.51 m

30. Dark gray vein-strip shaped limestone. 5.52 m

29. Dark gray medium laminated argillaceous limestone, very thin horizontal bedding developing in the layers. 1.19 m

28. Gray fine thick vein-strip shaped–banded micrite. 2.40 m

27. Gray medium laminated marl, horizontal bedding developing. 11.33 m

26. Interbed consisting of gray thin laminated vein-strip shaped micrite and marl. The marl is 1–10 mm thick, with horizontal bedding developing. The vein-strip shaped micrite is 1–10 mm thick and 3–40 cm long. The ratio of the two elements is about 1:1. 1.77 m

25. Interbed consisting of dark gray medium laminated marl and small-vein-strip shaped micrite. The thickness of a single layer of the marl is 10–20 cm; the micrite vein-strip is 2–5 cm thick and 10–30cm long. The single-rhythm vein-strip shaped micrite increases from 10% to 50% from bottom to top. Very thin horizontal bedding develops in all layers. 6.90 m

24. Dark gray medium laminated marl, the thickness of a single layer: >10 cm, very thin horizontal bedding developing, flaky after weathering. 9.83 m

23. Dark gray vein-strip shaped micrite and banded marl. The micrite: vein-strip shaped–banded, thickness: 1–3 cm, length: 10–100 cm, distributed discontinuously along the layer; the marl: very thin horizontal bedding developing, thickness: 1—3 cm, bypassing the strips. The ratio the marl to the micrite: 6:5 approximately. 2.61 m

22. Dark gray medium laminated marl interbedded with vein-strip shaped micrite, mainly consisting of the marl. As for the vein-strip shaped micrite, the thickness of a single layer is 3–6cm and the total thickness is 3–30 cm; the thickness of a single layer of the marl is 40–60 cm. 2.52 m

21. Dark gray apparently-thick laminated small-vein-strip shaped micrite, interbedded with a small amount of thin laminated argillaceous limestone; the vein-strip shaped micrite accounting for 70% of the layer. 7.67 m

20. Dark gray medium laminated dolomitic limestone, interbedded with a layer of micrite and a thickness of 5 cm in the lower part, very thin horizontal bedding developing in the layers. 1.45 m

19. Dark gray medium laminated small-vein-strip shaped micrite, the thickness of a strip: < 1cm, the micrite accounting for 50% of the layer, marl existing between the strips. 0.91 m

18. Dark gray medium laminated carbonaceous limestone, horizontal bedding developing. 1.36 m

17. Dark gray small-vein-strip shaped limestone. The small-vein-strip shaped micrite is 1–2 cm thick and 3–5 cm long, the micrite accounts for 70% of the layer. 1.12 m

16. Dark gray medium laminated micrite, very thin horizontal bedding developing. 3.32 m

15. Interbed of dark gray thin laminated marl and small-vein-strip micrite. The single vein-strip is 1–2 cm thick; the micrite accounts for 70% of the layer. 1.26 m

14. Dark gray medium–thick laminated marl, very thin horizontal bedding developing. 5.07 m

13. Two rhythmic interbed of dark gray vein-strip shaped marl and vein-strip limestone. The strips of limestone gradually increase and become thinner from bottom to top, accounting for 10%–30% in the lower part and 70% in the upper part; the overall ratio between the two components is 1:1. 7.61 m

———— Conformable contact ————

The first member of Xiyangshan Formation Total thickness: 223.5 m

12. Dark gray medium–thick laminated marl interbedded with a small amount of lenticular micrite. The marl:

the thickness of a single layer: 20–100 cm, interbedded with small-vein-strips in the middle part locally, very thin horizontal bedding developing in layers. The micrite lens: 5 × 30 cm, hollow owing to weathering. 26.00 m

11. Interbed consisting of dark gray vein-strip shaped–banded micrite and marl. The micrite: vein-strip shaped–banded, thickness: 1–2 m thick, length: 5–100 cm. The ratio of the vein-strip shaped micrite to the marl: 1:1 approximately. 2.49 m

10. Dark gray medium laminated carbonaceous silty marl, horizontal bedding developing, the thickness of a single layer: 10–30 cm. 3.56 m

9. Rhythm interbed consisting of dark gray medium laminated marl and apparently-thick laminated vein-strip shaped limestone. The lower marl: very thin horizontal bedding developing, the thickness: 2 m; the upper apparently-thick laminated vein-strip shaped limestone: the thickness of a strip: 1–5 cm; the ratio of the marl to the vein-strip shaped limestone: about 1:1. 15.87 m

8. Dark gray vein-strip shaped–banded micrite interbedded with thin laminated marl. The size of vein-strip shaped–banded micrite: 1–5 cm thick and 5–100 cm long; the marl: the thickness of a single layer: 1–2 cm, accounting for 10% of the bed. 3.81 m

7. Dark gray apparently-thick laminated vein-strip shaped micrite, interbedded with thin laminated argillaceous limestone. The thickness of a single layer of argillaceous limestone: 2–8 cm; the thickness of a vein-strip of micrite: 1–5 cm thick. 11.54 m

6. Dark gray medium laminated marl interbedded with lenticular carbonaceous marl. The marl: very thin horizontal bedding developing, the thickness of single bed: 20–50 cm; the carbonaceous limestone lens: size: (3–8) × (15–30) cm, appearing generally in the form of a single layer and partly in the form of 2–3 layers as a whole. 45.47 m

5. Dark gray medium laminated calcareous siliceous mudstone, the thickness of a single layer: 20–30 cm, prone to flake off, interbedded with a small amount of thin laminated micrite 10 meters upwards. 51.91 m

4. Interbed consisting of dark gray medium–thick laminated marl and thin–medium laminated micrite. The marl: very thin horizontal bedding developing, the thickness of single layer: 20–80 cm; the micrite: the thickness of a single layer: 10cm in the lower part of the layer and 30–50cm in the upper part of the layer. 11.79 m

3. Interbed consisting of dark gray thin laminated marl and vein-strip shaped micrite. The thickness of a single layer of the marl: 1–4 cm; the micrite: the thickness of a single layer: 2–4 cm, horizontal bedding developing. 1.32 m

2. Dark gray medium–thick laminated carbonaceous siliceous mudstone, interbedded with lenticular limestone. The carbonaceous siliceous mudstone: very thin horizontal bedding developing, prone to be peeled as platy, the thickness of a single layer: 30–60 cm. The lenticular limestone: 5 × 20 cm in size, distributed discontinuously along the layer. 15.25 m

1. Interbed consisting of dark gray medium laminated carbonaceous marl and thin–medium laminated micrite. The carbonaceous marl: very thin horizontal bedding developing, platy owing to weathering, the thickness of a single layer: 12–30 cm. The micrite: horizontal bedding developing, the thickness of a single layer: 6–30 cm generally. There is slightly more marl than the micrite. 6.16 m

——— Conformable contact ———

Huayansi Formation Total thickness: >11.09 m

0. Dark gray medium laminated micrite, micro-fine horizontal bedding developing. 11.09 m

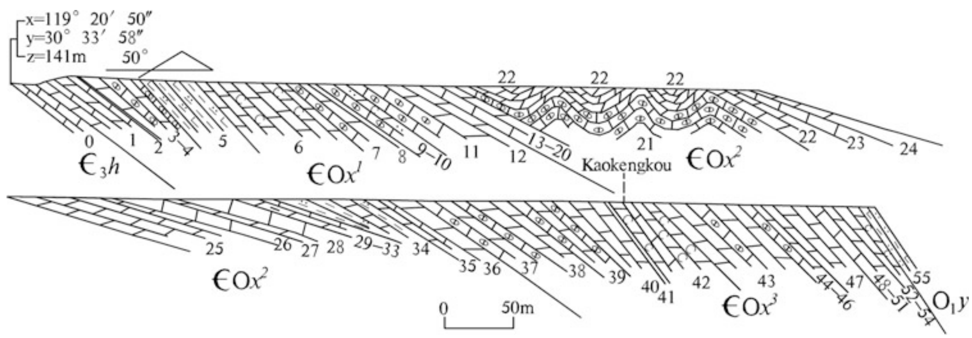


Fig. 2.22 Surveyed stratigraphic profile of the Cambrian Xiyangshan Formation (ЄO*x*) in Kaokengkou Village, Hanggai Town, Anji County, Zhejiang Province

2. **Lithological characteristics**

The lithology of the Xiyangshan Formation (ЄO*x*) is mainly characterized by dark gray micrite, dolomitic limestone, argillaceous limestone, marl, and siliceous mudstone. Among these rocks, siliceous mudstone is only distributed in the lower part of the first member and the upper part of the second member, and other rocks are generally distributed in all members of the Xiyangshan Formation.

(1) The micrite: gray and dark gray, microcrystalline structure, major component: calcite (75–90%), minor components: argillaceous matter (10–20%) and amorphous carbonaceous matter (0–10%). The respective content of CaO and MgO: 30–42% and 2–4%.
(2) The dolomitic limestone: gray, micro- to argillaceous–crystalline structure, major components: calcite (40–60%), dolomite (3–5%), and terrigenous clastic matter (quartz, sericite, etc.) (10–30%). The respective content of CaO and MgO: 30–40% and 1–9%.
(3) The argillaceous limestone: dark gray, microcrystalline structure, major component: calcite (55–70%), minor components: argillaceous matter (10–30%) and amorphous carbon (5–10%). The respective content of CaO and MgO: 15–30% and 2–4.8%.
(4) The marl: dark gray, argillaceous structure, major component: argillaceous matter (50%), minor components: calcite (15–25%), sericite (5%), and quartz (25–30%). The respective content of CaO and MgO: 9–13% and 3–5%.
(5) The siliceous mudstone: dark gray, mainly composed of argillaceous matter (60%), cryptocrystalline siliceous matter (30%), and amorphous carbonaceous or calcareous matter (10%); very thin horizontal bedding developing; prone to flake-off owing to weathering.

3. **Basic sequences**

There are three types of basic sequences in the first member of Xiyangshan Formation ($ЄOx^1$) (Fig. 2.23).

Basic sequences of type A: distributed in the lower part of the first member of Xiyangshan Formation, and consisting of rhythmic interbed of ① medium laminated marl and ② thin–medium laminated micrite. From bottom to top, the component ① gradually increases and component ②

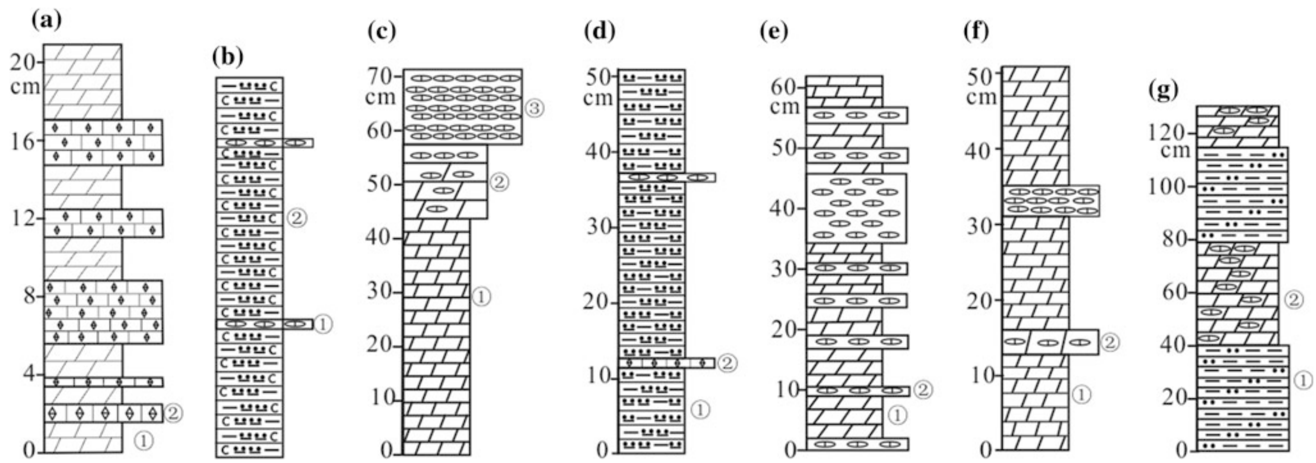


Fig. 2.23 Basic sequences of Xiyangshan Formation (ЄO*x*)

gradually decreases. The basic sequences of this type are of non-cyclic basic sequence with argillaceous matter gradually increasing upward.

Basic sequences of type B: distributed in the middle-lower part of the first member of Xiyangshan Formation, and composed of ① a small amount of micritic marl occasionally interbedded with ② medium laminated carbonaceous siliceous mudstone or the calciferous siliceous mudstone. The basic sequences of this type are of non-cyclic basic sequence with monotonous lithology.

Basic sequences of type C: distributed in the upper part of the first member of Xiyangshan Formation, and consisting of ① thin–medium laminated marl, ② cake-striped micritic marl, and ③ lenticular and cake-striped micrite. The lithological boundary is completely different, and the monocyclic lithologic association is characterized by the gradual increase of the cake-striped micrite from bottom to top, as well as the gradual increase of micrite. It is indicated that the sea level once became shallower. In the basic sequences of this type, the proportion of the cake-striped micrite increases from bottom to top. Generally, the basic sequences of this type are of polycyclic basic sequence with argillaceous matter decreasing and microcrystalline calcite increasing.

The sediments in the lower part of this member are mainly carbonates followed by a small amount of siliceous argillaceous matter, with very thin horizontal bedding developing in the layers. It is indicated that the sedimentary environment is of deep shelf siliceous mud facies–shallow shelf calcareous carbonate facies. The sediment in the upper part is mainly calcareous carbonate followed by argillaceous matter, with horizontal bedding developing. It is indicated that the rudimentary environment is of shallow shelf argillaceous carbonate facies.

There are two types of basic sequences in the second member of Xiyangshan Formation (ЄOx^2).

Basic sequences of type D: distributed in the upper part of the second member of Xiyangshan Formation, and consisting of ① medium laminated carbonaceous siliceous mudstone or calcareous siliceous mudstone interbedded with ② a small amount of micritic marl. The lithologic association is relatively monotonous, and the basic sequences of this type are of non-cyclic basic sequence.

Basic sequences of type E: the main components of the second member of Xiyangshan Formation, and composed of ① thin to medium laminated marl, ② cake-striped micritic marl, ③ cake-striped micrite. Micro-fine horizontal bedding developed. In the lithologic association consisting of ① and ③, the cake-striped micrite gradually increases and the marl gradually decreases from bottom to top, indicating that the sea level once became shallower. Therefore, the basic sequences of this type are of cyclic basic sequence with the sea level gradually rising and calcareous matter increasing.

The sediment in this member is mainly calcareous matter followed by a small amount of argillaceous matter. The basic sequences of this type are of shallow shelf carbonate facies.

There are two basic sequences in the third member of Xiyangshan Formation (ЄOx^3).

Basic sequences of type F: distributed in the middle-lower part of the third member of Xiyangshan Formation and composed of ① medium–thick laminated marl and ② lenticular, cake-shaped micrite. Among them, the component ① is 2–3 times of the component ②. Since micro-fine horizontal bedding developed, the marl is prone to flake off. The cake-striped limestone decreases upward. Therefore, the basic sequences of this type are of polycyclic basic sequence with calcareous matter gradually decreasing and argillaceous matter gradually increasing upward.

Basic sequences of type G: distributed in the upper part of the third member of Xiyangshan Formation, and consisting of ① silty mudstone and ② cake-striped micritic marl. Micro-fine horizontal bedding developed in all layers, the silty mudstone increases, and the cake-striped mudstone decreases. Therefore, the basic sequences of this type are of a non-cyclic basic sequence with argillaceous matter increasing upward.

The sediment in the lower part of this member is mainly calcareous followed by a small amount of argillaceous matter, with micro-fine horizontal bedding developing and thus reflecting that the main body is of carbonate facies of deep shelf with weak hydrodynamic force. The sediment in the upper part is argillaceous and calcareous carbonate-bearing terrigenous clasts, indicating carbonate facies of shallow shelf.

2.3.5.2 Sequence Stratigraphy

According to the characteristics of rocks and the types of the top and bottom, a second-order sequence SS7 is divided from the Late Cambrian Xiyangshan Formation to the Late Ordovician Yanwashan Formation. Furthermore, the SS7 is further divided into six third-order sequences (Sq16–Sq21) and one sub-second-order orthosequence set Ss1. According to the association of lithology and lithofacies as well as the characteristics of the boundary of Kaokengkou profile of Hanggai map sheet, there are two third-order sequences Sq16 and Sq17 in the Xiyangshan Formation (€O*x*) (Fig. 2.24).

Third-order sequence Sq16: Located in the first member and the second member of Xiyangshan Formation, it includes TST and HST. The bottom of Sq16 is composed of medium laminated argillaceous limestone and is in conformable contact with the thin laminated micrite of the underlying Huayansi Formation. The top consists of small-vein-strip shaped micritic marl and in conformable contact with the medium laminated argillaceous mudstone of the overlying third member. The top and bottom are all of type-II sequence boundary. TST is located in Bed 1–Bed 5 in the middle-lower part of the first member of Xiyangshan Formation. The sediment of TST is carbonaceous siliceous argillaceous matter and calcareous carbonate. Therefore, TST belongs to weak reduction environment of deep shelf during the maximum flooding period–weak oxidization environment of the outer margin of shallow shelf under the wave base. HST is located in Bed 6–Bed 35 in the upper part of the first member and the second member of Xiyangshan Formation. The sediment is mainly microcrystalline calcite followed by a small amount of argillaceous matter. Accordingly, HST belongs to shallow shelf oxidation environment after the maximum flooding period. Therefore, this sequence reflects a complete transgression–regression process, generally indicating the decline of the sedimentary basin after Huayansi Formation period and belonging to the sequence of progradational–aggradational type. In terms of time, the age range of Sq16 is 489.5–485.4 Ma, spanning 4.1 Ma.

Third-order sequence Sq17: Located in the area from the third member of Xiyangshan Formation to the first member of Yinzhubu Formation, it includes TST and HST. The bottom is an interface with a lithological abrupt change between the marl of the third member of Xiyangshan Formation and the caky limestone of the overlying second member of Xiyangshan Formation. Regionally, graptolite is discovered in the third member of Xiyangshan Formation and planktonic Agnostus is the main palaeobios in the second member. Furthermore, the values of oxygen and sulfur stable isotopes fluctuate near the bottom. This is presumably caused by global tectonic events. Therefore, the bottom belongs to the type-I sequence boundary. The top is a conformity interface and a type-II sequence boundary. TST is located in Bed 36–Bed 54. The main sediment in it includes carbonate and argillaceous matter, but horizontal bedding developed. Therefore, TST should be under weak oxidization sedimentary environment with weak hydrodynamic force and belongs to deep shelf–shallow shelf carbonate rock facies. HST is located in the first member of Yinzhubu Formation. The main sediment in it is siliceous argillaceous matter, belonging to the siliceous argillaceous facies under deep shelf weak oxidization environment during the maximum flooding period. Therefore, this sequence represents the continuous transgression process and is of retrogradation–aggradation type. In terms of time, the age range of Sq17 is inferred to be 485.4–481.00 Ma, spanning about 4.4 Ma.

Fig. 2.24 Sequence stratigraphic framework of Cambrian Xiyangshan Formation in the area

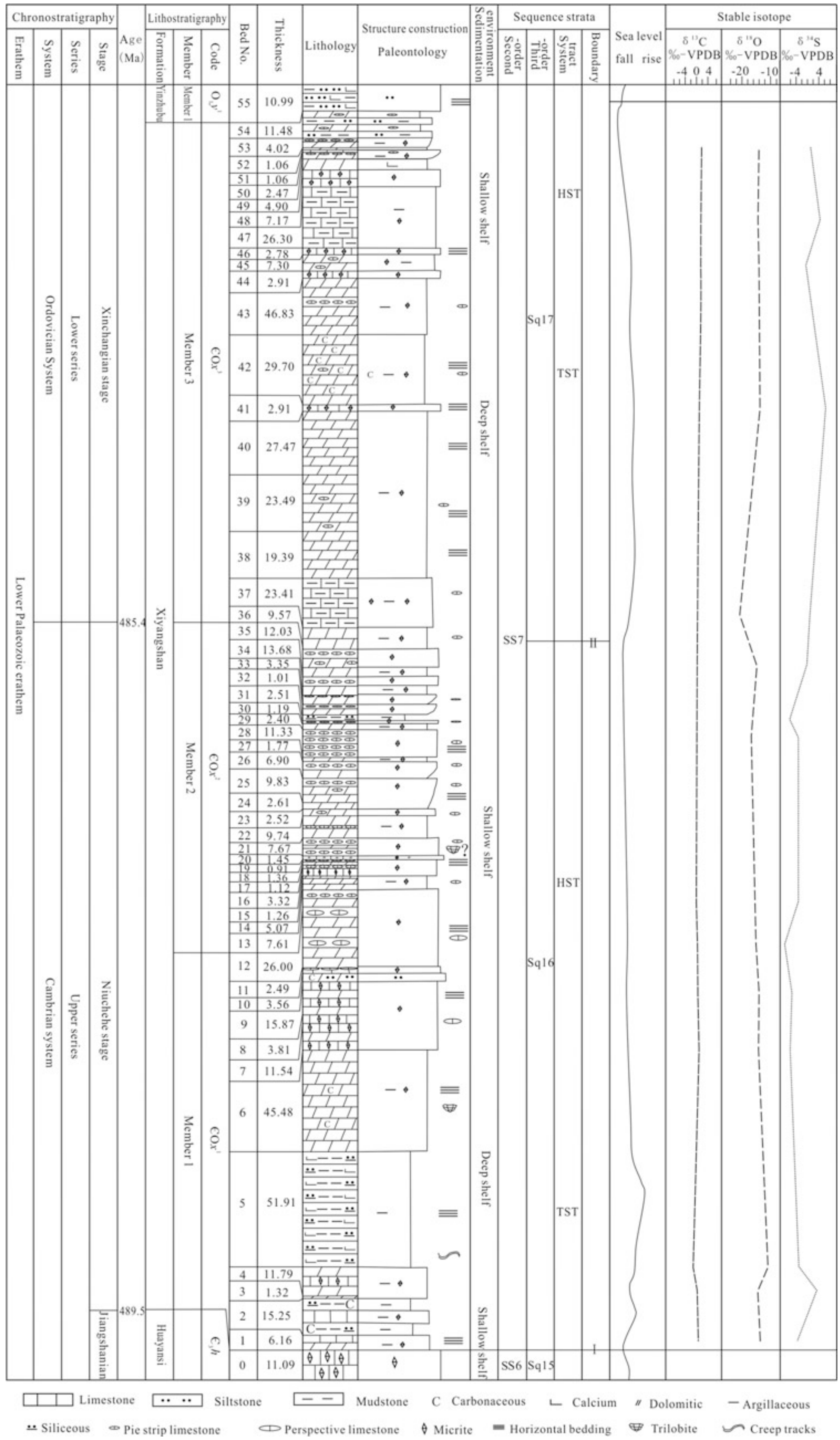


Fig. 2.25 *Lotagnostus americanus* in the first member of Xiyangshan Formation

2.3.5.3 Biostratigraphy and Chronostratigraphy

In this Project, *Lotagnostus americanus* fossils, the standardized fossils of the *Lotagnostus americanus* zone, are initially found in Bed 6 of the first member of Xiyangshan Formation (ЄOx^1) of Kaokengkou profile in Hanggai Town, Anji County (Fig. 2.25). They are also the first ones discovered in the north Zhejiang Province. Besides, the trackway of grid-like creeps is found in the marl of the Bed 2.

According to the *Stratigraphic Chart of China* (2014), the fossil zones in the Xiyangshan Formation are as follows: The *Lotagnostus americanus* zone occurred in the medium laminated marl of the first member of Xiyangshan Formation, the *Lotagnostus hedini–Cordylodus proavus* zone produced in the small cake-striped rocks and the thin–medium laminated marl in the second member of Xiyangshan Formation according to speculation, and the *Hysterolenus–Staurograptus dichotomus* zone produced in the marl and calcareous mudstone in the third member of Xiyangshan Formation. Xiyang Formation can be divided into the Tenth Stage and the Xinchangian Stage from bottom to top. The *Lotagnostus americanus* zone in the first member of Xiyangshan Formation belongs to the Tenth Stage of the Cambrian. The *Lotagnostus hedini* zone in the second member of Xiyang Formation also belongs to the Tenth Stage of the Cambrian. The *Hysterolenus–Staurograptus dichotomus* zone in the third member of Xiyangshan Formation belongs to the Ordovician Xinchang Stage.

2.3.5.4 Characteristics of Stable Isotopes

Six, five, and five limestone samples for whole-rock stable isotopes δ^{13}C, δ^{18}O, δ^{34}S analysis were, respectively, collected from the first member, the second member, and the third member of Xiyangshan Formation in Kaokengkou Profile (PM004).

The δ^{13}C value of the first member of Xiyangshan Formation is from −1.35 to 0.71‰, with an average of 0.108‰; the δ^{13}C value of the second member is from −0.06 to −0.37‰, with an average of 0.13‰; the δ^{13}C value of the third member is 0.53–1.61‰, with an average of 1.20‰. The δ^{13}C value of the whole Xiyangshan Formation is consistent with the δ^{13}C value of the limestone of normal marine facies (0 ± 2‰), reflecting that the sea level was comparatively calm at that time. This also indicates deep shelf sedimentation and that the organic matter in the sediment was buried and deposited at a normal rate.

The δ^{18}O value of the first member of Xiyangshan Formation is from −14.6 to –0.76‰, with an average value of −13.46‰; the δ^{18}O value of the second member is from −16.54 to −14.89‰, with an average of −15.476‰; the δ^{18}O value of the third member is from −20.87 to −13.62‰, with an average of −15.44‰. Compared with the δ^{18}O value of the limestone of normal marine facies (from −13.0 to −1.30‰), the δ^{18}O value of the Xiyangshan Formation features negative excursion. The reason may be that the Xiyangshan Formation inherited the temperature of the seawater from the Huayansi Formation. Therefore, the burial temperature of the sediment increased with time, and the temperature of the seawater was comparatively high and remained stable in the late period of the Xiyangshan Formation.

The δ^{34}S value of the first member of Xiyangshan Formation is −6.1‰–3.8‰, with an average value of −1.833‰; the δ^{34}S value of the second member is from −8.0‰ to −0.1‰, with an average of −4.52‰; the δ^{34}S value of the third member is −0.6‰–6.6‰, with an average of 2.46‰. Compared with the sulfate in seawater during the Xiyangshan Formation period in the geological history, the Xiyangshan Formation features significant negative anomaly of δ^{34}S value, which is abnormally low. This may be related to the sedimentary–diagenetic environment. The Xiyangshan Formation was in the alternation period of Cambrian and Ordovician periods, and the Area entered the sedimentary period in an open environment (deep shelf sedimentation → shallow shelf sedimentation). The rate of sulfate reduction is much lower than the supply rate of SO_4^{2-}. As a result, the δ^{34}S value of the sulfide formed owing to the reduction of sulfate-reducing bacteria in the seawater is 40–60‰, lower than the δ^{34}S value of the seawater, with an average of 50‰ (Zhang 1989).

2.3.5.5 Analysis of Sedimentary Environment

The Xiyangshan Formation is located in the middle-upper part of the Cambrian. In the lower part of the first member, the main sediment is dark gray siliceous argillaceous matter and marl and the trackway of mollusk creeps are visible along the layers. It is indicated that the sedimentary environment is near the redox interface, which is unfavorable for the survival of benthic shellfish and belongs to a deep shelf environment. In the upper part of the first member, the sediment is argillaceous carbonate interbedded with a small amount of lenticular and banded microcrystalline calcite. In the sediment, there are Agnostus and deepwater trilobite with comparatively complex planktonic structure. Besides, horizontal bedding developed. It is indicated that the hydrodynamic force was weak and oxidation was comparatively enough at that time. Therefore, the sedimentary environment in this part belongs to a shallow shelf sedimentary environment. In the second member, vein-strips of microcrystalline calcite increase, indicating that the sea level continued to fall and the seawater became shallow. Therefore, the second member belongs to a stable shallow shelf environment. In the lower part of the third member, the main sediment is thin–medium laminated sand mud interbedded with a small amount of microcrystalline calcite, with micro-fine horizontal bedding developing. It is indicated that the sea level rose and the hydrodynamic force was weak then, and the sedimentary environment belongs to deep shelf environment. In the part toward the top of Xiyangshan Formation, the sediment is carbonate, indicating that sea level fall occurred and the sedimentary environment is turned into a shallow shelf environment.

Regionally, the lithology of the Xiyangshan Formation in the Area is basically the same as that in the Area. That is, the lithology of the Xiyangshan Formation is mainly characterized by carbonate rocks followed by a small amount of calcareous mudstone. In the areas such as Duibian of Jiangshan City and Fuyang-Dongqiao of Tonglu County, the lithofacies of the upper part or the top of the Xiyangshan Formation is transformed into a sparry limestone, with mudstone lacking and conglomerate and landslide tectonic limestone interspersing. It is indicated that the sedimentary environment was converted into a slope. In Yuhang area, the lithofacies of Xiyangshan Formation turned into dolomite and the sedimentary environment transformed into a carbonate platform environment.

2.3.5.6 Trace Elements in Strata (Ore-Bearing)

1. **Characteristics of Trace Elements in Strata**

Sixty-five rock spectra were collected from three lithological members of Xiyangshan Formation of Kongkengkou profile (PM004) in Hanggai Town, Anji County. According to spectral analysis, the first member of Xiyangshan Formation is enriched in Bi, Sb, Ag, F, S, and TFe, the second member is enriched in Bi, F, S, and TFe, and the third member is enriched in Bi, F, S, and TFe. The content of S decreases upward, indicating the sea level rise and the oxygen content increase at that period.

2. **Content of CaO and MgO in Main Limestone and Marl**

According to the *Report on the Survey and Evaluation Results of Cambrian Limestone Resources of Zhejiang Province* (2007), the analysis results of the limestone and marl samples obtained by chip-channel method from the first member and the second member of Xiyangshan Formation of Yekengwu Profile in Hanggai Town, Anji County, are as follows. The respective average content of CaO and MgO of the six samples at the bottom of the first member is 38.83 and 3.32%. The respective average content of CaO and MgO of the four samples in the middle-lower part of the first member is 43.97 and 2.40%. The content of CaO and MgO of the rocks in other parts of Xiyangshan Formation is 15%–30% and 2%–5.64%, respectively.

2.3.6 Comparison of Regional Stratigraphy

In Zhejiang Province, the Cambrian topographic pattern was inherited from the Sinian. The sediments of it are mainly composed of siliceous argillaceous matter and carbonates from early to late period. The lithology of the sediment varies in different sedimentary zones as the sea level rises and falls. The regional stratigraphy was compared by taking the samples of the profile in the Area in Hanggai area, Chaoshan profile in Yuhang area, and Shima profile in Zhuji, Xiaoshan area from the northwest to the southeast.

The regional stratigraphy in the Early Cambrian is as follows. The strata of the early stage in Hanggai area mainly consist of the rocks in the first member of the Hetang Formation, including carbonaceous, argillaceous, and siliceous rocks of abyssal basin facies, intercalated with stone coal layers and phosphorite nodule layers. There are 1–3 layers of stone coal in the siliceous rocks and sedimentary pyrite contained generally. The thickness of the strata is 411 m. The strata of the middle stage in Hanggai area mainly consist of the rocks in the second member of Hetang Formation, which mainly includes carbonaceous siliceous mudstone of bathyal facies followed by carbonaceous argillaceous–siliceous rocks. The thickness of the strata is 200 m. The strata of the later stage in Hanggai area mainly consist of the rocks in Dachenling Formation, including the interbed consisting of carbonate and siliceous argillaceous matter of deep shelf facies–bathyal basin facies. The thickness of the strata is 52 m. In Yuhang–Fuyang area, the strata of the early stage consist of carbonaceous dolomitic mudstone of deep shelf facies in Chaoshan Formation, with a thickness of 25 m; the strata of the middle and late stage consist of the rocks of Dachenling Formation including the dolomite of platform facies containing a small amount of chert, with a thickness of 98–103 m. In Xiaoshan–Zhuji area in the southeast, the strata of the early stage consist of carbonaceous mudstone and stone coal layers of semi-closed estuarine facies in Hetang Formation, with a thickness of less than 30 m; the strata of the middle stage consist of carbonaceous siliceous mudstone and argillaceous–siliceous rocks of deep shelf facies in the middle-upper part of Hetang Formation, with a thickness of 120 m; the strata of the late period consist of the dolomitic limestone and micrite of neritic platform facies in Dachenling Formation, with a thickness of 120 m.

The regional stratigraphy in the Middle Cambrian is as follows. In Hanggai area, the strata consist of the rocks in Yangliugang Formation, which gradually change from the siliceous argillaceous matter of deep shelf facies–bathyal basin facies from bottom to top, indicating the falling process of the seawater. In Yuhang–Fuyang area, the strata consist of dolomitic limestone of shallow shelf facies–platform facies in Yangliugang Formation, with a thickness of 100 m. In Xiaoshan–Zhuji area, the strata are composed of banded marl and limestone of shallow shelf facies in Yangliugang Formation, with a thickness of 230 m.

The regional stratigraphy in the Later Cambrian is as follows. In Hanggai area, the strata of the early stage consist of the micrite of shallow shelf facies in Huayansi Formation with fine horizontal bedding developing, and the thickness of the strata is 123 m; the strata of the middle stage consist of the argillaceous limestone of deep shelf facies interbedded with lenticular micrite in the first member of Xiyangshan Formation, with a thickness of 145 m; the strata of the late stage consist of the interbed of argillaceous limestone and lenticular micrite of shallow shelf facies in the second member of Xiyangshan Formation, with a thickness of 113 m. In Yuhang–Fuyang area in the central area, the strata consist of dolomite and psephitic dolomite of platform facies in Chaofeng Formation, with a thickness of 175 m. In Xiaoshan–Zhuji area, the strata of the early stage consist of carbonate of shallow shelf facies in Huayansi Formation, with a thickness of 130 m; the strata of the middle stage consist of marl and micrite of shallow shelf facies in the lower part of Xiyangshan Formation, with a thickness of 60 m; the strata of the later stage consist of knotlike and lenticular argillaceous limestone of shallow shelf facies–platform facies in the middle-upper part of Xiyangshan Formation, which is the sediment in environment with high-energy oxidization and 200 m thick.

In northwest Zhejiang, the sediment gradually changes from siliceous mud and calcareous carbonate in Hanggai area to magnesium carbonate in Yuhang area and argillaceous calcareous carbonate in Xiaoshan area from northwest to southeast. In the central and southern areas with high terrain, some sediments are missing owing to the falling of the sea level in the Early and Later Cambrian (Fig. 2.26).

2.4 Ordovician System–Silurian System

Widely distributed in the Area, the Ordovician and the Silurian are exposed mainly in the eastern half of Hanggai map sheet and secondarily in the southwest of Xianxia map sheet. Besides, they are sparsely distributed in the southeast corner of Xianxia map sheet as well as the northwest, southeast, and northwest corners of Chuancun map sheet. The total outcrop area is 206.11 km^2, accounting for 16.21% of the bedrock area.

The Ordovician in the Area outcrops completely and continuously, and is divided into seven formations from bottom to top, namely: Yinzhubu Formation (O_1y), Ningguo Formation ($O_{1\text{-}2}n$), Hule Formation ($O_{2\text{-}3}h$), Yanwashan Formation (O_3y), Huangnigang Formation (O_3h), Changwu Formation (O_3c), and Wenchang Formation (O_3w). The Silurian in the Area mainly outcrops in Xiaxiang Formation (S_1x) and is in conformable contact with the underlying Wenchang Formation. According to the lithologic association, Yinzhubu Formation (O_1y), Hule Formation ($O_{2\text{-}3}h$), and Changwu Formation (O_3c) can be further divided into three members, respectively, and Xiaxiang Formation (S_1x) into two members.

2.4.1 Yinzhubu Formation (O_1y)

The name Yinzhubu Formation was established by Tinghu Zhu in 1924 in Yinzhubu, Fenshui Town, Tonglu County, Zhejiang. The stratotype profile of it was not yet determined then. The Yinzhubu Formation called by Lu et al. (1955) referred specifically to the stratum producing trilobite fossils in the former Yinzhubu System. It was subsequently used in the literature such as *Qu County Map Sheet on a Scale of*

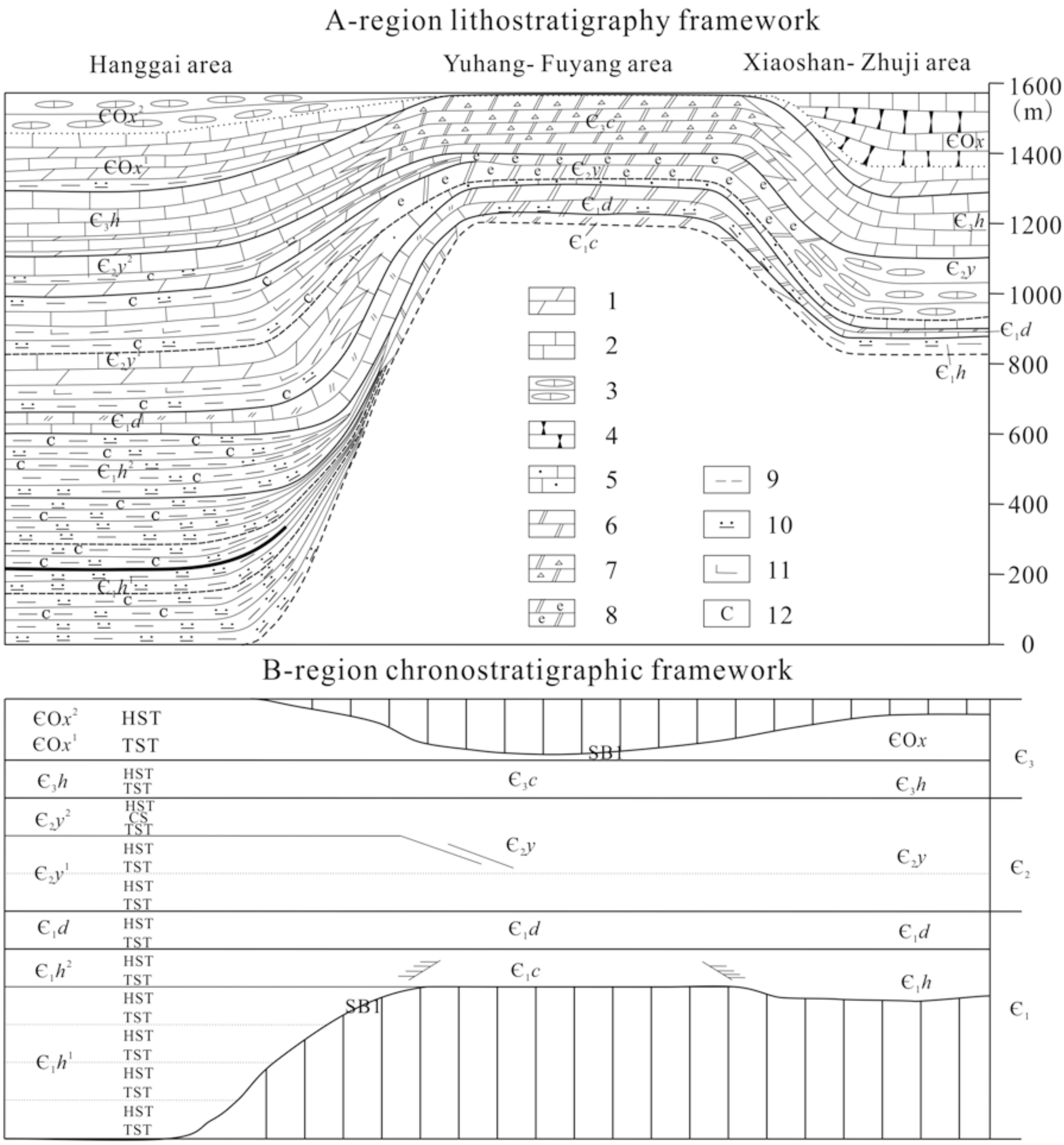


Fig. 2.26 Stratigraphic framework of Cambrian Hanggai–Yuhang–Fuyang–Xiaoshan–Zhuji area: 1. marl; 2. limestone; 3. banded limestone; 4. knotlike limestone; 5. sandy limestone; 6. dolomite; 7. brecciaous dolomite; 8. bioclastic dolomite; 9. argillaceous rock; 10. siliceous rock; 11. calcareous matter; 12. carbonaceous matter; $\in_1 h^1$—the first member of Hetang Formation; $\in_1 d$—Dachenling Formation; $\in_2 y^1$—the first member of Yangliugang Formation; $\in_2 y^2$—the second member of Yangliugang Formation; $\in_3 h$—Huayan Temple Formation; $\in Ox^1$—the first member of Xiyangshan Formation; $\in Ox^2$—the second member of Xiyangshan Formation; $\in_1 c$—Chaoshan Formation; $\in_3 c$—Chaofeng Formation; SB1—type-I unconformity interface; TST—transgressive systems tract; CS—starved section; HST—highstand systems tract

1:200,000 (1969), *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), and *Regional Geology of Zhejiang Province* (1989). In *Lithostratigraphy of Zhejiang Province* (1995), Yinzhubu Formation refers to a set of strata above caesious–olive thick laminated calcareous mudstone. This is different from the Yinzhubu Formation called by Lu et al. (1955). In this Project, the name Yinzhubu Formation (O_1y) is still adopted according to the lithological characteristics of Huangdouwu profile (PM005) and Lijiabian profile (PM011) in Hanggai map sheet, and the geological observation traverse within the Area.

2.4.1.1 Lithostratigraphy

Yinzhubu Formation (O_1y) in the Area, the most widespread stratum in the Lower Paleozoic, outcrops basically in the same way with Late Cambrian Xiyangshan Formation. The outcrop area is about 58.38 km^2, accounting for 4.59% of the bedrock area.

According to the lithologic association, Yinzhubu Formation (O_1y) can be divided into the first member of Yinzhubu Formation (O_1y^1), the second member of Yinzhubu Formation (O_1y^2), and the third member of Yinzhubu Formation (O_1y^3). Yinzhubu Formation is in conformable contact with its overlying Ningguo Formation and underlying Xiyangshan Formation.

The first member of Yinzhubu Formation (O_1y^1): consisting of gray medium laminated siliceous mudstone, medium–thick laminated silty siliceous mudstone interbedded with a small amount of micro-thin laminated knotlike micrite, and carbonaceous silty mudstone or argillaceous silt interbedded with calcareous siliceous mudstone from bottom to top; very thin horizontal bedding developing in the layers; the thickness of a single layer: 10–50 cm. The size of a piece of knotlike micrite: 2–4 cm generally. The thickness of this member: 76.07–510.00 m.

The second member of Yinzhubu Formation (O_1y^2): consisting of rhythm interbeds of dark gray calcareous siliceous mudstone or calcareous sandy mudstone, silty mudstone-bearing small-vein-strip shaped micrite; locally interbedded with argillaceous silt and marl. The small-vein-strip shaped micrite: no bedding developing, length × width: about (1–10) × (0.5–2) cm, small-vein-strip shaped micrite in a single rhythm increasing gradually from bottom to top. The thickness of this member: 24.36 m.

The third member of Yinzhubu Formation (O_1y^3): the lower part: gray medium laminated calcareous mudstone or interbeds consisting of medium laminated calcareous mudstone and knotlike micrite, locally interbedded with small-vein-strip shaped micrite; the middle part: dark gray medium laminated marl interbedded with vein-strip shaped micrite visible occasionally; the middle and upper part: caesious and gray medium laminated silty siliceous mudstone, bioturbation relics developing. The thickness of this member: 149.79–222.74 m.

1. **Stratigraphic section**

The lithology of Yinzhubu Formation is described by taking the example of Ordovician Yinzhubu Formation (O_1y) profile (Fig. 2.27) of Hanggai map sheet in Huangdouwu–Qiaotou area, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Ningguo Formation ($O_{1\text{-}2}n$) Total thickness: > 37.00 m

25. Gray–dark gray siliceous silty mudstone. 37.00 m

——— Conformable contact ———

Yinzhubu Formation Total thickness: 323.17 m

The third member of Yinzhubu Formation Total thickness: 222.74 m

24. Interbed consisting of caesious and gray medium laminated siliceous mudstone and medium laminated argillaceous siltstone, the main component: siliceous mudstone, horizontal bedding developing. 81.34 m

23. Gray medium laminated silty siliceous mudstone, locally interbedded with medium laminated calcareous sandstone and calcareous mudstone. Very thin horizontal bedding developing, organism burrows and creep trackway locally visible, carbonaceous matter with a size of 3 mm visible. 92.46 m

22. Gray medium laminated marl interbedded with vein-strip shaped limestone, horizontal bedding developing in the vein-strip shaped limestone. 4.85 m

21. Gray medium laminated silty siliceous mudstone, locally interbedded with thin laminated silty mudstone. The thickness of a single layer of the silty mudstone: 2–6 cm. Silty siliceous mudstone: horizontal bedding developing, the thickness of a single layer: 10–50 cm. 34.34 m

20. Gray thin laminated siliceous mudstone, interbedded with knotlike limestone. The siliceous mudstone: very thin horizontal bedding developing, the thickness of a single layer: 2–4 cm. The knotlike limestone:

spreading along the layer discontinuously, the size of a knot: (2–3) cm× (2–5) cm, the thickness of a single layer: 25–35 cm. 9.11 m

19. Interbed consisting of dark gray medium laminated silty siliceous mudstone and knotlike limestone and thin laminated silty mudstone bearing small-vein-strip shaped limestone. The size of vein-strip shaped limestone: 1–3 cm thick and 5–30 cm long. The thickness of a single layer of knotlike limestone: 3–15 cm; the thickness of a single of silty siliceous mudstone: 13–70 cm; the thickness of a single layer of silty mudstone bearing small-vein-strip shaped limestone: 15–140 cm. 7.12 m

18. Dark gray–gray medium laminated siliceous mudstone, horizontal bedding developing, the thickness of a single layer: 10–30 cm. 4.40 m

17. Dark gray thin laminated silty siliceous mudstone bearing vein-strip shaped limestone, silty strips (< 1mm) developing along the mudstone bedding, the thickness of a single layer: 2–5 cm. A vein strip: (1–2) cm × (1–25) cm, distributed along the layer discontinuously. 2.35 m

16. Gray medium laminated siliceous mudstone, fine-texture horizontal bedding developing, containing a small amount of carbonaceous clastics. Bioturbation structure locally visible. 21.37 m

15. Gray thick laminated calcareous mudstone interbedded with knotlike limestone. The calcareous mudstone: horizontal bedding developing, the thickness of a single layer: 55–82 cm. The knotlike limestone: distributed discontinuously along the layer. The diameter and thickness of a node of the knotlike limestone: 1–15 cm and 1–2 cm respectively. 11.36 m

———— Conformable contact ————

The second member of Yinzhubu Formation Total thickness: 24.36 m

14. The lower part: dark gray calciferous siliceous mudstone, the thickness: 70 cm. The top: dark gray, calcareous siliceous mudstone bearing dense small-vein-strip shaped limestone, thickness: 40 cm. Very thin horizontal bedding developing in the calciferous siliceous mudstone. 2.77 m

13. The lower part: dark gray calcareous silty mudstone interbedded with small-vein-strip shaped argillaceous limestone; the calcareous silty mudstone: no evident horizontal bedding developing, the thickness: 8–15 cm; the size of vein-strip shaped argillaceous limestone: (1–1.5) cm × (8–12) cm. The upper part: calcareous siltstone interbedded with a layer of vein-strip shaped limestone, very thin horizontal bedding developing. 3.39 m

12. The lower part: dark gray calcareous mudstone bearing vein-strip shaped marl, the upper part: calcareous siltstone. The proportion of vein-strip marl is the same as that of the calcareous mudstone. The size of vein-strip: 1–2 cm in thickness and 1–50 cm in length. The calcareous mudstone: bioturbation structure developing, the thickness of a single layer: 60–110 cm. The ratio of the siltstone to the mudstone: approximately (3–5):1. 2.03 m

11. Dark gray medium–thick laminated silty calcareous mudstone, horizontal bedding developing. 2.64 m

10. Gray thin–medium laminated calcareous silty mudstone interbedded with thin laminated knotlike limestone. The thickness of a single layer of the calcareous silty mudstone: 6–33 cm generally and 60 cm locally. The thickness of a single layer of knotlike limestone: 1–3 cm generally and 6–12 cm locally. Deformed lotus-root shaped structure visible. 3.39 m

9. The lower part: dark gray calciferous siliceous mudstone, containing vein-strip shaped micrite. The top: calciferous fine-sand siltstone (15 cm). Very thin horizontal bedding developing in all layers. 3.74 m

8. The lower part: dark gray calciferous siliceous mudstone bearing small-vein-strip shaped marl; the vein-strip: 30 × 1–3 cm, distributed discontinuously along the layers with an interval of 5–10 cm; the calciferous siliceous mudstone gradually changing to calcareous fine sandstone upwards. Very thin horizontal bedding developing in the fine sandstone. The ratio between the calciferous siliceous mudstone and the calcareous fine sandstone: 1:1. 1.72 m

7. Dark gray marl bearing vein-strip shaped limestone. The marl: very thin horizontal bedding developing, the bedding surrounding the vein-strip. The vein-strip shaped limestone: no bedding developing, the length × thickness: approximately (1–10) × (0.5–2) cm, distributed discontinuously along the layer. The interval between the vein-strips: 1–2 cm in the lower part, gradually increasing to 5–10 cm upwards. The upper part: calcareous mudstone or marl bearing vein-strip shaped limestone, the thickness: 78 cm. 4.68 m

——— Conformable contact ———

The first member of Yinzhubu Formation Total thickness: 76.07 m

6. Dark gray thick-blocky and laminated calcareous argillaceous siltstone, interbedded with a small amount of calcareous siliceous mudstone. The calcareous argillaceous siltstone: very thin horizontal bedding developing, fine-bar shaped after weathering. 3.85 m

5. Dark gray silty mudstone interbedded with calcareous siliceous mudstone. The calcareous siliceous mudstone: very thin horizontal bedding developing, silt stripes visible along the bedding. The width of a single strip: 0.1–0.3 cm. The argillaceous matter in the lower part is interbedded with much small-vein-strip shaped limestone, which decreases upwards. A single of the vein-strip: 1–2 cm × 5–20 cm. The marl in the middle part of the layer is 60 cm thick, with bioturbation structure developing. 3.39 m

4. Gray–dark gray medium laminated siliceous mudstone interbedded with thin laminated knotlike limestone. A layer of vein-strip shaped limestone interspersed in the middle part of the layer. The siliceous mudstone: very thin horizontal bedding and bioturbation structure developing, a small amount of small pyrite nodule visible. 4.93 m

3. Gray thick laminated siliceous mudstone, very thin horizontal bedding developing in the layers, creep trackway and many charcoal flats visible, a small amount of pyrite nodule with a particle size of 1–3 mm discovered. 6.95 m

2. Gray thick laminated to blocky silty siliceous mudstone, interbedded with micro–thin laminated knotlike marl. The silty siliceous mudstone: very thin horizontal bedding developing, the thickness of a single layer: 75–220 cm. The knotlike marl: accounting for 1%–2% of this layer, the size of a single node: 2–4 cm generally. Small pyrite nodules visible occasionally. 6.51 m

1. Gray medium laminated siliceous mudstone, very thin horizontal bedding developing in the layers. 50.44 m

——— Conformable contact ———

Xiyangshan Formation (ЄO*x*) Total thickness: > 14.10 m

0. Dark gray medium laminated marl interbedded with a small amount of medium laminated micrite. A layer of pie-stip shaped limestone interspersed in the top. The marl: horizontal bedding developing, the thickness of a single layer: 20–30 cm. The size of vein-strip shaped limestone: (5–20) cm × (3–8) cm. 14.10 m

The lithology of Yinzhubu Formation is described by taking the example of the profile of the third member of Yinzhubu Formation (O_1y^3) (Fig. 2.28) in Lijiabian Village, Hanggai Town, Anji County, Zhejiang. The details are as follows:

Ningguo Formation Total thickness: >72.33 m

15. Black medium–thin laminated siliceous silty carbonaceous shale, containing a small amount of pyrite, bedding developing extremely, graptolite visible. 10.1 m

14. Grayish black–modena medium laminated hornfelsic siliceous silty mudstone, containing a small amount of dark fine specks, bedding developing extremely, graptolite visible. 19.3 m

13. Black micro–thin laminated carbonaceous siliceous silty mudstone, bedding extremely developing, the thickness of a single layer: 3–10 mm, graptolite visible. 28.26 m

12. Grayish black–modena hornfelsic siliceous silty mudstone, horizontal bedding extremely developing, graptolite visible. 10.97 m

11. Black micro–thin laminated carbonaceous silty siliceous mudstone, bedding extremely developing, the thickness of a single layer: 1–3 mm. 3.69 m

——— Conformable contact ———

The third member of Yinzhubu Formation Total thickness 149.26 m

10. Gray-black hornfelsic mudstone, horizontal bedding developing extremely, much pyrite concentrating along the bedding. 2.81 m

9. Grayish black hornfelsic mudstone, micro-fine horizontal bedding developing. 43.05 m

8. Grayish black pyrite-bearing hornfelsic mudstone, the content of the pyrite: about 5%, the pyrite occurring in lamellar shape along the horizontal bedding. 8.18 m

7. Grayish black pyrite-bearing hornfelsic mudstone, the content of the pyrite: about 5%, and the pyrite distributed in the fine-grained disseminated form. 29.52 m

6. Grayish purple speckled hornfelsic mudstone, horizontal bedding developing comparatively in the layer. 7.92 m

5. Grayish yellow hornfelsic mudstone, horizontal bedding developing comparatively in the layer. 2.50 m

4. Gray speckled altered mudstone, the particle size of the specks: about 1 mm, pyrite sparsely distributed, horizontal bedding visible clearly in the layer. 10.95 m

3. Gray hornfelsic mudstone, horizontal bedding developing in the layer. 3.79 m

2. Gray–dark gray hornfelsic mudstone, sporadic pyrite of small particle size visible (2–3%), horizontal bedding developing in the layers. 29.54 m

1. Gray medium laminated mudstone interbedded with a small amount of knotlike limestone, the node diameter of the knotlike limestone: 4–6 cm, horizontal bedding developing in the mudstone. 11.00 m

——— Conformable contact ———

The second member of Yinzhubu Formation Total thickness: > 8.67 m

0. Gray calcareous mudstone bearing vein-strip shaped limestone. The length and width of a vein-strip of Limestone: 7–10 cm and about 1–2 cm generally. 8.67 m

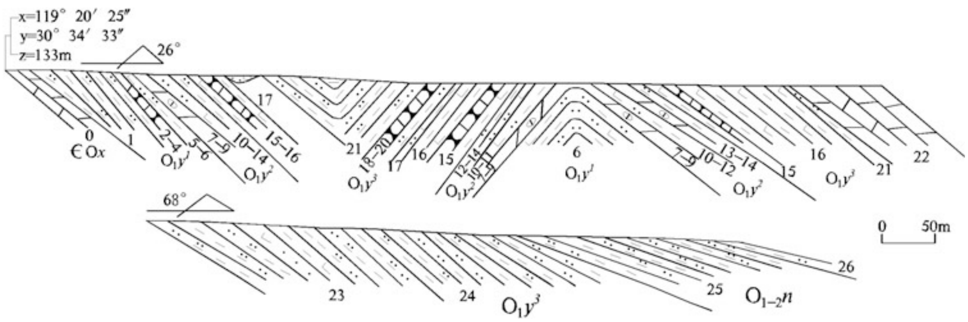


Fig. 2.27 Ordovician Yinzhubu Formation (O_1y) profile in Huangdouwu–Qiaotou area, Hanggai Town, Anji County, Zhejiang Province

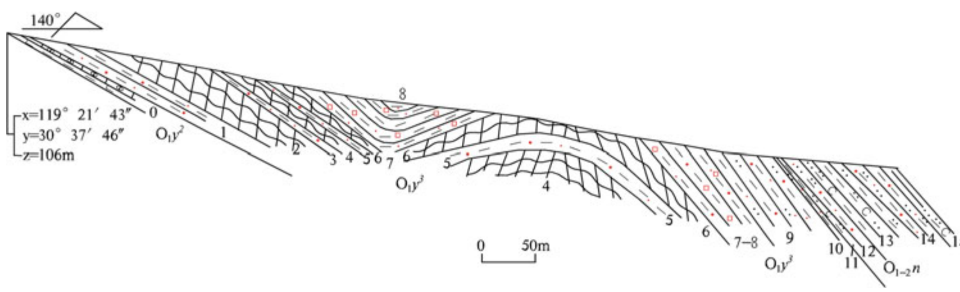


Fig. 2.28 Profile of the third member of Yinzhubu Formation (O_1y^3) in Lijiabian Village, Hanggai Town, Anji County, Zhejiang Province

2. **Lithological characteristics**

The lithology of the first member of Yinzhubu Formation (O_1y^1) is characterized by calcareous argillaceous silts and silty siliceous mudstone, siliceous mudstone, and knotlike marl.

(1) The calcareous argillaceous silts: gray; medium–thick laminated structure; composition: quartz silt (60%), argillaceous matter (25–30%), and micritic calcite (15–20%); very thin horizontal bedding developing; distributed in the upper part of the first member of Yinzhubu Formation.
(2) The silty siliceous mudstone: gray; medium–thick laminated structure; composition: argillaceous (60%), cryptocrystalline siliceous matter (20–25%), and quartz silt (10–15%); very thin horizontal bedding developing; the thickness of a single layer: 45–220 cm; distributed in the lower part of the first member of Yinzhubu Formation.
(3) The siliceous mudstone: gray–dark gray; medium laminated structure; composition: argillaceous (70%), cryptocrystalline siliceous matter (25%), silt occasionally visible (5%); very thin horizontal bedding developing; creep trackway and many charcoal flats distributed; distributed in the middle and lower parts of the first member of Yinzhubu Formation.
(4) The knotlike marl: gray; composition: micritic calcite (55–60%) and argillaceous matter (45–50%); diameter of a node of knotlike marl: 2–4 cm generally; mostly distributed discontinuously in mudstone along the bed; small pyrite nodules occasionally visible; distributed in the middle and lower parts of the first member of Yinzhubu Formation.

The lithology of the second member of Yinzhubu Formation (O_1y^2) is mainly characterized by calciferous siliceous mudstone and small-vein-strip shaped argillaceous limestone followed by calcareous silty mudstone.

(1) The calciferous siliceous mudstone: gray–dark gray; medium laminated structure; composition: argillaceous matter (55–75%), siliceous matter (25–30%), a small amount of micritic calcite (10–15%), and silt occasionally visible (5–10%); distributed in the upper and lower parts of the second member of Yinzhubu Formation.
(2) The small-vein-strip shaped argillaceous limestone: gray; size of vein-strip: about 30 × (1–3) cm; composition: microcrystalline calcite (50–65%), argillaceous matter (20–25%), and a small amount of silt; vein-strips distributed discontinuously along the layer at the interval of 3–10 cm; consisting of the main lithology of the second member of Yinzhubu Formation.

(3) The calcareous sandy mudstone: gray; medium laminated structure; composition: argillaceous (60%), micritic calcite (25–30%), and a small amount of silt (10–15%); the thickness of a single layer: 6–33 cm, up to 60 cm locally; distributed in the middle part of the second member of Yinzhubu Formation.

The lithology of the third member of Yinzhubu Formation (O_1y^3) is mainly characterized by silty siliceous mudstone, calcareous mudstone, knotlike marl, and silicon-bearing mudstone.

(1) The silty siliceous mudstone: gray–caesious; thick to medium laminated; composition: argillaceous matter (60–65%), cryptocrystalline siliceous matter (20–25%), and a small amount of silt (10–15%); silty stripes with a thickness of < 1 mm developing along bedding; consisting of the main lithology of the third member of Yinzhubu Formation.
(2) The calcareous mudstone: gray; medium laminated structure; composition: argillaceous matter (60–65%), microcrystalline calcite (20–30%), and a small amount of silt and carbonaceous clastics; fine-texture horizontal bedding developing; distributed in the bottom of the third member of Yinzhubu Formation.
(3) The marlstone: gray; composition: micritic calcite (65–70%) and argillaceous (30–5%); mostly knotlike; size: 2–4 cm generally; small-vein-strip partly shaped; distributed discontinuously along the layers in the mudstone; distributed in the middle and lower parts of the third member of Yinzhubu Formation.
(4) The siliceous mudstone: gray; medium laminated structure; composition: argillaceous (70–75%), cryptocrystalline siliceous (20–25%), and silt (5%); horizontal bedding developing; the thickness of a single layer: 10–30 cm; distributed in the middle part of the third member of Yinzhubu Formation.

3. **Basic sequences**

There are three types of basic sequences developing in the first member of Yinzhubu Formation (O_1y^1) (Fig. 2.29).

Basic sequences of type A: distributed in the middle and lower parts of the first member; composed of medium to thick laminated siliceous mudstone; the thickness of a single layer: 20–60 cm; horizontal bedding developing; belonging to low-energy siliceous argillaceous facies near the oxidation–reduction zone. Therefore, the basic sequences of this type belong to the monotonous basic sequence.

Basic sequences of type B: distributed in the middle part of the first member; composed of ① gray medium to thick laminated silty siliceous mudstone or siliceous mudstone and ② micro-thin laminated mudstone-bearing knotlike limestone; the mudstone: horizontal bedding developing, many bioturbation structure visible; the knotlike limestone: generally 2–4 cm in diameter, distributed discontinuously along the layers; from bottom to top, the thickness of the layers decreasing, knotlike limestone increasing, and siliceous argillaceous matter decreasing, reflecting the rise of the sea level. Therefore, the basic sequences of this type belong to non-cyclic basic sequence with siliceous argillaceous matter decreasing and calcareous matter increasing upward.

Basic sequences of type C: distributed in the upper part of the first member; composed of ① dark gray, medium to thick laminated carbonaceous silty mudstone or thick laminated argillaceous silt, interbedded with ② calcareous siliceous mudstone; micro-fine horizontal bedding developing in the layers; bioturbation structure commonly visible; from bottom to top, silt and the layer thickness increasing. Therefore, the basic sequences of this type belong to non-cyclic basic sequence with layer thickness and grain size increasing upward.

The sediments in the first member mainly include argillaceous–siliceous matter followed by a small amount of calcareous and terrigenous silt. Horizontal bedding is generally visible. Bioturbation structures are also commonly visible. The siliceous argillaceous matter comparatively decreases upward, reflecting siliceous argillaceous facies near oxidation–reduction interface under the wave base in deep shelf sedimentary environment. There are terrigenous clastics and silt in the sediments upward, indicating that there is a gradual sea level fall.

There is one type of basic sequence developing in the second member of Yinzhubu Formation (O_1y^2).

Basic sequences of type D: composed of ① dark gray calcareous siliceous mudstone or calcareous silty mudstone, ② siliceous mudstone-bearing small-vein-strip shaped limestone, and ③ small-vein-strip shaped limestone interbedded with mudstone. From bottom to top, the silt and siliceous argillaceous matter decrease gradually, the calcareous matter increases gradually, and the thickness of the layers decreases. Therefore, the basic sequences of this type belong to cyclic basic sequence with grain size increasing and layer thickness decreasing upward.

The sediments mainly contain calcareous argillaceous matter and sparse fossils, and therefore the second member belongs to carbonatite facies of deep–shallow shelf sedimentary environment near the oxidation–reduction interface.

There are two types of basic sequences developing in the third member of Yinzhubu Formation (O_1y^3).

Basic sequences of type E: distributed in the middle and lower parts of the third member, composed of ① gray

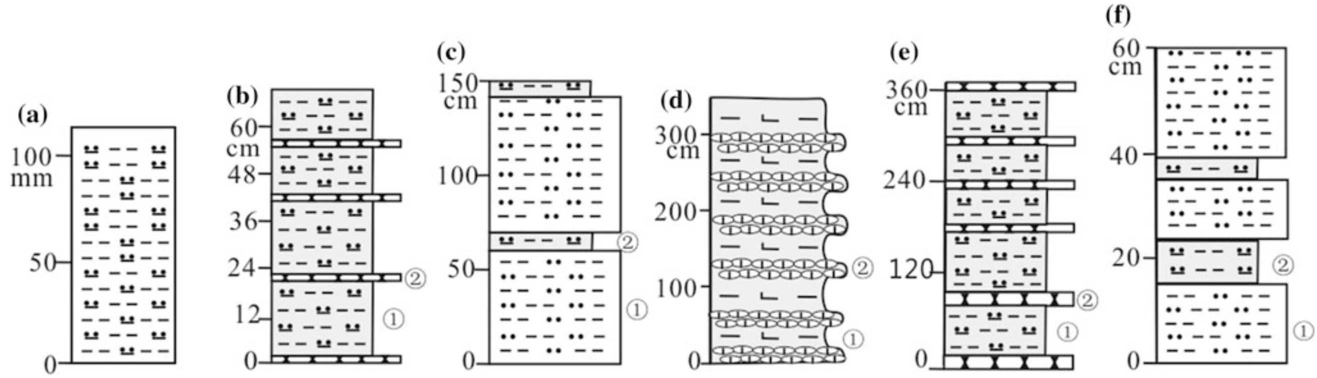


Fig. 2.29 Basic sequences of Yinzhubu Formation (O_1y)

medium to thick laminated silty siliceous mudstone or siliceous mudstone and ② mudstone-bearing micro-thin laminated knotlike limestone. The knotlike limestone is 2–4 cm in size generally, distributed discontinuously along the layers; from bottom to top, the thickness of the layers decreasing, the silt and knotlike limestone decreasing, and the siliceous argillaceous matter increasing, reflecting the sea level rising. Therefore, the basic sequences of this type belong to a non-cyclic basic sequence with layer thickness and grain size decreasing upward.

Basic sequences of type F: distributed in the upper part of the third member, composed of the interbeds of ① dark gray, medium laminated, silty mudstone or argillaceous siltstone and ② thin–medium laminated calcareous siliceous mudstone. Silt content and the thickness of the layers increase upward. Therefore, the basic sequences of this type belong to the basic sequence with layer thickness and grain size increasing upward.

In this member, sediments are mainly argillaceous–siliceous, a small amount of calcareous and terrigenous silt, and rock strata generally have horizontal bedding and sparse biological fossils, and it is the deepwater shelf carbonate-bearing silicon mud facies.

According to the lithological column of Yinzhubu Formation, from the second member, the calcareous matter decreases and siliceous argillaceous increases gradually upward and downward. Therefore, the sediments are characterized by symmetric distribution vertically.

2.4.1.2 Sequence Stratigraphy

According to rock features and types of top and bottom of Ordovician–Silurian systems, a second-order sequence SS7 is divided from Late Cambrian Xiyangshan Formation to Late Ordovician Yanwashan Formation and one second-order sequence SS8 is divided from Late Ordovician Huangnigang Formation to Early Silurian Xiaxiang Formation. According to the changes of sedimentary facies in the second-order sequences, SS7 is further divided into six third-order sequences (Sq16–Sq21) and one sub-second-order orthosequence set Ss1 while SS8 is further divided into four third-order sequences (Sq22–Sq 25) (Fig. 2.30).

According to the features of the lithologic association in Yinzhubu Formation (O_1y) profile of Huangdouwu–Qiaotou area in Hanggai Town, Anji County, Zhejiang Province, Yinzhubu Formation can be divided into two third-order sequences (Sq17–Sq18), both of which belong to second-order sequence SS7. Among these sequences, the third-order sequence Sq17 is composed of the third member of Xiyangshan Formation and the first member of Yinzhubu Formation as described in the previous section.

Third-order sequence Sq18: Located from the second member to the third member of Yinzhubu Formation, it consists of transgressive systems tract (TST) and highstand systems tract (HST). The top and bottom of Sq18 belong to type-II sequence boundary. TST is situated from Bed 7 to Bed 14, and the main sediments include thin–medium laminated microcrystalline calcite and siliceous argillaceous matter. Micro-fine horizontal bedding developed in the siliceous argillaceous matter, indicating deep shelf siliceous-argillaceous facies. The vein-strip shaped limestone in the sediments is shallow shelf carbonate facies, indicating frequent vibration and alternate change of the sea level during a new round of transgression. HST is situated from Bed 15 to Bed 24, and the main sediment is siliceous argillaceous matter. Besides, the lower part is interbedded with a small amount of knotlike limestone. Bioturbation structures and charcoal flakes are visible in mudstone of the upper part of HST. Very thin horizontal bedding developed in the rocks, indicating deep shelf siliceous-argillaceous facies in a weak oxidation environment. The sequence represents continual transgression and is a sequence of retrogradation–aggradation type.

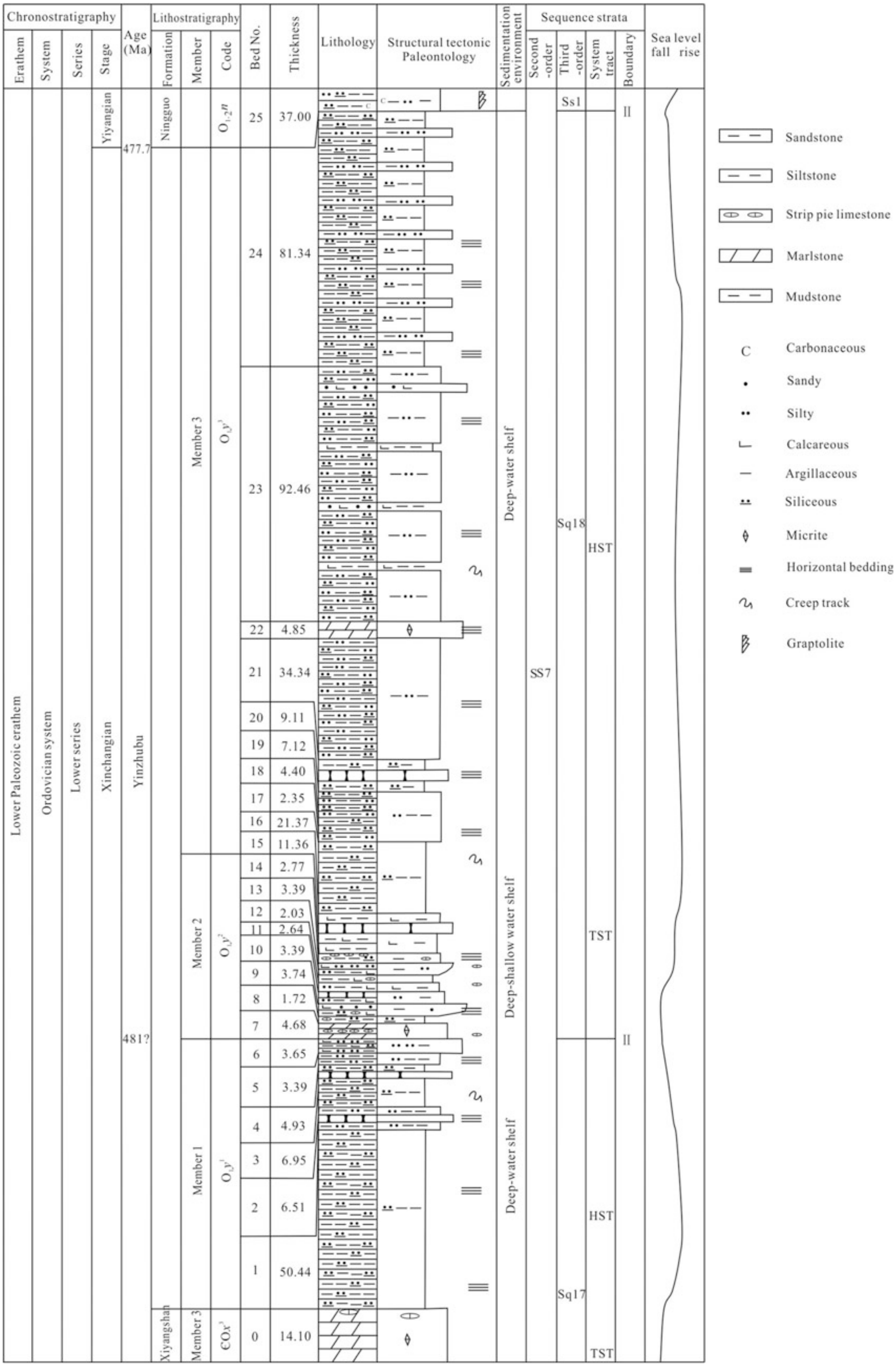


Fig. 2.30 Sequence stratigraphic framework of Ordovician Yinzhubu Formation in the area

2.4.1.3 Biostratigraphy and Chronostratigraphy

Yinzhubu Formation of the Area features sparse fossils. In this Project, no fossils were obtained and only bioturbation structure of Mollusca was found in the mudstone. According to *Regional Geology of Zhejiang Province* (1989), trilobite, brachiopod, and graptolite fossils are produced in the mudstone-bearing knotlike limestone in the upper profile of Yinzhubu Formation in Zhitang Village, Longyou County, and in the lower part of Yinzhubu Formation in Duibian Village, Jiangshan City. They belong to *Anisograptus–Clonograptus* zone. According to *Stratigraphic Chart of China* (2014), they are parts of Xinchangian Stage of the later period of the Early Ordovician. Therefore, Yinzhubu Formation is Early Ordovician strata.

2.4.1.4 Analysis of Sedimentary Environment

After the Cambrian when the sediments were dominated by carbonatite, great changes took place in the Ordovician sedimentary environment in northwest Zhejiang, and the sediments became dominated by argillaceous and terrigenous clasts and interbedded with a small amount of carbonate.

The sedimentary environment of Yinzhubu Formation of the early period of the Early Ordovician is as follows. In the first member, the sediments mainly include argillaceous matter followed by a small amount of siliceous matter, and very thin horizontal bedding developed, indicating a deep shelf environment under the oxidation–reduction interface. Terrigenous silt increases upward, the interbed of knotlike microcrystalline calcite appears, and Mollusca trackway of soft body developed in the siliceous mud, reflecting the rise of sea level and the increase of oxygen content in seawater and indicating the sedimentary environment above deep shelf oxidation zone.

The sedimentary environment of Yinzhubu Formation of the middle period of the Early Ordovician is as follows. In the second member, the sediments mainly include siliceous argillaceous matter and carbonate, which appears alternately in a rhythmic way, reflecting the frequent change of the seal level and indicating the sedimentary environment with alternate vibration of the deep shelf and shallow shelf.

The sedimentary environment of Yinzhubu Formation of the middle–late period of the Early Ordovician is as follows. In the third member, the sediments in this sequence are contrary to that of the early period. In detail, from bottom to top, the sediments gradually change from carbonate-bearing siliceous argillaceous matter into silty siliceous argillaceous matter, indicating a deep shelf sedimentary environment with sea level rise.

In conclusion, the sediments in Yinzhubu Formation change symmetrically upward and downward from the second member, generally reflecting the falling → rise process of the sea level and indicating the change process consisting of deep shelf → shallow shelf → deep shelf in the ancient geographic environment.

There is no considerable change in lithology and stratum thickness of Yinzhubu Formation in the Area, suggesting that Yinzhubu Formation is located in the same stable sedimentary basin. Regionally, in Dongqiao, Fuyang–Jingshanling, Hangzhou area, the lithofacies is transformed into knot-strip shaped marl, reticulate limestone, and banded limestone in Lunshan Formation (O_1l) and limestone with a polygonal reticulate structure in Honghuayuan Formation (O_1h), indicating platform sedimentary environment. In Jiangshan–Shaoxing area, the lithology is changed into caesious mudstone and silty mudstone, which contain sporadical calcareous nodule. In Changshan–Tonglu area, the lithology is characterized by amaranthine, caesious, and olive calcareous mudstone that contains calcareous concretion universally. The mudstone is 160–280 m thick and contains trilobite fossils, indicating a shallow shelf oxidation zone sedimentary environment.

2.4.1.5 Trace Elements in Strata (Ore-Bearing)

Sixty-five rock spectrums were systemically collected in the Yinzhubu Formation (O_1y) profile (PM005, 6) in Huangdouwu and Qiaotou, Hanggai Town, Anji County, Zhejiang Province, and statistics were made on the arithmetic mean values and concentration coefficients of 14 main trace elements of the three members of Yinzhubu Formation. According to the analysis and calculation results, the rocks of the three members are mainly enriched in Bi and F followed by Be, Sb, Cu, Pb, Zn, W, Ag, Sn, S, and TFe. This suggests that after long-distance transformation and sorting of terrigenous clasts, the content of most trace elements in pelagic siliceous argillaceous sediment is unchanged and only a small amount of trace elements get enriched and diluted.

2.4.2 Ningguo Formation ($O_{1\text{-}2}n$)

Ningguo Formation ($O_{1\text{-}2}n$) was established and named by Jie Xu in 1934 in Hulesi Town, Ningguo City, Anhui Province. Lu et al. (1955) introduced it to Zhejiang and named a section of the upper part (producing Early Ordovician *Didymograptushirundo*, etc.) in the former Yinzhubu System (established by Liu and Zhao in 1927) in northwest Zhejiang as Ningguo Formation, since the section features the same lithology and fossils as the Ningguo Formation in south Anhui. It was subsequently used by the preparation group of the regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text*

(1982) and *Regional Geology of Zhejiang Province* (1989). In this Project, the name Ningguo Formation ($O_{1\text{-}2}n$) was still adopted according to the lithological characteristics of Jiumulong profile (PM007) of Hanggai map sheet and the survey traverse.

2.4.2.1 Lithostratigraphy

The Ningguo Formation ($O_{1\text{-}2}n$) in the Area is mainly distributed in east Hanggai map sheet and secondarily in south Xianxia map sheet. The total outcrop area is about 4.79 km^2, accounting for 0.38% of the bedrock area.

The lithology and lithologic association of Ningguo Formation ($O_{1\text{-}2}n$) are characterized by dark gray thin to medium laminated silty mudstone, carbonaceous siliceous silty mudstone, and grayish black thin–medium laminated carbonaceous siliceous mudstone. In addition, very thin horizontal bedding developed and rich graptolite is present. It is in conformable contact with overlying Hule Formation and underlying Yinzhubu Formation. The thickness of the formation is 93.69 m.

1. **Stratigraphic section**

The stratigraphic profile of Ningguo Formation is described by taking the example of the Ordovician Ningguo Formation ($O_{1\text{-}2}n$)–the first member of Hule Formation ($O_{2\text{-}3}h^1$) profile (Fig. 2.31) in Jiumulong, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

The first member of Hule Formation Total thickness: >3.89 m

23. Grayish black thin–medium laminated carbonaceous silicalites interbedded with a small amount of carbonaceous mudstone. The carbonaceous silicalites: 6–20 cm per single layer, horizontal bedding developing. The carbonaceous siltstone: 1–5 cm thick per layer, accounting for 10% of the layer, horizontal bedding developing in the layers, and graptolite fragments visible. 3.89 m

——— Conformable contact ———

The first member of Hule Formation Total thickness: 5.24 m

22. Grayish black medium laminated silty carbonaceous siliceous mudstone, interbedded with a small amount of thin laminated carbonaceous silicalite, the thickness of a single layer: 10–15 cm, horizontal bedding developed. The thickness of a single layer of thin laminated carbonaceous silicalite: 1 cm and gradually increasing to 6–10 cm upwards. In the part with a distance of about 0–70 cm from the bottom of the layer, plenty of fossils of the following ancient organisms were obtained: *Pterograptuselegans* Holm, 1881, *Tetragraptus erectus* Mu, Geh et Yin, *dichograptid gen*. et sp., *Haddingograptuseurystoma* (Jaanusson, 1960) *Archiclimacograptus* sp. indet., *Kalpinograptusovatus* (Hall, 1902) *Haddingograptusoliveri* (Bouček), *Proclimacograptusangustatus* (Ekström), *Glossograptus* sp. Indet., *Archiclimacograptus* cf. *Caelatus* (Lapworth), and *Archiclimacograptusangulatus* (Bulman). 2.86 m

21. Grayish black thin laminated silty carbonaceous mudstone, occasionally interbedded with micro laminated silicalite. The silty carbonaceous mudstone: 5–9 cm thick per single layer, horizontal bedding developing. The silicalite: 3–0 mm thick per single layer, evenly distributed. Many fossils of *Pterograptus elegans* Holm 1881 visible in the carbonaceous silty carbonaceous mudstone 120 cm and 180–210 cm away from the bottom. 2.38 m

——— Conformable contact ———

Ningguo Formation ($O_{1\text{-}2}n$) Total thickness: 93.69 m

20. Grayish black thin–medium laminated silty carbonaceous siliceous mudstone, the thickness of a single layer: 7–20 cm, very thin horizontal bedding developing. Many fossils of *Nicholsonograptusfasciculatus* visible 200 cm away from the top (true thickness), plenty of graptolite visible 100–140 cm to the top, *Nicholsonograptusfasciculatus* visible 60–70 cm away from the top. 10.06 m

19. Covering. 1.64 m

18. Grayish black thin–medium laminated siliceous silty mudstone, the thickness of a single layer: 7–20 cm, very thin horizontal bedding developing. 2.31 m

17. Grayish black medium laminated carbonaceous siliceous mudstone, interbedded with mudstone and a thickness of 1–3cm; the siliceous carbonaceous mixture: banded, the thickness of a single layer: 10–20 cm; very thin horizontal bedding developing. 4.46 m

16. Grayish black thin laminated carbonaceous siliceous mudstone, the carbonaceous matter in the mudstone distributed in the shape of micro-fine stripe along the layers, very fine horizontal bedding developing along the layers. 3.26 m

15. Covering. 5.25 m

14. Dark gray thin–medium laminated carbonaceous siliceous mudstone, the thickness of a single layer: 6–13 cm, very thin horizontal bedding developing. 4.69 m

13. Grayish black thin laminated carbonaceous siliceous mudstone, the thickness of a single layer: 3–8 cm, very thin horizontal bedding developing. 3.38 m

12. Dark gray carbonaceous siliceous mudstone, the thickness of a single layer: 10 cm, very thin horizontal bedding developing, graptolite fossil visible. 1.92 m

11. Grayish black thin–medium laminated banded carbonaceous siliceous mudstone, the thickness of a single layer: 7–20 cm, very thin horizontal bedding developing, the following graptolite fossils obtained: *Cryptograptustrieornis*, *Tylograptusintermedsis*Mu, and *Phyllograptusilicifolios* Holl. 9.18 m

10. Dark gray thin laminated carbonaceous siliceous silty mudstone, off-white striates occurring along the bedding owing to weathering, the thickness of a single layer: < 10 cm, very thin horizontal bedding developing, carbonaceous matter concentrating along the bedding. 6.00 m

9. Grayish black thin laminated carbonaceous siliceous mudstone, the thickness of a single layer: < 10cm, very thin horizontal bedding developing. No graptolite fossil visible in the mudstone. 1.64 m

8. Dark gray–grayish-black thin–medium laminated silty fine-sandy mudstone, the thickness of a single layer: 8–15 cm, very thin horizontal bedding developing, *Dichograptid* gen. & sp. acquired. 5.98 m

7. Grayish black medium laminated carbonaceous siliceous silty mudstone, the thickness of a single layer: 10–30 mm. 1.83 m

6. Dark gray thin–medium laminated carbonaceous mudstone, the thickness of a single layer: 10 cm generally and 15 cm locally, very thin horizontal bedding developing. *Tylograptus* sp., *Allograptus* sp., and *Archiclimacograptus* sp. acquired. 15.00 m

5. Covering. 6.80 m

4. Dark gray thin–medium laminated siliceous silty mudstone, the silt distributed in the shape of micro-fine strips along the layer, the thickness of a single layer: 6–20 cm, very thin horizontal bedding developing. *Diplograptid* gen. & sp. acquired 1.48 m

3. Covering. 4.32 m

2. Dark gray thin–medium laminated siliceous silty mudstone, the thickness of a single layer: mostly 8–15 cm and >10 cm, horizontal bedding developing, off-white after weathering. 1.08 m

1. Dark gray–grayish-black thin–medium laminated silty mudstone, grayish-black mostly owing to high carbon content, the thickness of a single layer: mostly 8–20 cm and >10 cm, horizontal bedding developing. 3.96 m

——— Conformable contact ———

Yinzhubu Formation Total thickness: > 1.44 m

0. Gray thin laminated silty mudstone, the thickness of a single layer: 3–10 cm, very thin horizontal bedding composed of grayish–dark gray matter developing. 1.44 m

2. **Lithological characteristics**

The lithology of Ningguo Formation ($O_{1\text{-}2}n$) is mainly characterized by siliceous silty mudstone and carbonaceous siliceous mudstone.

(1) The siliceous silty mudstone: dark gray, thin–medium laminated, composition: argillaceous matter (50–55%), silt (15–35%), and a small amount of carbonaceous matter and cryptocrystalline siliceous matter (10–20%), containing rich graptolite.
(2) The carbonaceous siliceous mudstone: grayish black, thin–medium laminated, banded, composition: argillaceous matter (50–65%), cryptocrystalline siliceous matter (10–25%), and amorphous carbonaceous matter (10–15%), very thin horizontal bedding developing, containing rich graptolite.

3. **Basic sequences**

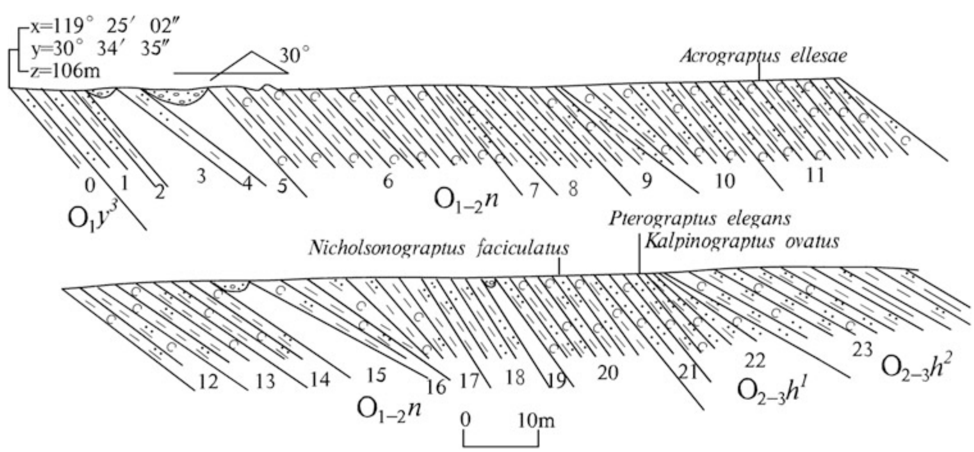
Two types of basic sequences (Fig. 2.32) developed in Ningguo Formation ($O_{1\text{-}2}n$), which is, respectively, composed of (carbonaceous) siliceous silty mudstone and carbonaceous siliceous mudstone. Therefore, the basic sequences of the two types are both characterized by a single lithology and are both of non-cyclic basic sequence composed with monotonous lithology. The siliceous mudstone constitutes the main body of Ningguo Formation. In the siliceous mudstone, there are rich graptolite as well as small amounts of terrigenous silt and carbonaceous, and micro-fine horizontal bedding developed extremely, indicating the sedimentation of abyssal graptolite shale facies.

2.4.2.2 Sequence Stratigraphy

Ningguo Formation in the Area features simple rock types, which are mainly argillaceous–siliceous matter followed by a small amount of carbonaceous matter and terrigenous silt, indicating that the sedimentary environment is a standing-water deepwater reduction environment. Therefore, only the changes in relative contents of siliceous matter, argillaceous matter, and terrigenous silt can be used to reflect the rise and falling of the sea level, identify transgression, maximum flooding surface, and regression, and determine the division of the systems tract.

On the basis of features of lithology, palaeontology, lithofacies association, and sequence boundary of Jiumulong profile of Hanggai map sheet, one sub-second-order orthosequence set Ss1 and one third-order sequence Sq19 were divided from Ningguo Formation ($O_{1\text{-}2}n$). Both Ss1 and Sq19 belong to the second-order sequence SS7 (Fig. 2.33).

Fig. 2.31 Ordovician Ningguo Formation ($O_{1\text{-}2}n$)–the first member of Hule Formation ($O_{2\text{-}3}h^1$) profile in Jiumulong, Hanggai Town, Anji County, Zhejiang, Province



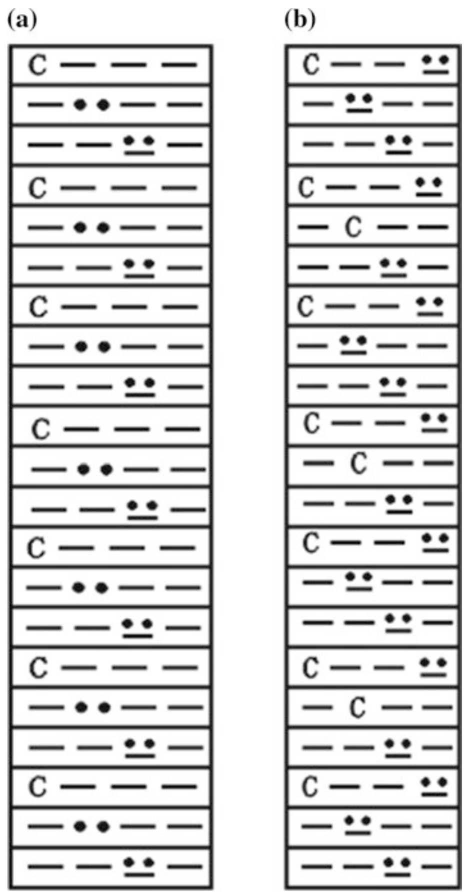


Fig. 2.32 Basic sequences of Ningguo Formation ($O_{1-2}n$)

Sub-second-order orthosequence set Ss1: Located in the lower part of Ningguo Formation, it consists of TST and HST. The top and bottom of Ss1 are of type-II sequence boundary. TST is located from Bed 1 to Bed 5. The sediments in the bottom of TST mainly include siliceous silty argillaceous matter followed by some terrigenous clasts, indicating the siliceous-argillaceous facies of bathyal sub-compensational basin. Till Bed 6, Ss1 entered the maximal flooding period, and the sediments in this bed are thick lamellar graptolite-bearing carbonaceous shale. HST is located from Bed 6 to Bed 9. The sediments in it mainly include argillaceous matter, containing rich siliceous carbonaceous matter and producing graptolite fossils, thus indicating the sedimentation in an abyssal basin reduction environment. The sequence set represents a weak process of transgression–retrogradation and is a sequence of aggradation type. Since the sequence set stands approximately in the Yiyangian Stage and the Dapingian Stage, the age range of it is 477.7–467.3 Ma, spanning about 10.4 Ma.

Third-order sequence Sq19: Located in the middle and upper parts of Ningguo Formation, it consists of TST and HST. The top and bottom of Sq19 are of type-II sequence boundary. TST is located from Bed 9 to Bed 14. The sediments in it mainly include argillaceous matter and occasionally contain terrigenous fine sand and silt. The terrigenous clasts decrease upward, indicating the rise of the sea level. In Bed 15–Bed 17, Sq19 entered the maximal flooding period, and the sediments in these beds are siliceous argillaceous matter with very thin horizontal bedding developing, indicating that the sedimentary environment is still a standing-water reduction environment. HST is located in Bed 18–Bed 20. The sediments in it mainly include argillaceous matter and a small amount of carbonaceous siliceous matter. The terrigenous clasts gradually increase upward, indicating the gradual falling of the sea level. Since the sediments mainly include carbonaceous siliceous argillaceous matter-bearing planktonic graptolite, HST shall be of siliceous-argillaceous facies in an abyssal reduction environment. Sq19 represents the sedimentation in the slight vibration of the sea level under continuous abyssal environment and is a sequence of aggradation type. The sequence starts from the bottom of Darriwilian Stage, and its top is located in the *Nicholsonograptusfasciculatus* zone, which is in the middle part of Darriwilian Stage. The age range of the sequence is 458.4–467.3 Ma, spanning about 8.9 Ma.

2.4.2.3 Biostratigraphy and Chronostratigraphy

During the period of Ningguo Formation, the Area was in basin sedimentation in closed reduction environment and featured most flourishing planktonic graptolite and other scarce ancient organisms. According to *Stratigraphic Chart of China* (2014), there are 10 graptolite zones in Ningguo Formation, and from bottom to top, they are: *Tetragrapproximatus* zone, *Pendeograptusfruticosus* zone, *Didymograptelluseobifidus* zone, *Baltograptus* (*Corymbograptus*) *deflexus* zone, *Azygograptussuecicus* zone, *Isograptuscaduceuimitatus* zone, *Exirgaptusclavus* zone, *Undulograptusaustrodentatus* zone, *Acrograptusellesae* zone, and *Nicholsonograptusfasciculatus* zone. In this Project, many graptolite fossils were obtained from Ningguo Formation and Hule Formation, and two graptolite zones were identified in Ningguo Formation. The distribution of the graptolite is shown in Fig. 2.34.

1. ***Acrograptusellesae* zone**

It is located in Bed 10–Bed 18 in the middle and upper parts of Ningguo Formation of Jiumulong profile. The graptolite obtained in the zone mainly includes *Acrograptusellesae* Rudemann (Fig. 2.35a) and other associated graptolites including *Tylograptusgeniculiformis* Mu, *Tylograptus intermedius* Mu, *Allograptus* sp. graptolite, *Archiclimacograptus* sp. graptolite, *lossograptus* sp., *Archiclimacograptus* sp., *Cryptograptustricornis* (Carruthers),

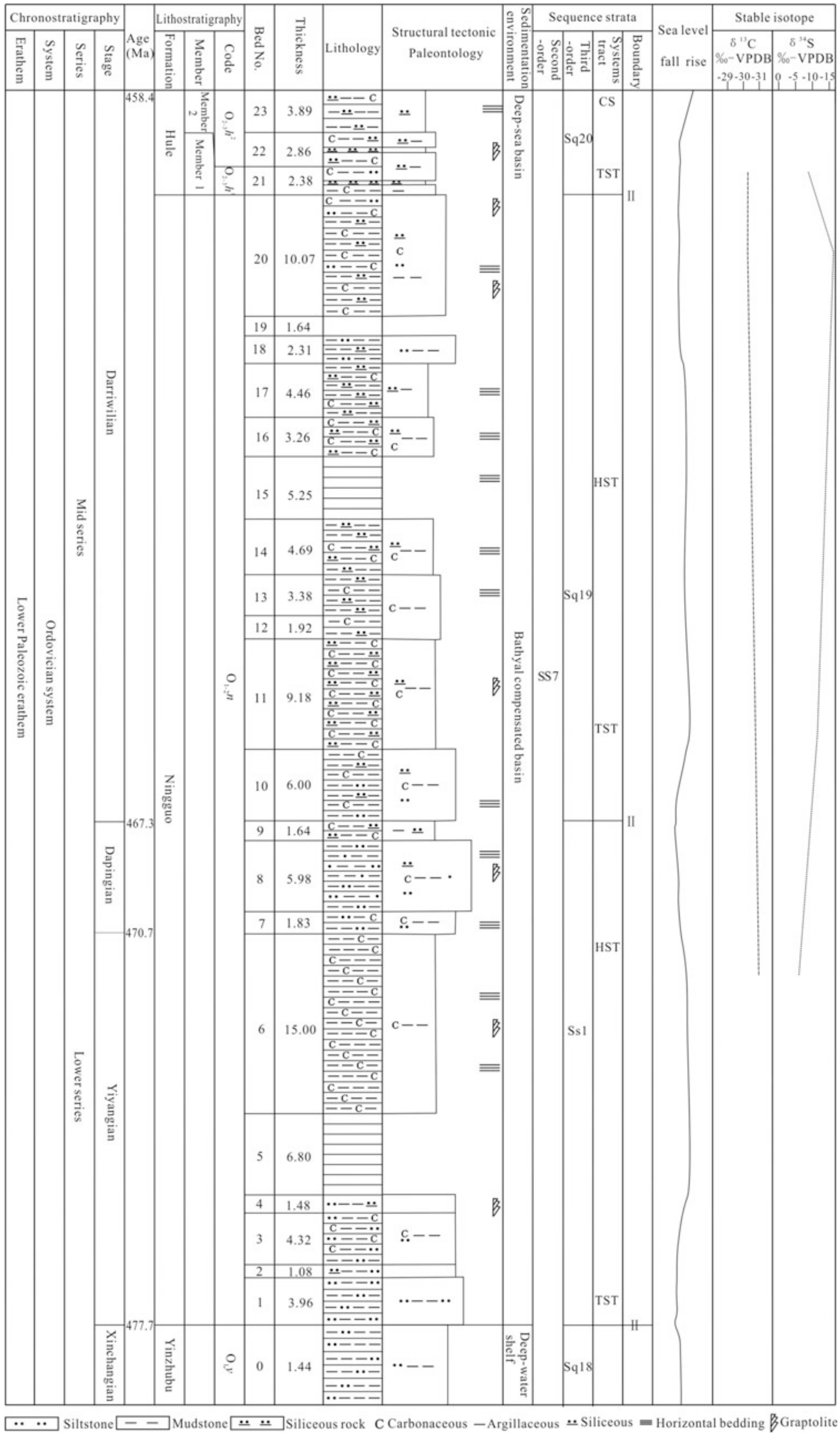


Fig. 2.33 Sequence stratigraphic framework of Ordovician Ningguo Formation in the area

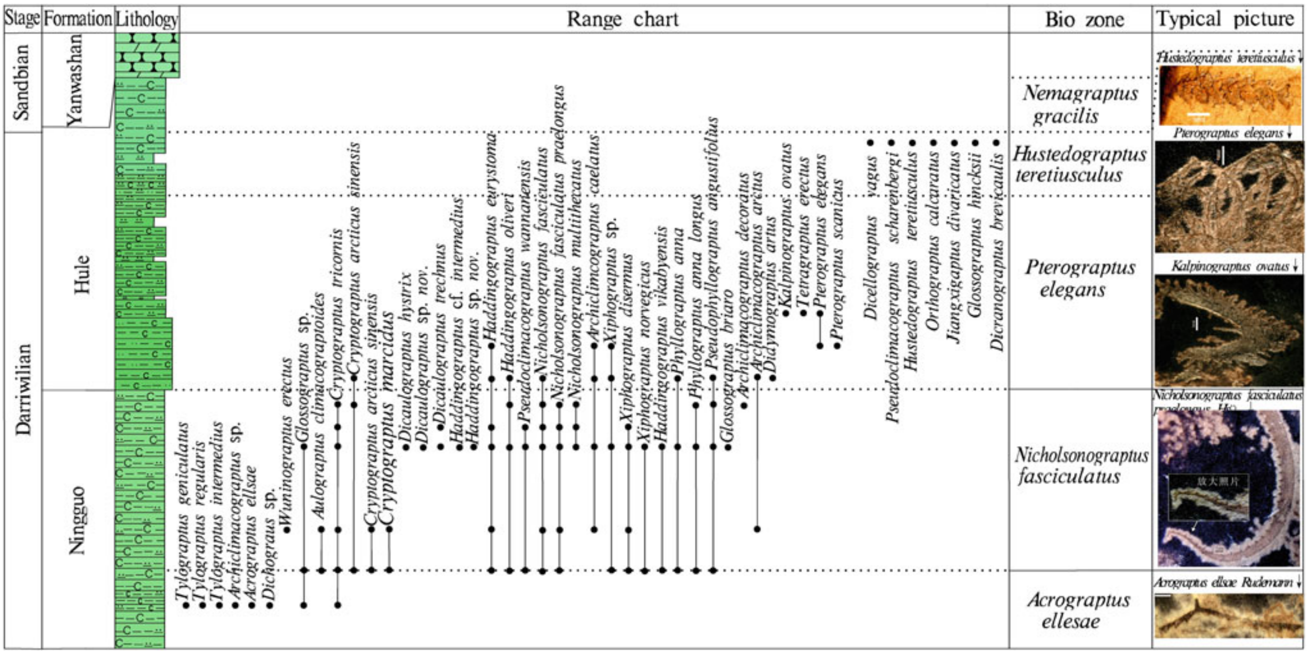
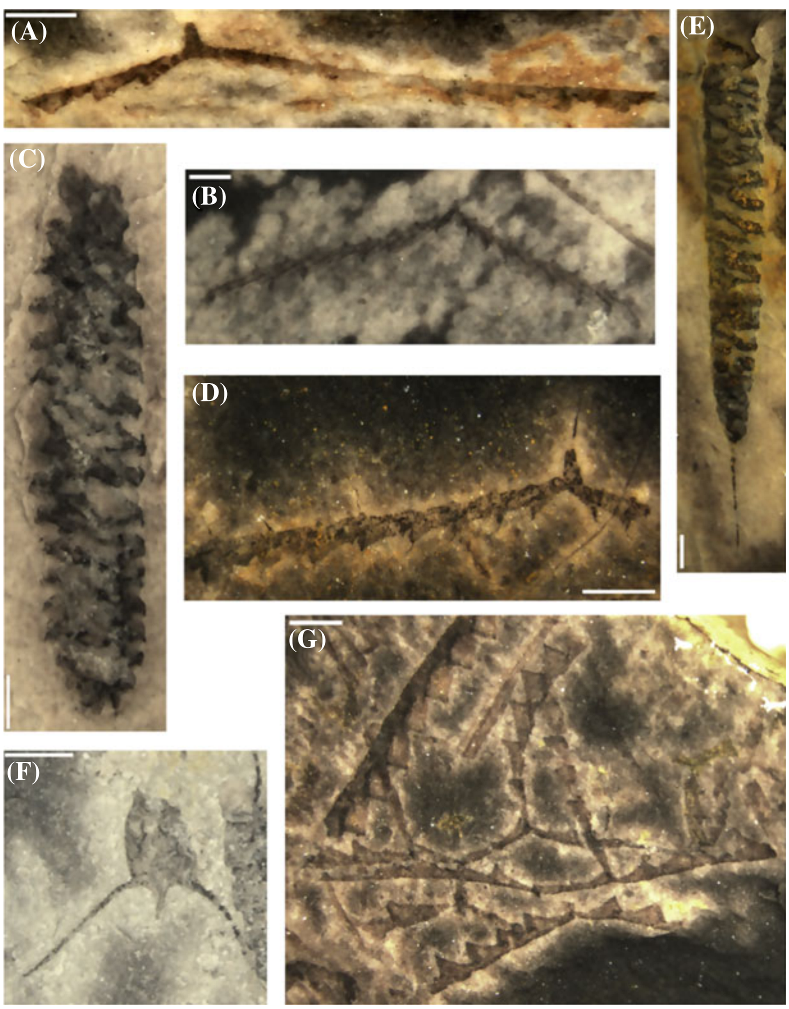


Fig. 2.34 Range chart of part fossils found in Ningguo Formation–Hule Formation in the area



(A) *Acrograptusellsae* Rudemann (PM007-11-4).

(B) *Tylograptus geniculiformis* Mu (PM007-11-3).

(C) *Glossograptus* sp. (PM007-11-1-28).

(D) *Tylograptus intermedius* Mu (PM007-11-1-22).

(E) *Archiclimacograptus* sp. (PM007-11-1-35).

(F) Cryptograptustricornis (Carruthers) (PM007-11-1-14).

(G) *Dichograptus* sp. (PM007-11-1-37).

Scale length = 1mm.

（The sample No. consists of Profile No. – Bed No. – specimen location – specimen No.)

Fig. 2.35 Graptolite in *Acrograptusellsae* zone in Bed 11 of Ningguo Formation ($O_{1-2}n$) in Jiumulong profile (PM007)

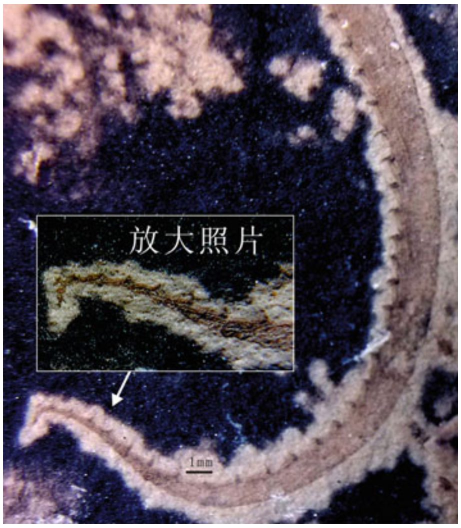


Fig. 2.36 *Nicholsonograptus fasciculatus praelongus* Hsü at the top of Ningguo Formation

Tylograptusintermedsis Mu, *Phyllograptusilicifolios* Holl, *Diplograptid*gen. & sp., *Dichograptid* gen. & sp. (Figure 2.35).

2. ***Nicholsonograptusfaciculatus* zone**

It is located at the top of Ningguo Formation. In this Project, the graptolite obtained from the four collection points located from bottom to top of Bed 20 in Jiumulong profile (PM007) mainly includes exquisite *Nicholsonograptus fasciculatus praelongus* Hsü (Fig. 2.36) and other paragenetic graptolite including *Nicholsonograptusfasciculatus* (Nicholson), *Nicholsonograptusmultithecatus* Ge, *Cryptograptusarcticussinensis* Ni, *Archiclimacograptuscaelatus* (Lapworth), *Archiclimacograptusdecoratus*, *Pseudoclimacograptuswannanensis* Li, *Archiclimacograptusarctus* (Elles and Wood), *Haddingograptusoliveri* (Bouček), *Dicaulograptus*sp. Nov., *Cryptograptustricornis* (Carruthers), *Xiphograptusnorvegicus* (Berry), *Aulograptusclimacograptoides, Wuninograptus erectus* Ni, *Pseudophyllograptus angustifolius* (Hall), *Glossograptusbriaros* Ni, *Dicaulograptushytrix* (Bulman), and Dicaulograptustrechnus Ni (Figs. 2.37, 2.38 and 2.39).

The above-mentioned is the typical paleontologic condition of Ningguo Formation in the Area. According to Stratigraphic Chart of China (2014), Ningguo Formation involves Yiyangian Stage, Dapingian Stage, and part of Darriwilian Stage. Among these 10 graptolite zones, Zone 1–Zone 4 belong to Yiyangian Stage of the Early Ordovician, Zone 5–Zone 7 belong to Dapingian Stage of the lower stage of the Middle Ordovician, and Zone 8–Zone 10 belong to Darriwillian Stage of the middle stage of the Middle Ordovician. Ningguo Formation spans from the lower and middle parts of the Ordovician.

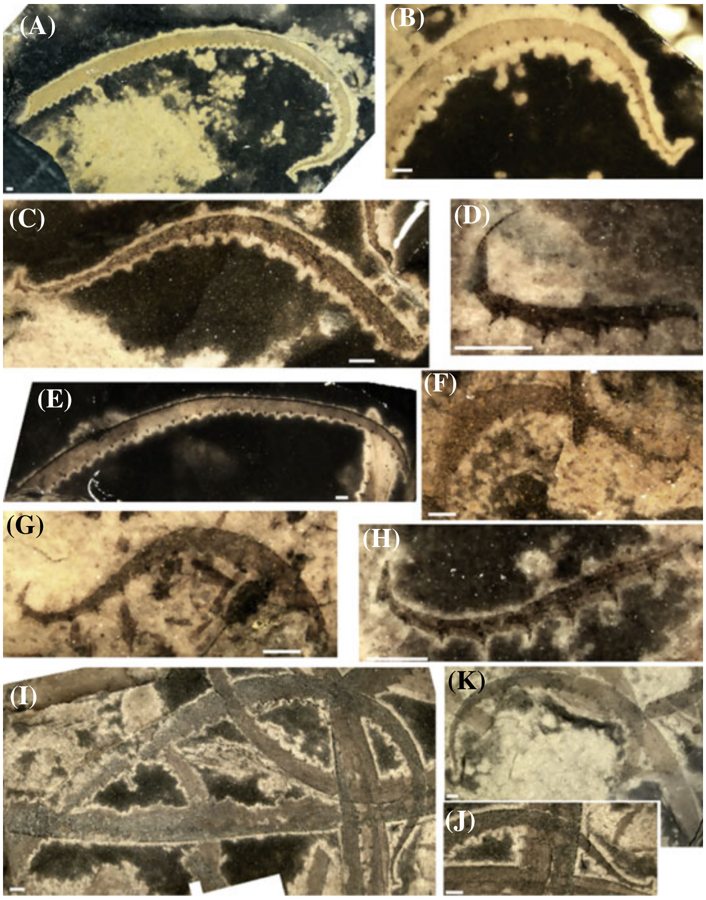
2.4.2.4 Characteristics of Stable Isotopes

Three whole-rock samples of stable isotopes $\delta^{13}C$ and $\delta^{34}S$ of carbonaceous mudstone were collected from Ningguo Formation of Jiumulong profile (PM007). The $\delta^{13}C$ value ranges between −30.99 and −30.24‰, with an average of −30.66‰. The $\delta^{34}S$ value ranges between −15.40 and −5.20‰, with an average of −10.33‰. According to Zheng and Chen (2000), the content of organic carbon $\delta^{13}C$ in sedimentary rocks of different periods in China ranges between −35 and −20‰, with an average of −24.4‰, and the content of $\delta^{34}S$ ranges between −10 and 10‰; the sedimentary rocks here mainly refer to fossil fuels (such as coal), most of which are humic coal and sapropelic coal with the $\delta^{13}C$ content mostly between −35 and −30‰. Therefore, it can be thought that the normal content of organic carbon $\delta^{13}C$ in sedimentary rocks ranges between −35 and −30‰. Obviously, the content of organic carbon $\delta^{13}C$ of Ningguo Formation in the Area is within the normal range. Therefore, it can be inferred that the sedimentary environment of Ningguo Formation in the Area is similar to the coal-forming environment, i.e., bathyal subcompensational basin sedimentation in which chitin lipoid organisms relatively developed. The $\delta^{34}S$ value is consistent with the normal content of $\delta^{34}S$ in shale. This further verifies that the Area of the Ningguo Formation period was in a reduction environment that was pretty favorable for coal forming.

2.4.2.5 Analysis of Sedimentary Environment

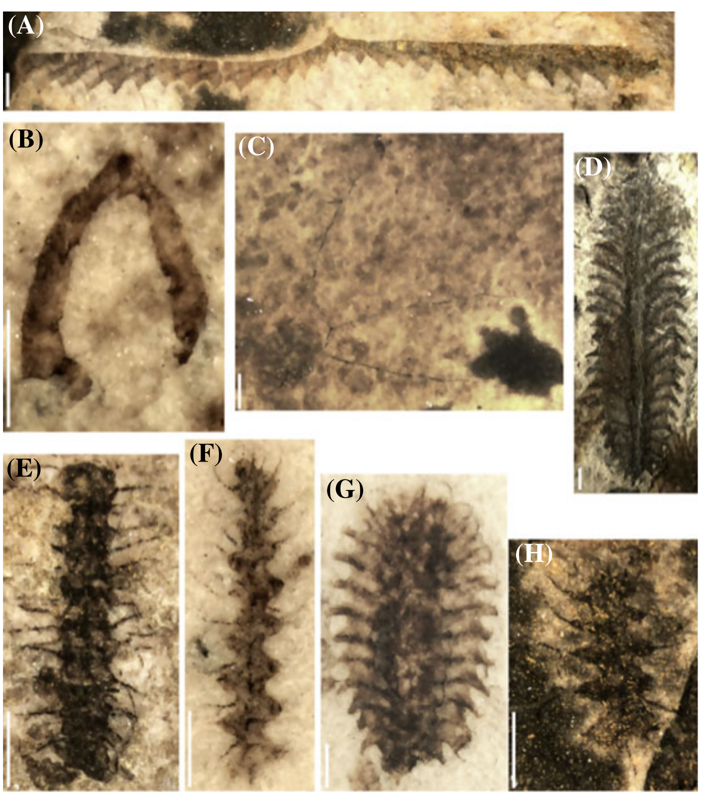
Compared with Yinzhubu Formation period, the Ordovician Ningguo Formation period experienced a qualitative change in sedimentary environments. That is, the open circulated oxidation environment in the Yinzhubu Formation period was transformed into the stagnant closed reduction environment Ningguo Formation period. This can be reflected by sediments. The sediments in Ningguo Formation are mainly dark gray–black siliceous argillaceous matter followed by carbonaceous. Besides, there are small amounts of terrigenous clastic silt and micro-fine-grained pyrite. The sediments contain rich well-preserved planktonic graptolite fossils and no demersal shellfish, with micro-fine horizontal bedding developing. All these indicate that the basin features extremely short sources of terrigenous clasts, very weak hydrodynamic force, and insufficient oxygen in the bottom. This is unfavorable for organism survival and belongs to bathyal subcompensational basin sedimentation with strong reduction.

Regionally, large lithofacies transition takes place in this formation. In the area along Banqiao (Lin'an)–Jingshanling



A-B. *Nicholsonograptus fasciculatus praelongus* Hsü (PM007-20).
C-E.*Nicholsonograptus fasciculatus* (Nicholson) (PM007-20-1-16).
D,H.*Nicholsonograptus* sp. (PM007-20-2-11,PM007-20-2-38). Two Juveniles.
F-G,I-K *Nicholsonograptus multithecatus* Ge (PM007-20-1-13, PM007-20-1-55, PM007-20-1, PM007-20-n-8). J is the amplified start point of I.
Scale length = 1mm.
(The sample No. consists of Profile No. – Bed No. – specimen location – specimen No.)

Fig. 2.37 Graptolite in *Nicholsonograptusfasciculatus* zone in Bed 20 of Ningguo Formation ($O_{1\text{-}2}n$) in Jiumulong profile (PM007)



A.*Xiphograptus Norvegicus* (Berry)(PM007-20-1-53).
B. *Aulograptus climacograptoides* (Bulman) (PM007-20-a-71).
C. *Wuninograptus erectus* Ni (PM007-20-b-32).
D. *Pseudophyllograptus angustifolius* (Hall) (PM007-20-a-89).
E. *Glossograptus briaros* Ni (PM007-20-1-14).
F. *Dicaulograptus hytrix* (Bulman) (PM007-20-1-58).
G. *Phyllograptus anna ultimus* Rudemann (PM007-21-53).
H. Dicaulograptus trechnus Ni (PM007-20-1-14)
Scale length = 1mm.
(The sample No. consists of Profile No. – Bed No. – specimen location – specimen No.)

Fig. 2.38 Other graptolite fossils in *Nicholsonograptusfasciculatus* zone in Bed 20 of Ningguo Formation ($O_{1\text{-}2}n$) in Jiumulong profile (PM007)

(Hangzhou), the lithofacies of Ningguo Formation is characterized by node-bearing calcareous mudstone interbedded with limestone lenticels, and demersal organisms and exotic conodont (the main ancient organisms), indicating a neritic platform oxidation environment. In Jiangshan area, the bottom of Ningguo Formation consists of calcarenite, and Huangnitang area of Changshan is interbedded with several layers of calcarenite and calcisiltite. In addition to graptolite, there are a small amount of pleopod and deepwater Brachiopoda in the formation of this area. This indicates that the Ningguo Formation of this area belongs to the sedimentary environment of slope transitional zone. In conclusion, from southeast to northwest, the lithology of the Ningguo Formation in Zhejiang Province gradually turns from interbeds of shale and intraclastic limestone into siliceous mudstone. Furthermore, the thickness of the formation gradually increases. In detail, it is 44.8–29.4 m in Jiangshan–Shaoxing area, 147.8 m in Liujia of Tonglu, 93.69 m in the Hanggai of Anji, and 175 m in Changhua–Anji area, indicating the paleogeographic landscape of lithofacies featuring gradually increasing depth of sedimentary basin, during decreasing hydrodynamic force, and sharply increasing oxygen content in seawater from southeast to northwest.

2.4.2.6 Trace Elements in Strata (Ore-Bearing)

Fifteen rock spectra were systemically collected in the Ningguo Formation of Jiumulong profile (PM007), and statistics were made on the arithmetic mean values and concentration coefficients of 14 main trace elements. According to spectral analysis and statistics, Ningguo Formation is mainly enriched in Sb, Bi, Pb, and Mo, and the enrichment coefficient of Bi is up to 46.13 times. Furthermore, most of the enriched elements are consistent with those in black rock series of Cambrian Hetang Formation. Therefore, it can be inferred that some materials from abyssal volcanic eruption and hot springs flowed and penetrated into the sediments.

2.4.3 Hule Formation ($O_{2-3}h$)

The name Hule Formation ($O_{2-3}h$) was created by Jie Xu in 1934 for Hulesi Town, Ningguo County, Anhui Province. The Hule Formation in Zhejiang refers to the shale in the lower part called Yanwashan System by Jichen Liu and Yazeng Zhao in 1927 since its biota is similar to but its lithology is a little different from Hule Formation in south Anhui. Lu et al. (1955) referred to the shale as Hule Formation. It was subsequently used by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). This formation includes graptolite zones N8–N9 in the former Ningguo Formation (previously called Niushang Formation). In this project, the name Hule Formation ($O_{2-3}h$) is still adopted given the lithological features of Xinqiao profile (PM001) and Lijiabian profile (PM012) in Hanggai map sheet, Xiajia profile (PM030) in Xianxia map sheet, and the geological observation traverse.

2.4.3.1 Lithostratigraphy

Hule Formation ($O_{2-3}h$) in the Area is a stratum with the highest content of siliceous matter in the Ordovician system of Lower Paleozoic Erathem. The outcrop range is basically the same as that of Ningguo Formation. The outcrop area is about 3.64 km^2, accounting for 0.29% of the bedrock area.

Based on the lithology and lithologic association, Hule Formation ($O_{2-3}h$) can be divided into three members: the first member ($O_{2-3}h^1$), the second member ($O_{2-3}h^2$), and the third member ($O_{2-3}h^3$). They are in conformable contact with its underlying Ningguo Formation and in disconformable contact with its overlying Yanwashan Formation.

The first member of Hule Formation ($O_{2-3}h^1$): rhythm beds consisting of grayish black thin–medium laminated carbonaceous silty shale interspersed with a small amount of micro-laminated silicalite, presence of graptolite. The thickness of this member: 4.98–12.41 m.

The second member of Hule Formation ($O_{2-3}h^2$): interbeds consisting of dark gray–grayish black thin laminated carbonaceous silicalite and thin–medium laminated silty argillaceous silicalite, producing graptolite locally. The thickness of this member: 55.60–81.14 m.

The third member of Hule Formation ($O_{2-3}h^3$): black thin laminated siliceous mudstone interspersed with micro-thin laminated carbonaceous silicalite, the components turning into siliceous mudstone upward, rich in graptolite. The thickness of this member: 3.47–15.04 m.

1. **Stratigraphic section**

The lithology of Hule Formation is described by taking the example of Ordovician Hule Formation ($O_{2-3}h$)–Huangnigang Formation (O_3h) profile (Fig. 2.40) in Xinqiao Village, Hanggai Town, Anji County, Zhejiang. The details are as follows:

Yanwashan Formation Total thickness: 13.75 m

10. Interbeds consisting of gray thin laminated marl and knotlike limestone. The marl: horizontal bedding developing, the thickness of a single layer: 3–7 cm; the node in the limestone: 2–7 cm in diameter, discontinuously distributed in moniliform shape and laminated form. The bottom of this bed: knotlike limestone with a thickness of 10 cm, the occurrence is consistent with that of its underlying stratum. 1.94 m

——— Conformable contact ———

The third member of Hule Formation Total thickness: 3.47 m

9. Dark gray siliceous carbonaceous shale, shale bedding developing. 1.93 m

8. Black thin laminated siliceous mudstone, interspersed with micro–thin laminated siliceous shale. The siliceous mudstone: very thin horizontal bedding developing; the thickness of a single layer of siliceous shale: 1–3 cm. Producing the following ancient organisms: *Dicellograptusvagus* Elles& Wood, 1904; *Pseudoclimacograptusscharenbergi*; *Hustedograptusteretiusculus* (Hisinger); *diplograptid* gen. &sp. Indet.; *Corynoides* sp.; *Orthograptuscalcaratus* Lapworth. 1.54 m

——— Conformable contact ———

The second member of Hule Formation Total thickness: 66.80 m

7. Black thin laminated argillaceous silicalite, containing silt (5–10%), the thickness of a single layer: 2–5 cm, very thin horizontal bedding developing, producing graptolite. 11.41 m

6. Dark thin laminated silty argillaceous silicalite, the thickness of a single layer: generally 2–8 cm and rarely 10–11 cm. 76 m

5. Dark gray thin laminated carbonaceous silicalite, the thickness of a single layer: 2–7 cm, pretty broken. 3.60 m

4. Black thin laminated silty argillaceous silicalite, the thickness of a single layer: 3–7 cm, horizontal bedding developing. 17.64 m

3. Grayish black thin laminated argillaceous siliceous shale, the thickness of a single layer: 2–10 cm, rich in graptolite. 7.29 m

2. Covering. 10.10 m

——— Conformable contact ———

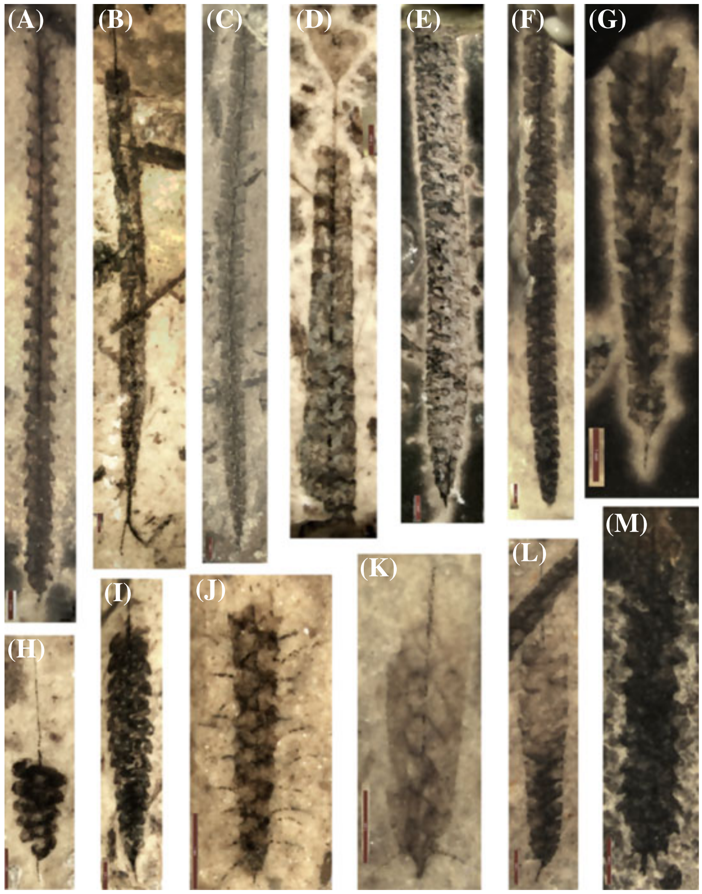
The first member of Hule Formation Total thickness: 4.98 m

1. Rhythmic layer consisting of grayish-black thin–medium laminated carbonaceous siliceous shale interspersed with micro laminated carbonaceous silicalite. The carbonaceous siliceous shale: mostly 19 cm thick per single layer, very thin horizontal bedding developing, graptolite visible; the silicalite: no bedding developing, hard, the thickness of a single layer: 0.3–0.5 cm. 4.98 m

——— Conformable contact ———

Ningguo Formation Total thickness: > 17.05 m

0. Black carbonaceous siliceous shale, very thin horizontal bedding developing along the layer, in black and white after weathering, white bands containing no carbonaceous matter. 17.05 m



A. Cryptograptusarcticussinensis Ni (PM007-20-3-87).
B-C. Archiclimacograptuscaelatus (Lapworth) (PM007-20-1-54, PM007-21-2-63).
D. Archiclimacograptusdecoratus (PM007-20-3-9).
E. Haddingograptus sp. (PM007-21-2-6).
F. Pseudoclimacograptuswannanensis Li (PM007-20-2-2).
G, L. Archiclimacograptusarctus Elles & Wood (PM007-21-84, PM007-20-b-14).
H-I. Haddingograptusoliveri (Bouček) (PM007-20-3-38, PM007-20-1-61).
J. Dicaulograptussp. nov.(PM007-20-1-47).
K. Cryptograptustricornis (Carruthers) (PM007-20-2-4).
M. Cryptograptus sp. (PM007-20-a-70).
（The sample No. consists of Profile No. – Bed No. – specimen location – specimen No.）

Fig. 2.39 Other graptolite fossils at Beds 20–21 of Ningguo Formation ($O_{1\text{-}2}n$)–Hule Formation ($O_{2\text{-}3}h$) of Jiumulong profile (PM007)

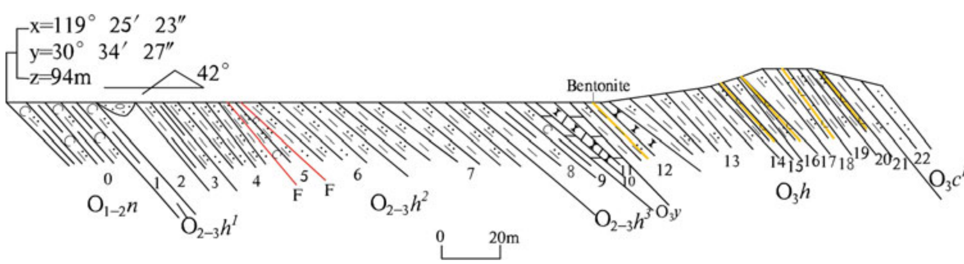


Fig. 2.40 Ordovician Hule Formation ($O_{2\text{-}3}h$)–Huangnigang Formation (O_3h) profile in Xinqiao Village, Hanggai Town, Anji County, Zhejiang

2. **Lithological characteristics**

The lithology in the first member of Hule Formation ($O_{2\text{-}3}h^1$) is mainly characterized by grayish black thin–medium laminated carbonaceous silty siliceous shale and micro-laminated silicalite.

(1) The carbonaceous silty siliceous shale: dark gray–black, composition: argillaceous matter (80–85%), a small amount of carbonaceous and siliceous matter (10–15%), and occasionally visible silt (5%), the thickness of a single layer: mostly about 19 cm, very thin horizontal bedding developing, rich in graptolite.
(2) The silicalite: dark gray, mainly composed of siliceous matter, no bedding developing, hard, the thickness of a single layer: 0.3–0.5 cm, projecting after weathering.

The lithology of the second member of Hule Formation ($O_{2\text{-}3}h^2$) is mainly characterized by dark gray–grayish black thin laminated carbonaceous silicalite and thin–medium laminated silty argillaceous silicalite.

(1) The carbonaceous silicalite: dark gray, composition: cryptocrystalline siliceous matter (50–60%) and carbonaceous matter (25–40%), hard.
(2) The silty argillaceous silicalite: dark gray, composition: cryptocrystalline siliceous (50%), argillaceous (25–30%), silt (15–20%), and micro-fine-grained pyrite (< 5%); silt is mainly composed of terrigenous quartz clasts.

The lithology of the third member of Hule Formation ($O_{2\text{-}3}h^3$) is mainly characterized by black thin laminated siliceous mudstone and thin–medium laminated carbonaceous silicalite.

(1) The siliceous mudstone: dark gray, composition: argillaceous matter (75%) and a small amount of siliceous matter (20–25%), very thin horizontal bedding developing, rich in graptolite.
(2) The charcoal-bearing silicalite: dark gray–black, composition: siliceous matter (80%–90%) and a small amount of carbonaceous matter (10–20%).

3. **Basic sequences**

One type of basic sequences developed in the first member of Hule Formation ($O_{2\text{-}3}h^1$) (Fig. 2.41).

Basic sequences of type A: composed of grayish black carbonaceous silty shale and micro-laminated silicalite; the thickness of a single of the micro-laminated silicalite: 1–2 mm in the lower part of the sequence and gradually increasing upward as 3–5 cm; belonging to non-cyclic basic sequence with layer thickness increasing and grain size decreasing upward.

In this member, the major and minor sediments are argillaceous matter and siliceous, respectively. The planktonic graptolite constitutes the main fossils. Therefore, this member belongs to graptolite-bearing mudstone facies of bathyal subcompensational basin.

Two types of basic sequences developed in the second member of Hule Formation ($O_{2\text{-}3}h^2$).

Basic sequences of type B: distributed in the middle part of the second member of Hule Formation; composed of dark gray–grayish black thin laminated carbonaceous siliceous; belonging to monotonous basic sequence.

Basic sequences of type C: main basic sequences in the second member of Hule Formation, composed of thin–medium laminated silty argillaceous silicalite, belonging to the non-cyclic basic sequence composed of monotonous lithology.

In this member, the major and minor sediments are siliceous matter and argillaceous matter, respectively. A small amount of planktonic graptolite is visible. Therefore, this member belongs to argillaceous–siliceous facies of abyssal subcompensational basin.

One type of basic sequences developed in the third member of Hule Formation ($O_{2\text{-}3}h^3$).

Basic sequences of type D: composed of rhythm interbed of ① black thin laminated siliceous mudstone and ② micro-thin laminated carbonaceous silicalite. From bottom to top, the micro-laminated silicalite in a small amount

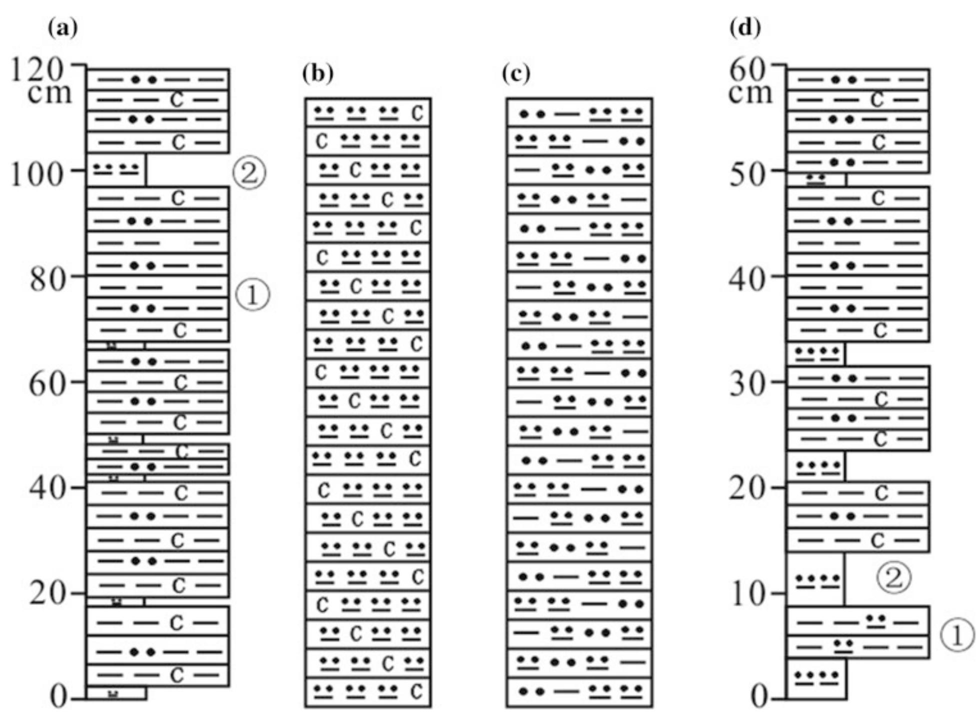


Fig. 2.41 Basic sequences of Hule Formation ($O_{2\text{-}3}h$)

gradually becomes visible occasionally and the thickness gradually decreases. This trend is contrary to that of the basic sequences of type A. Therefore, the sequences of this type are of non-cyclic basic sequence with argillaceous matter increasing and thickening upward.

In this member, the sediments are mainly argillaceous matter followed by siliceous matter, and planktonic graptolite is rich in the rocks. Therefore, this member belongs to graptolite-bearing argillaceous–siliceous facies of bathyal subcompensational basin.

2.4.3.2 Sequence Stratigraphy

According to the features of lithology, palaeontology, lithofacies association, and sequence boundary of Xinqiao profile in Hanggai map sheet, there is one third-order sequence (Sq20) in Hule Formation ($O_{2\text{-}3}h$), which belongs to second-order sequence SS7 (Fig. 2.42).

***Third-order sequence Sq*20**

Located in Hule Formation, Sq20 consists of TST, CS, and HST. The top and bottom of it are of type-II sequence boundary. TST is located in Bed 1–Bed 4, i.e., the first member of Hule Formation and the upper part of the second member. The lower part of TST is grayish black silty carbonaceous siliceous mudstone interspersed with micro-laminated silicalite, which turns to dark gray–black thin- to medium-blocky siliceous mudstone and argillaceous silicalite upward with siliceous matter increasing and argillaceous matter decreasing. Very thin bedding and graptolite developed, indicating a siliceous-argillaceous facies of bathyal subcompensational basin–abyssal subcompensational basin and reflecting transgression process with the sea level rising gradually. CS is located in the thin laminated carbonaceous silicalite of Bed 5, which is in the middle part of the second member of Hule Formation, indicating silicalite facies in the abyssal stagnant reduction environment during the maximum flooding period. HST is located in Bed 6–Bed 8 involving the second member of Hule Formation and the third member. From bottom to top, the components of HST change from dark gray thin laminated silty argillaceous silicalite and argillaceous silicalite into siliceous mudstone. The silicalite gradually decreases, argillaceous matter increases gradually, and the siliceous mudstone in the upper part is rich in graptolite, indicating siliceous-argillaceous facies of bathyal–abyssal basin in the high water-level stagnant reduction environment and reflecting the falling process of the sea level. In conclusion, this sequence, from bottom to top, reflects a complete process of transgression–regression and is a sequence of retrogradation–progradation type.

2.4.3.3 Biostratigraphy and Chronostratigraphy

The Hule Formation in the Area inherited the sedimentary environment of Ningguo Formation period. The ancient organisms in this formation are mainly planktonic graptolite and can be divided into three graptolite zones, i.e., *Pterograptus elegans* zone, *Hustedograptus teretiusculus* zone, and *Nemagraptus gracilis* zone. In this Project, *Pterograptus elegans* zone was found in the first member of Hule Formation, *Hustedograptus teretiusculus* zone was found in the lower part of the third member of Hule Formation, and no fossils were found in the black carbonaceous shale, which is 2 m thick at the top of the third member of Hule Formation. But there is *Nemagraptus gracilis* zone in similar horizons of other regions in Zhejiang Province. The features of ancient organism association in *Pterograptus elegans* zone and *Hustedograptus teretiusculus* zone in Hule Formation are described as below:

1. ***Pterograptus elegans zone***

Pterograptus elegans zone is roughly located in Bed 21–Bed 23 in the first member of Hule Formation in Jiumulong profile (PM007) in Hanggai Town, Anji County, and the main graptolite includes *Pterograptus elegans* Holm 1881 (Fig. 2.43) and associated graptolites including *Tetragraptus erectus* Mu, Geh et Yin, dichograptid gen. et sp., *Haddingograptuseurystoma* (Jaanusson 1960), *Archiclimacograptus* sp. Indet., *Kalpinograptus ovatus* (Hall 1902, Fig. 2.44c, d), *Haddingograptusoliveri* (Bouček), *Proclimacograptusangustatus* (Ekström), *Glossograptus* sp. Indet., *Archiclimacograptus cf. caelatus* (Lapworth), and *Archiclimacograptus angulatus* (Bulman).

Among these graptolite, *Kalpinograptus ovatus* (Hall 1902) (Fig. 2.44) is a typical fossil in Keping region, Xinjiang, and is also the one found for the first time in Lower Yangtze area, thus providing the basis for stratigraphic comparison between South China and North China.

2. ***Hustedograptus teretiusculus*** zone

Hustedograptus teretiusculus zone is in the lower part of the third member of Hule Formation of Lijiabian profiles PM012 and D2025. The fossils in the zone from bottom to top mainly include *Hustedograptus teretiusculus* (Hisinger, Fig. 2.45) and associated fossils including *Dicellograptus vagus* (Elles and Wood 1907), *Pseudoclimacograptus scharenbergi*, diplograptid gen. &sp. Indet., *Corynoides* sp., *Orthograptus calcaratus* (Lapworth), *Dicellograptus geniculatus*, *Dicranograptus brevicaulis*, and *Climacograptus* sp.

Hustedograptus teretiusculus zone belongs to Darriwilian Stage and also represents the graptolite zone at the top.

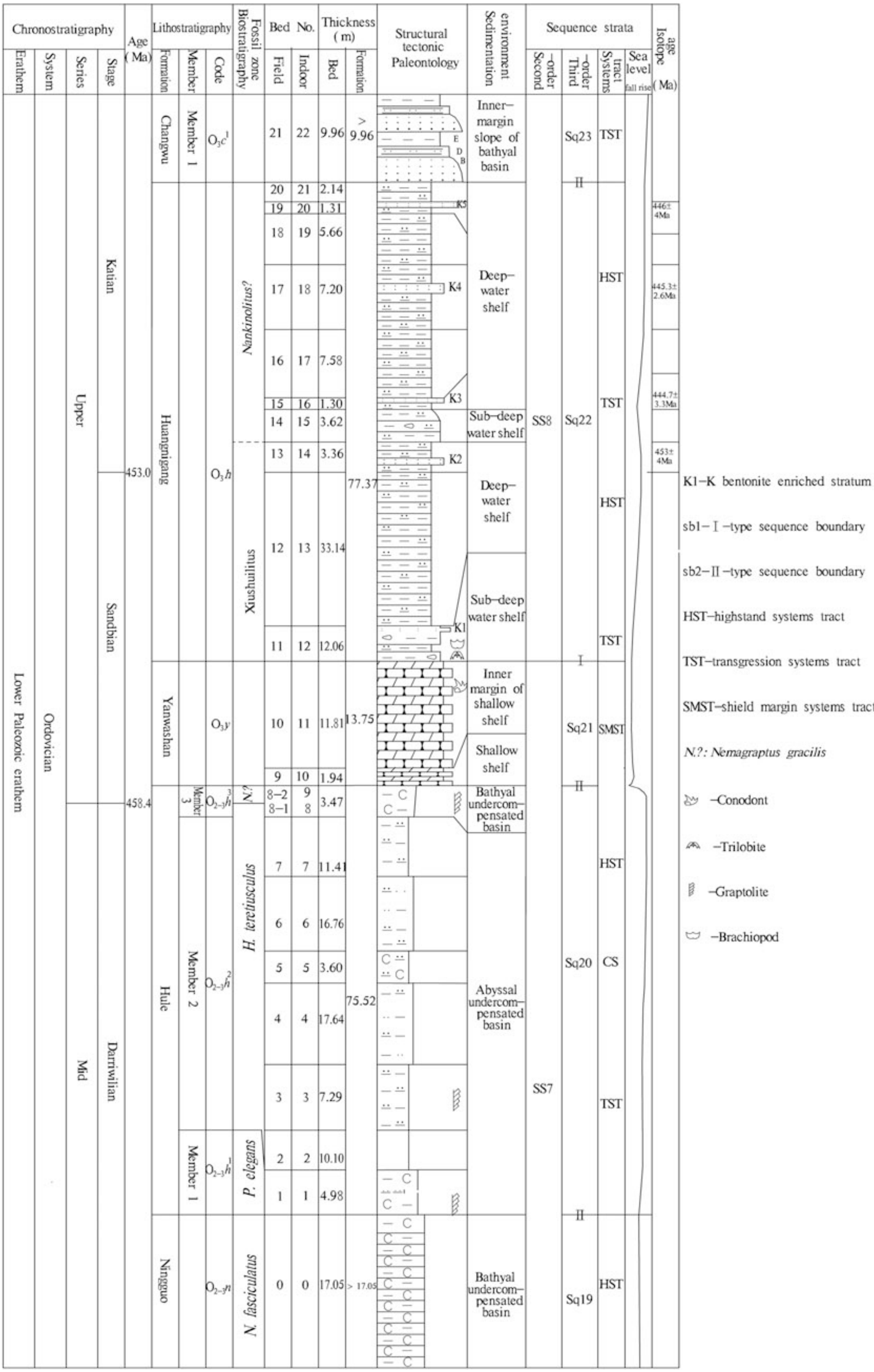


Fig. 2.42 Sequences of stratigraphic framework of Ordovician Hule Formation–Huangnigang Formation in the Area

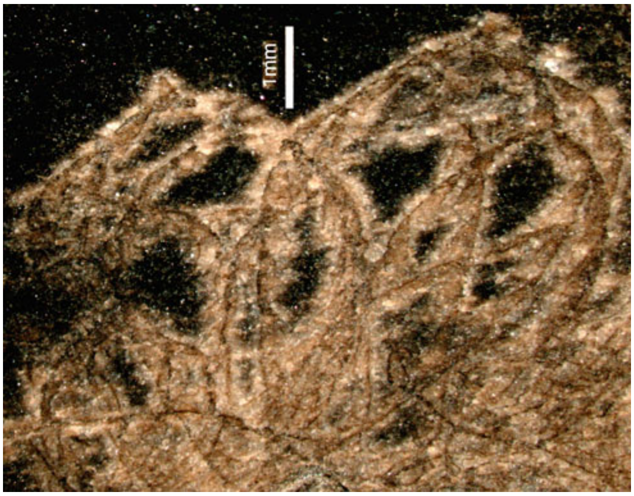


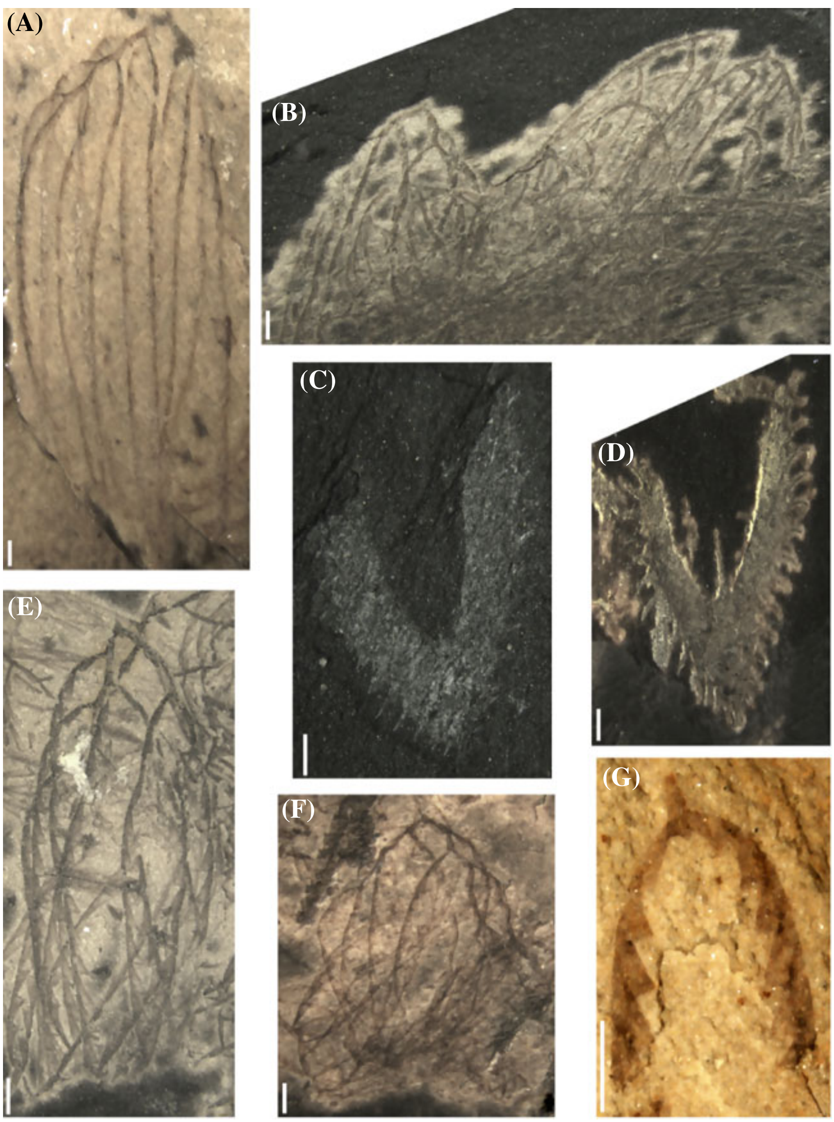
Fig. 2.43 *Pterograptus elegans* in the bottom of the first member of Hule Formation

No fossil was obtained in the black shale, which is about 2 m thick at the top of the third member of Hule Formation. By comparison with Hule Formation in other regions of Zhejiang, it is inferred that there may be *Nemagraptus gracilis zone* in the shale.

According to *Stratigraphic Chart of China* (2014), the *Pterograptus elegans* zone and the *Hustedograptus teretiusculus* zone in the lower part of Hule Formation belong to Darriwilian Stage of the Middle Ordovician. The *Nemagraptus gracilis zone* in its upper part of Hule Formation belongs to Sandbian Stage of Late Ordovician Epoch. Hule Formation spans Middle and Lower Ordovician Series.

2.4.3.4 Features of Stable Isotopes

Four carbonaceous mudstone samples, respectively, are collected from Hule Formation, including one collected in



A-B, E-F. *Pterograptus elegans* Holm (PM007-22-1-24, PM007-22-1-49, PM007-21-2-69, PM007-22-1-58).

C-D. *Kalpinograptus ovatus* (T.S.Hall) (PM007-22-1-35, PM007-22-1-65).

G. *Didymograptus artus* Elles and Wood (PM007-21-3-4). Scale length = 1 mm. (The sample No. consists of Profile No. – Bed No. – specimen location – specimen No.)

Fig. 2.44 Graptolite fossil in *Pterograptus elegans* zone of Hule Formation ($O_{2\text{-}3}h$) in Bed 21–Bed 22 of Jiumulong profile (PM007)

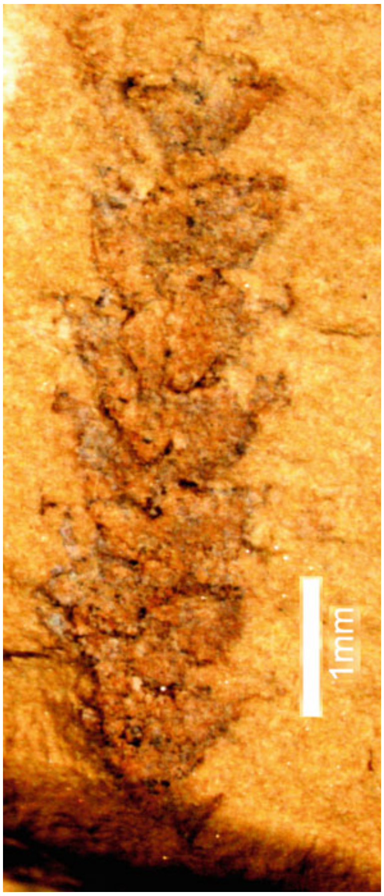


Fig. 2.45 *Hustedograptus teretiusculus* in the third member of Hule Formation

the first member of Hule Formation of Jiumulong profile (PM007) and three collected in the third member of Hule Formation of Lijiabian profile (PM012) to conduct whole-rock stable isotope test and analysis of $\delta^{13}C$ and $\delta^{34}S$. The $\delta^{13}C$ value of Hule Formation ranges between −30.31 and −27.93‰ with the mean of −28.78‰, approximate to those of Ningguo Formation and still within the content of organic carbon $\delta^{13}C$ in coal. Hule Formation inherited the sedimentary environment of Ningguo Formation, i.e., bathyal subcompensational basin sedimentation. The $\delta^{34}S$ value of Hule Formation is from −8.90 to 23.90‰ with an average of 13.60‰, indicating an obvious positive anomaly. However, it is still within the range of $\delta^{34}S$ in global coal (−30‰–24‰) (Zheng and Chen 2000). The possible cause of the anomaly is that the marine organisms were thriving relatively owing to the warm temperature in the Area and thus the isotope fractionation of the sulfate-reducing bacteria was comparatively strong.

2.4.3.5 Analysis of Sedimentary Environment

Hule Formation inherited the sedimentary environment of Ningguo Formation, i.e., the stagnant closed reduction environment. This can be reflected as follows. In the top and bottom of Hule Formation, the sediments are mainly dark gray–black argillaceous matter followed by siliceous matter. Besides, there are small amounts of terrigenous clastic silt, micro-fine pyrite, and carbonaceous matter. The top and bottom are rich in well-preserved planktonic graptolite fossils, without any benthic shellfish. Micro-fine horizontal bedding developed. All these indicate that the sedimentary environment of the top and bottom of Hule Formation features weak hydrodynamic force, short sources of terrigenous clasts in basin, and insufficient oxygen in bottom basin. Therefore, the sedimentary environment is not favorable for the survival of organisms and belongs to bathyal subcompensational basin environment with strong reduction. In the middle part of Hule Formation, the sediments are mainly siliceous matter followed by argillaceous matter. Besides, there are small amounts of carbonaceous matter and sulfide. All these indicate that the sedimentary environment of the middle part of Hule Formation features extremely weak hydrodynamic force, extremely short sources of terrigenous clasts in basin, and extremely insufficient oxygen in the bottom basin, thus belonging to closed bathyal subcompensational basin environment with strong reduction. Regionally, this formation features slight lithofacies transition and the lithology of it is mainly characterized by siliceous matter followed by argillaceous matter. In Banqiao (in Lin'an)–Jingshanling (in Hangzhou) area, the thickness of the formation decreases to be merely 7 m. In Jiangshan and Changshan areas, the bottom of Hule Formation is interspersed with a small amount of calcarenite and belongs to slope outer margin sedimentary environment.

In conclusion, the Hule formations all through Zhejiang Province are the products of the stable closed abyssal reduction sedimentary environment and are critical marker strata for the geological survey of the Ordovician.

2.4.3.6 Trace Elements in Strata (Ore-Bearing)

Eight rock spectrum samples were systematically collected from Hule Formation of Jiumulong profile (PM007) in this Project. Among these samples, one was collected from the first member, five from the second member, and two from the third member. Furthermore, three spectrum samples of carbon mudstone were collected from the third member of Hule Formation of Lijiabian profile (PM012). Analysis was made on 14 main trace elements, and statistics were made on the arithmetic mean values and concentration coefficients.

The first member of Hule Formation features similar enriched trace elements to the second member of Hule Formation and Ningguo Formation. They are all enriched in Sb, Bi, Pb, and Mo. The enrichment of Ag and F is slightly different among them. The third member of Hule Formation features different enriched trace elements compared with the first and the second members. In this member, the Vinogradov values of all the trace elements except Au are greater than 1; the enriched elements include Sb, Bi, Cu, Pb, Zn, W, Mo, Ag, and S, among which Bi, Cu, Zn, Ag, and S are extremely rich. Therefore, it can be inferred that materials from abyssal volcanic eruption and hot springs possibly penetrated this member.

2.4.4 Yanwashan Formation (O_3y)

The name Yanwashan Formation (O_3y) was created by Jichen Liu and Yazeng Zhao in 1927 in Yanwashan, Changshan County, Zhejiang Province. This formation roughly refers to the limestone in the central part of Yanwashan System created by Liu and Zhao (1924), which was renamed Yanwashan Formation by Lu et al. (1955). It was subsequently used up to now by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text* (1982), *Regional Geology of Zhejiang Province* (1989), and *Lithostratigraphy of Zhejiang Province* (1995). In this Project, the name Yanwashan Formation (O_3y) was still adopted according to the lithological characteristics of Xinqiao profile (PM001) and Lijiabian profile (PM011) in Hanggai map sheet, Xianxia profile (PM030) of Xianxia map sheet, and the survey traverse.

2.4.4.1 Lithostratigraphy

The Yanwashan Formation (O_3y) in the Area is mainly distributed in the east of Hanggai map sheet, followed by the south of Xianxia map sheet. The outcrop area is about 1.15 km^2, accounting for 0.09% of the bedrock area.

The lithology and lithologic association of Yanwashan Formation (O_3y) are characterized by the rhythm interbed consisting of gray thin laminated marl and thin–medium laminated knotlike micrite. In the lower part, the main component is marl and horizontal bedding developed. The upper part is dominated by knotlike limestone. The single rhythm features gradual transition from micrite to marl from bottom to top. Yanwashan Formation (O_3y) is in conformable contact with the overlying Huangnigang Formation (O_3h) and in disconformable contact with the underlying third member of Hule Formation ($O_{2\text{-}3}h^3$) (Fig. 2.46). The thickness of Yanwashan Formation (O_3y) is 9.40–13.75 m.

1. **Stratigraphic section**

The lithology of the Yanwashan Formation (O_3y) is described by taking the sample of Ordovician Hule Formation ($O_{2\text{-}3}h$)–Huangnigang Formation (O_3h) profile (Fig. 2.40) in Xinqiao Village, Hanggai Town, Anji County, Zhejiang Province, as an example. The details are as follows:

Huangnigang Formation Total thickness: > 12.06 m

12. Gray medium laminated siliceous mudstone interspersed with knotlike limestone or interbeds consisting of the two components. 12.06 m

———— Conformable contact ————

Yanwashan Formation Total thickness: 13.75 m

11. Gray apparently-thick-laminated knotlike micrite interspersed with a small amount of dark gray thin laminated marl. The thickness of a single apparent thick layer: 40–100 cm generally; the thickness of a single layer of knotlike micrite: 2–5cm generally and up to 10–18 cm individually. the thickness of a single layer of marl: 2–8 cm. Gradual change from knotlike micrite to marl occurring from bottom to top. Conodont fossils in the upper part of the layer: *Protopanderodus liripipus*, *p. varicostatus, Spinodus spinatus*, *Periodon* sp., *Baltoniodus* sp., and *Yaoxianognathsus* sp., etc. 11.81 m

10. Interbeds consisting of gray thin laminated marl and knotlike limestone. The marl: horizontal bedding developing, the thickness of a single layer: 3–7cm. The notes of knotlike limestone: 2–7cm in diameter, distributed in moniliform shape and laminated form. The bottom of this bed: knotlike limestone with a thickness of 10 cm, flat, the occurrence is consistent with the overlying strata. 1.94 m

———— Conformable contact ————

The third member of Hule Formation Total thickness: > 1.93 m

9. Dark gray siliceous carbonaceous shale, shale bedding developing. 1.93 m

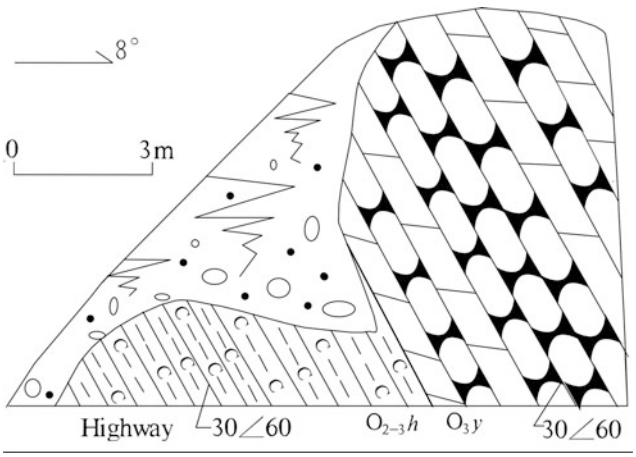


Fig. 2.46 Geological sketch map of conformable contact between Yanwashan Formation and Hule Formation

2. **Lithological characteristics**

The lithology of the Yanwashan Formation (O_3y) is mainly characterized by knotlike limestone and marl.

(1) The nodular limestone: grayish–gray, composed of cryptocrystalline calcite (> 90%), the thickness of a single layer: 2–5 cm generally, up to 10–18 cm individually, part of the knotlike limestone nodule containing trilobite fossils.
(2) The marl: gray; composition: microcrystalline calcite (55–60%) and argillaceous (40–45%); calcite: particle size: less than 0.01 mm generally, cryptocrystalline.

3. **Basic sequences**

Two types of basic sequences developed in the Yanwashan Formation (O_3y) (Fig. 2.47).

Basic sequences of type A: composed of knotlike limestone and thin laminated marl. The marl accounts for a large proportion in the lower part. Upward, the content of knotlike limestone gradually increases and the thickness of a single layer increases. Therefore, the basic sequences of this type belong to the non-cyclic basic sequence with thickness and calcareous matter increasing upward.

Basic sequences of type B: composed of thin laminated micrite, knotlike limestone, and thin laminated marl.

The sediments in this formation are mainly calcareous matter followed by argillaceous matter with conodont fossils in the rocks, belonging to the argillaceous carbonate facies of inner edge of continental shelf → the shallow shelf.

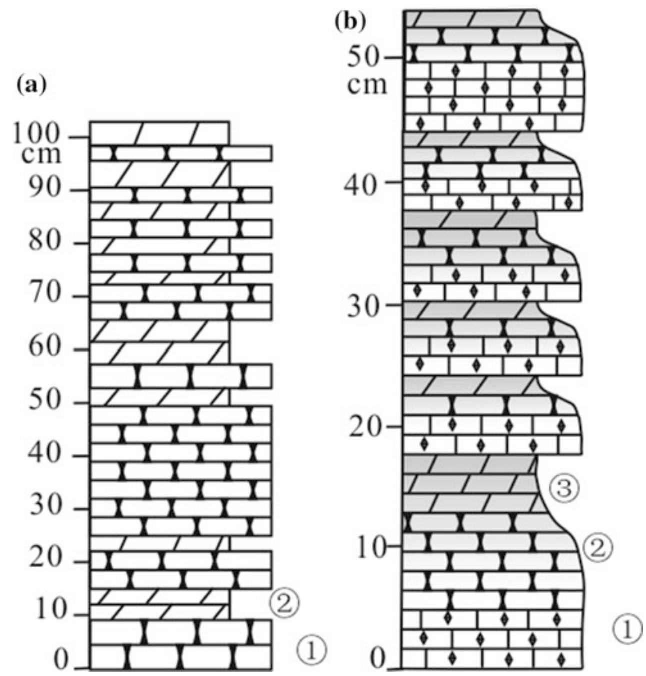


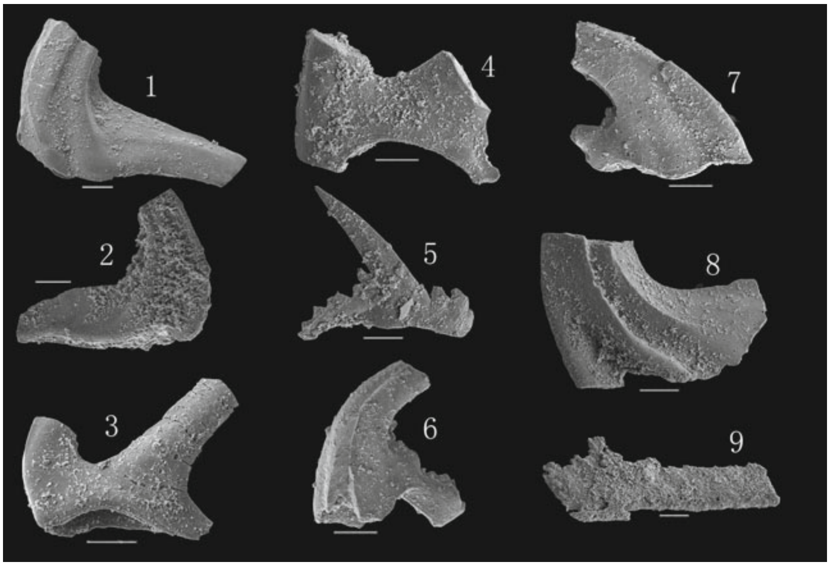
Fig. 2.47 Basic sequences of Yanwashan Formation (O_3y)

2.4.4.2 Sequence Stratigraphy

According to the characteristics of the lithology, palaeontology, lithofacies association, and sequence boundary of Xinqiao profile in Hanggai map sheet, there is one third-order sequence (Sq21) in the Yanwashan Formation (O_3y), which belongs to the second-order sequence SS7.

Third-order sequence Sq21

Located in the Yanwashan Formation, it contains shelf margin systems tract (SMST), transgressive systems tract (TST), and highstand systems tract (HST). The bottom of Sq21 is the interface between the thin laminated marl or knotlike limestone of the Yanwashan Formation and the black siliceous carbonaceous mudstone of the third member of the Hule Formation. From the graptolite shale of the Hule Formation to the Yanwashan Formation, the bathyal sedimentation abruptly changed into the shallow shelf sedimentation. As a result, a large number of sediments in transitional environments are missing, while no weathering



1-2: *Protopanderodus liripipus* Kennedy, Barnes et Uyeno, 1979 Lateral views of S elements;
3-4: *Spinodus spinatus* (Hadding, 1913) Lateral views of S elements;
5-6: *Periodon* sp. Lateral views of P and S elements;
7: *Baltoniodus?* sp. *Lateral view of S element;*
8: *Protopanderodus varicostatus* (Sweet et Bergström, 1962) Lateral view of S element;
9: *Yaoxianognathus* sp. Lateral view of S element

Fig. 2.48 Conodont fossils in knotlike limestone in the upper part of Yanwashan Formation

and erosion are visible. The top of Sq21 is the conformity interface between the knotlike micrite interspersed with a small amount of marl of Yanwashan Formation and siliceous mudstone of Huangnigang Formation. The bottom is of type-II boundary, and the top is type-I sequence boundary (Fig. 2.42). SMST is located in the Yanwashan Formation. The lower part of it consists of thin laminated marl and knotlike micrite. A small number of shellfish fragments are visible. Therefore, SMST belongs to argillaceous carbonate facies of shallow shelf. TST is located in the lower part of the Huangnigang Formation where the siliceous mudstone part interspersed with knotlike limestone is distributed. The knotlike limestone contains a large number of benthic trilobite and brachiopoda fossils and a small number of planktonic Pseudagnostus idalis. Therefore, TST belongs to siliceous mudstone facies near the oxidation zone. HST is located in the lower part of the Huangnigang Formation where the siliceous mudstone is distributed. Horizontal bedding developed, and there is no presence of biological fossils. Therefore, HST belongs to deep shelf siliceous mudstone facies with weak reduction during the maximum flooding period.

The sequence generally reflects the process of sea level rise from bottom to top and is a sequence of retrogradation type.

2.4.4.3 Biostratigraphy and Chronostratigraphy

Yanwashan Formation experienced a transformation of sedimentary environment. Affected by Guangxi movement, the sedimentary environment of the Area changed from closed deep sea to open shallow sea, carbonate began to be deposited, and conodonts constitute the main ancient organism fossils.

A total of five conodont samples were collected in Yanwashan Formation. Only a small amount of conodonts was found in the PM002YX4 sample of knotlike limestone in the upper part of this formation, including *Protopanderodus liripipus, P. varicostatus, Spinodus spinatus, Periodon* sp., *Baltoniodus* sp., and *Yaoxianognathsus* sp. (Figure 2.48). They are of the Late Ordovician, but the fossil zones in which they belong are undetermined.

According to the *Stratigraphic Chart of China* (2014), there are two conodont zones in Yanwashan Formation, which belong to the middle part of the Sandbian Stage; Yanwashan formation is of the Upper Ordovician Series.

2.4.4.4 Analysis of Sedimentary Environment

From Ordovician Yanwashan Formation, closed stagnant reduction sedimentary environment of the Area ended, and a set of argillaceous carbonate formation was deposited. Owing to the absence of organic carbon and sulfide in the sediments, the production in reduction environment, the absence of benthic shellfish fossils, and the product in the oxidation environment, it is inferred that the sedimentary environment is an open basin. Furthermore, the Area should be in deepwater environment under redox zone of shallow shelf, which is unfavorable for the survival of benthos. Judging from the incomplete preservation of conodonts, the sedimentary area should be close to the high-energy shallow sea, resulting in the defect of conodonts. Regionally, Yanwashan Formation features slight lithofacies transition and is an important marker stratum. However, the thickness of the formation changes, indicating that there is a stable and consistent shallow shelf environment in Zhejiang Province.

2.4.4.5 Trace Elements in Strata (Ore-Bearing)

Three rock spectra were collected in the Yanwashan Formation of Xinqiao map (PM001), and statistics of the arithmetic mean values and concentration coefficients of the analysis results were made. According to the statistics, Yanwashan Formation is enriched in Sb, Bi, Pb, W, and Mo, among which Bi is extremely rich.

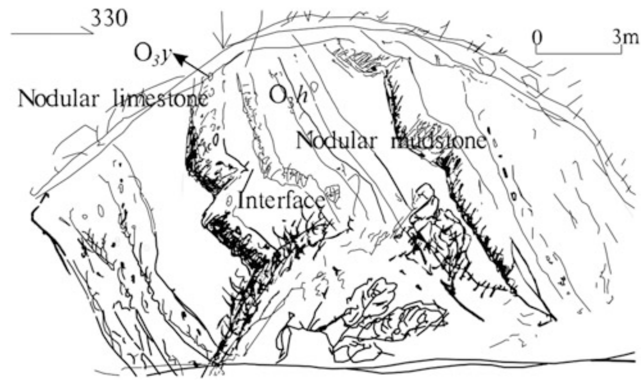


Fig. 2.49 Geological sketch map of the contact relation of Huangnigang Formation with Yanwashan Formation

2.4.5 Huangnigang Formation (O_3h)–Late Ordovician Volcanic Event Stratum

The name Huangnigang Formation (O_3h) was created by Lu et al. (1955) in Huangnigang Village, Jiangshan City, Zhejiang Province, and was used to refer to the shale in the upper part of the Yanwashan created by Liu and Zhao (1924). It was subsequently used up to now by the preparation group of regional stratigraphic table of Zhejiang Province (1979) as well as in the literature including *Stratigraphic Correlation Chart in China with Explanatory Text* (1982) and *Regional Geology of Zhejiang Province* (1989). In this Project, the name Huangnigang Formation (O_3h) was still adopted according to the lithological characteristics of Xinqiao profile (PM001) in Hanggai map sheet, Xianxia profile (PM030) in Xianxia map sheet, and geological observation traverse.

2.4.5.1 Lithostratigraphy

Huangnigang Formation (O_3h) in the Area is mainly distributed in the east of Hanggai map sheet followed by the south of Xianxia map sheet. The outcrop area is about 3.62 km^2, accounting for 0.28% of the bedrock area.

According to the lithology and lithologic association, Huangnigang Formation (O_3h) can be divided into four parts, i.e., the bottom, the lower part, the middle part, and the upper part. The bottom consists of grayish yellow medium laminated siliceous mudstone interbedded with knotlike limestone or the interbeds of the two components. It is about 1.5 m to the top. Three layers of micro-laminated light grayish yellow K-bentonite developed in the bottom. Generally, there are rich fossils of trilobite and brachiopoda in the knotlike limestone.

The lower part is composed of gray thin–medium laminated siliceous mudstone and interbedded with nine layers of light grayish yellow micro-laminated K-bentonite near the top. The maximum thickness of the K-bentonite is 2 cm. The middle part consists of grayish yellow medium laminated siliceous mudstone interbedded with three layers of knotlike limestone. The upper part is composed of gray thin–medium laminated siliceous mudstone interbedded with four eruption cycles of buff K-bentonite, which are, respectively, located in Layer 14, Bed 16, Bed 18, and Bed 20 from bottom to top. The maximum thickness of the K-bentonite layer in each layer is 5.5 cm, 3.5 cm, 2 cm, and 9 cm, respectively. From bottom to top, Huangnigang Formation can be further induced into two large rhythm beds, namely siliceous mudstone interbedded with knotlike limestone rhythm bed and siliceous mudstone rhythm bed. A total of 42 layers of K-bentonite are visible with thickness varying from 0.2 to 9 cm. This formation is in conformable contact with the overlying Changwu Formation and the underlying Yanwashan Formation (Fig. 2.49). The thickness of the formation is 71.55–77.37 m.

1. **Stratigraphic section**

The lithology of Huangnigang Formation is described by taking the example of Ordovician Hule Formation ($O_{2\text{-}3}h$)–Huangnigang Formation (O_3h) profile (Fig. 2.40) in Xinqiao Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

The first member of Changwu Formation Total thickness: > 9.96 m

22. Interbeds consisting of caesious sandstone, silty mudstone, and mudstone, BDE Bouma sequences developing. The grayish–gray sandstone: fine sand gradually turning into silt from bottom to top, the thickness of a single layer: 10–30 cm; the gray silty mudstone: horizontal bedding developing, the thickness of a single layer: 5–10 cm; the gray mudstone: no bedding developing, the thickness of a single layer: 10–20 cm. 9.96 m

——— Conformable contact ———

Huangnigang Formation (O_3h) Total thickness: 77.37 m

21. Caesious medium laminated siliceous mudstone, no bedding developing, the thickness of a single layer: 30–50 cm generally. 2.14 m

20. Gray medium laminated siliceous mudstone interbedded with six layers of light grayish-yellow K-bentonite, silt visible occasionally in the siliceous mudstone; the respective thickness of the six layers of K-bentonite from bottom to top: 0.2 cm, 9 cm, 3 cm, 0.5 cm, 0.2 cm, and 0.5 cm. 1.31 m

19. Gray medium laminated siliceous mudstone, silt visible occasional in the mudstone, the thickness of a single layer: 10–30 cm generally. 5.66 m

18. Gray thin–medium laminated siliceous mudstone interbedded with 17 layers of light grayish-yellow K-bentonite. Silt visible occasionally in the siliceous mudstone; the respective thickness of the 17 layers of K-bentonite from bottom to top: 2 cm, 0.5 cm, 1 cm, 0.2 cm, 0.6 cm, 0.2 cm, 2 cm, 0.2 cm, 0.5 cm, 0.5 cm, 0.2 cm, 0.2 cm, 0.2 cm, and 1 cm. 7.2 m

17. Gray medium laminated siliceous mudstone, no bedding developing, the thickness of a single layer: 35 cm generally and 4–8 cm locally. 7.58 m

16. Gray medium laminated siliceous mudstone interbedded with seven layers of light grayish-yellow K-bentonite; the respective thickness of the seven layers of K-bentonite from bottom to top: 0.5 cm, 3.5 cm, 0.5 cm, 0.2 cm, 0.2 cm, 0.2 cm, and 1 cm. 1.30 m

15. Gray medium laminated siliceous mudstone; no bedding developing; the thickness of a single layer: 25–50 cm generally and 5–10 cm in the bottom; interbedded with three layers of knotlike micrite with a width of 2–3 cm. 62 m

14. Gray thin–medium laminated siliceous mudstone interbedded with nine layers of light grayish-yellow K-bentonite; main components of the K-bentonite: illite, quartz, montmorillonite, and kaolinite; the respective thickness of the nine layers of K-bentonite from bottom to top: 1 cm, 0.5 cm, 0.5 cm, 0.5 cm, 0.2 cm, 0.5 cm, 5.5 cm, 1 cm, 2 cm; gray siliceous mudstone existing between the layers of K-bentonite. 3.36 m

13. Gray medium laminated siliceous mudstone, the thickness of a single layer: 30–50 cm general and 10–20 cm locally. 33.14 m

12. Gray thin–medium laminated siliceous mudstone interbedded with knotlike micrite or interbeds

consisting of the two components. The siliceous mudstone: 8–18 cm thick per layer, no bedding developing. The knotlike micrite: discontinuously distributed along the bed in the shape of an ellipsoid with the size of 1–5 cm, long axis parallel to the bedding. Three layers of K-bentonite visible about 1.5 m to the top, the respective thickness of the three layers: 1.5 cm, 1 cm, 1 cm; mudstone with the thickness of 5cm existing between the first layer and the second layer; mudstone with a thickness of 1.5 cm existing between the second layer and the third layer. A large number of fossils of trilobite obtained in the knotlike micrite 3–4 cm away from the bottom including *Alceste sinensis* (Sheng) the assesse insect + tail, chest *Corrugatagnostus* sp., wrinkled face ball subgroups in the head, *Cyclopyge recurva* Lu, *Dionide* sp., *Dionidella subquadrata* Han & Ju, *Ovalocephalus tetrasulcatus* (Kielan), *Saukia* cf. *Superioris* Zhou, and *Xiushuilithus* sp. 12.06 m

——— Conformable contact ———

Yanwashan Formation Total thickness: > 11.81 m

11. Gray apparently-thick laminated knotlike micrite interbedded with a small amount of dark gray thin laminated marl. The thickness of apparently thick bed: 40–100 cm generally; the thickness of a single layer of knotlike limestone in the apparently thick layer: 2–5 cm generally and up to 10–18 cm individually. The thickness of a single layer of marl: 2–8 cm. From bottom to top, the knotlike micrite gradually changes into marl. Fossils of the following conodonts in the upper part: *Protopanderodus liripipus*, *P. varicostatus, Spinodus spinatus, Periodon* sp., *Baltoniodus* sp. and *Yaoxianognathsus* sp. 11.81 m

1. **Lithological characteristics**

The lithology of the Huangnigang Formation (O_3h) is mainly characterized by gray–caesious thin–medium laminated silicon-bearing mudstone, siliceous mudstone, knotlike micrite, and K-bentonite.

(1) The knotlike micrite: gray–grayish, composed of cryptocrystalline calcite (> 90%), the diameter of a single node: 2–5 cm in general, fossils and fragments visible in the middle part.
(2) The siliceous mudstone: generally gray and locally gray–caesious, composition: argillaceous matter (70–80%) and cryptocrystalline siliceous matter (20–30%), no bedding developing, the thickness of a single layer: 10–35 cm generally.
(3) The silicon-bearing mudstone: gray–caesious, composition: argillaceous matter (85–90%) and a small amount of cryptocrystalline siliceous matter (10%), silt visible occasionally, the thickness of a single layer: 8–50 cm, no bedding developing.
(4) The K-bentonite: grayish (celadon), tuffaceous structure, blocky tectonics, weak bedding structure, composition: volcanic ash and a small amount of fine-grained subangular feldspar (5–10%), minerals mostly turning into kaolin owing to compression and hydrolysis, with weak waxy luster and soap-like slippery feeling, distinctly different from the upper and lower gray silicon-bearing mudstone and silty mudstone.

3. **Basic sequences**

Three types of basic sequences developed in the Huangnigang Formation (O_3h) (Fig. 2.50).

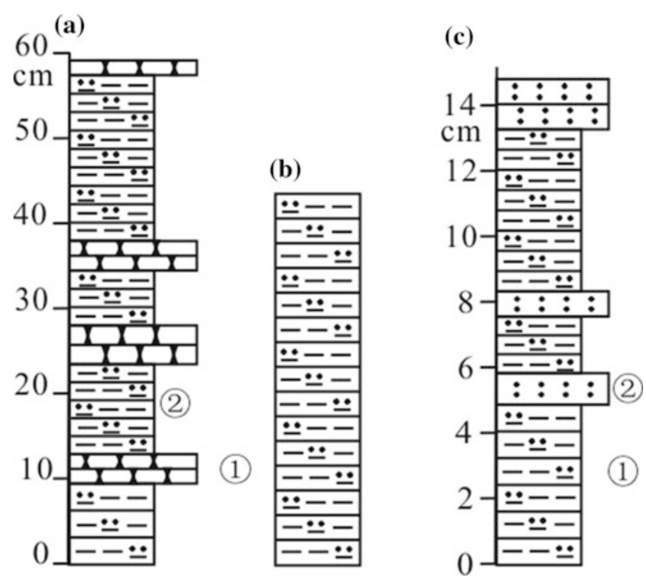


Fig. 2.50 Basic sequences of Huangnigang Formation (O_3h)

Basic sequences of type A: distributed in the lower parts of the two large rhythm beds that are located in the lower and middle parts of Huangnigang Formation, consisting of silicon-bearing mudstone-bearing knotlike limestone and siliceous mudstone; the knotlike limestone: 2–5 cm thick, ellipsoid, discontinuously distributed along the siliceous mudstone, concentrating in Bed 2–Bed 5 and gradually decreasing upward; belonging to the cyclic basic sequence with argillaceous–siliceous matter increasing upward.

Basic sequences of type B: distributed in the middle-lower and middle-upper parts of Huangnigang Formation, consisting of thin–medium laminated siliceous mudstone with medium laminated siliceous mudstone as main component, belonging to monotonic basic sequence.

Basic sequences of type C: distributed in the middle-upper part of the Huangnigang Formation; consisting of thin–medium laminated siliceous mudstone and micro-thin laminated K-bentonite; the K-bentonite: the product of volcanic eruption, the thickness of a single layer: mostly less than 1 cm and up to 9 cm as the maximum; belonging to the monotonic basic sequence.

The sediments in this formation are dominated by siliceous argillaceous matter, followed by knotlike marl. The siliceous mudstone: no fossils of ancient organisms discovered, micro-fine horizontal bedding developing, belonging to siliceous-argillaceous facies under the oxidation zone of deep shelf. The knotlike limestone: containing the fossils of benthic trilobites, gastropod, brachiopoda, crinoid, and planktonic Pseudagnostus idalis. Therefore, this member belongs to carbonate facies of basin on the margin of shallow shelf.

2.4.5.2 Sequence Stratigraphy

According to the characteristics of the lithology, ancient organisms, lithofacies association, and sequence boundary of Xinqiao profile in Hanggai map sheet, there is one third-order sequence Sq22 in the upper part of the Huangnigang Formation, which belongs to the second-order sequence SS8.

Third-order sequence Sq22

Located in the Huangnigang Formation, it contains TST and HST. The bottom of Sq22 is of type-I sequence boundary, and the top of it is of type-II sequence boundary (Fig. 2.42). TST is located in the lower part of the Huangnigang Formation where thin–medium laminated siliceous mudstone interbedded with knotlike limestone is distributed. The sediments of TST are dominated by silicon-bearing mudstone. Besides, there is a small amount of micritic calcite. Nankinolithus was ever obtained from the knotlike limestone, indicating that seawater was rich in oxygen. All these indicate that TST belongs to the sedimentation of siliceous-argillaceous facies of the outer edge of shallow shelf. HST is located in the upper part of the Huangnigang Formation. The sediments of it are composed of silicon-bearing argillaceous matter. Furthermore, HST features scarce palaeontology and little organic matter. Besides, horizontal bedding developed. All these indicate that HST belongs to the siliceous-argillaceous facies of deep shelf in weak oxidation–reduction environment under wave base. In conclusion, the sequence experienced continuous transgression process and is a sequence of retrogradation type.

2.4.5.3 Biostratigraphy and Chronostratigraphy

The benthic paleontological fossils dominated by trilobites developed in the knotlike micrite or calcareous mudstone in the Huangnigang Formation. According to the *Stratigraphic Chart of China* (2014), two trilobite zones developed in the Huangnigang Formation, i.e., *Xiushuilithus* zone in the lower part and *Nankinolithus* zone in the upper part.

In this Project, a total of 7–8 fossils of trilobite genus were obtained in the knotlike limestone in the bottom of the Huangnigang Formation (O_3h) of Xinqiao profile (PM001) in the Area: *Xiushuilithus* sp., *Alceste sinensis* (Sheng), *Corrugatagnostus* sp., *Cyclopyge recurva* Lu, *Dionide* sp., *Dionidella subquadrata* Han & Ju, *Ovalocephalus tetrasulcatus* (Kielan), and *Saukia* cf. *Superioris* Zhou. All these trilobites belong to the *Xiushuilithus* zone (Fig. 2.51). Owing to the poor outcrop, only trilobite fragments were found in the rhythm layers of knotlike limestone in Bed 2 in the middle part of the Huangnigang Formation in the Area. According to the material of Longtan profile in Tonglu County in the south, which is in the middle part of the profile, the caesious calcareous mudstone-bearing knotlike limestone occasionally produces the fossils of *Nankinolithus, Birmanites,* and *Hammatocnemis* which belong to the *Nankinolithus* zone.

The Xiushuilithus and *Nankinolithus* zones are located above the conodonts in the Yanwashan Formation, and the SHRIMP isotope age (D006TW) of the K-bentonite collected from the bottom of the siliceous mudstone-bearing knotlike limestone in Bed 2 of Xinqiao map (PM001) is 453 ± 4 Ma. According to the *Stratigraphic Chart of China* (2014), the two trilobite zones in the Huangnigang Formation belong to the Late Ordovician, among which the *Hustedograptus teretiusculus* zone belongs to Sandbian and *Xiushuilithus* zone is of Katian.

2.4.5.4 Event Stratigraphy

A total of 47 K-bentonite interbeds were discovered in the strata of Huangnigang Formation and Changwu Formation in Xinqiao map (PM001), which can be divided into eight cycles (K_1–K_8) as per the distribution density. The

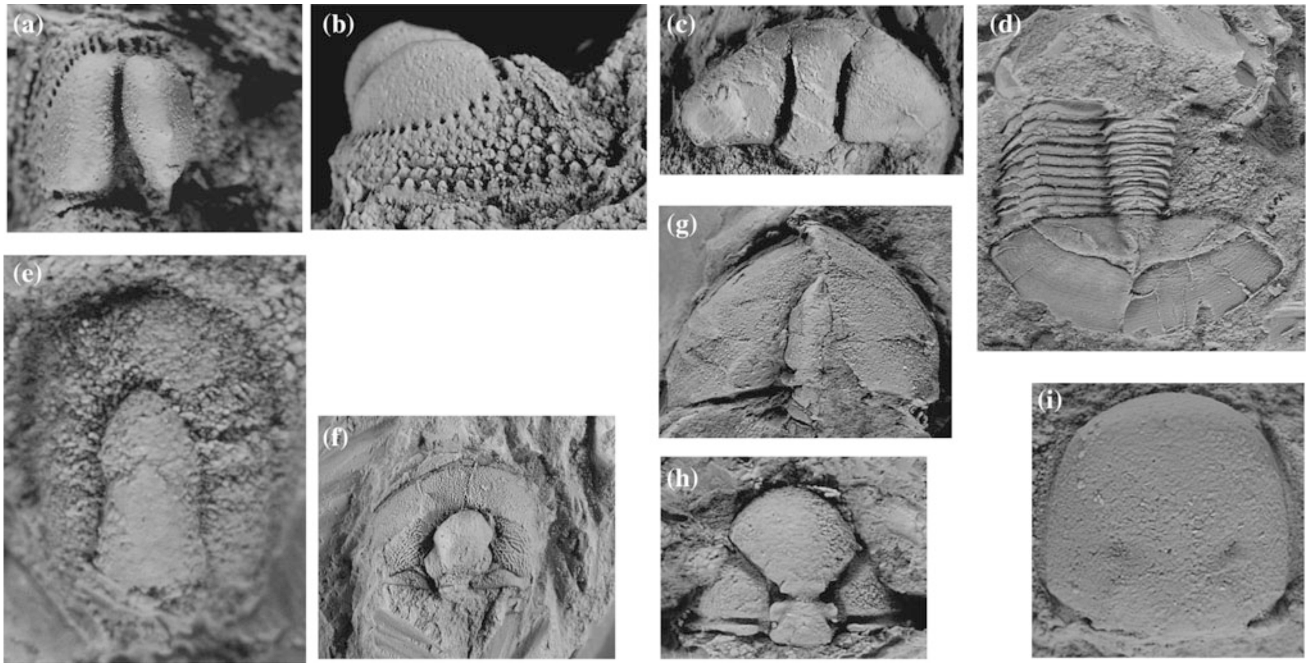


Fig. 2.51 Trilobite fossils in *Xiushuilithus* zone in lower part of Huangnigang Formation (O_3h) in Xinqiao profile (PM001) A.B-*Xiushuilithus* sp. (head, dorsal view); C-*Alceste sinensis* (Sheng) (head, dorsal view); D-*Alceste sinensis* (Sheng) thorax + tail (dorsal view); E–*Corrugatagnostus* sp. (head); F-*Dionidella subquadrata*, Han and Ju; (head, dorsal view); G-Saukia cf. superioris Zhou (head, dorsal view); H-*Ovalocephalus tetrasulcatus* (Kielan) (head cover, dorsal view); I-*Cyclopyge recurva* Lu (head cover)

K-bentonite interbeds developed at the highest degree in Huangnigang Formation, where a total of 42 K-bentonite interbeds were found and are divided into five cycles (K_1–K_5). In this Project, the samples were systematically collected followed by a series analysis including rock mineralogy, X-ray diffraction, silicates, rare earth, trace elements, rock spectra, and zircon SHRIMP U-Pb dating. The mineral composition and the characteristics of geochemistry and isotopic geochronology of the K-bentonite were studied. Furthermore, the genesis, tectonic environment, and event stratigraphic significance of the K-bentonite were discussed.

1. **Lithological Characteristics**

The bentonite: grayish (celadon), tuffaceous structure, blocky tectonics, weak bedding structure, composition: volcanic ash and a small amount of fine-grained subangular feldspar (5–10%), minerals mostly turning into kaolin owing to compression and hydrolysis, with weak waxy luster and soap-like slippery feeling, distinctly different from the upper and lower gray silicon-bearing mudstone and silty mudstone (Fig. 2.52). The K-bentonite in the Huangnigang Formation of the Area features a stable distribution horizon. It is visible in the outcrop of the Huangnigang Formation in Baishiwu Village, Songkengwu Village, and Baofu Town. Furthermore, stable K-bentonite interbeds are also visible in the Huangnigang Formation in the boreholes of Songkengwu Village.

X-ray diffraction analysis was made on six samples of K-bentonite collected from K_2 to K_7. The samples were tested in the State Key Laboratory of Endogenous Metal Deposit Mineralization, Nanjing University. Rigaku Dmax III-a $\theta/2\theta$-type powder diffractometer with fixed Cu target was adopted for test, and the settings are as follows: operating voltage: 40 kV; operating current: 25 mA; slit system: 1° scatter silt/antiscatter silt, accepting 0.3 mm slit; monochromator system: graphite curved crystal monochromator; receiving device: Ta-activated sodium iodide scintillation counting device; scanning method: step scan, 0.02°/step; preset time: 0.3 s/step.

The main mineral components of sample D006X1: quartz and illite; the main mineral components of samples D006X2, D006X4, D006X5, D006X6: illite, illite–montmorillonite mixed-layer clay minerals, a small amount of quartz, an extremely small amount of albite; the main mineral components of sample D006X3: montmorillonite, illite, kaolinite, and quartz (Fig. 2.53). There are different amounts of amorphous material (siliceous) in all the six samples. Furthermore, the mineral association above features the characteristics of the minerals as a result of weathering and

Fig. 2.52 Characteristics of K-bentonite in Layers 19 and 38, Xinqiao section

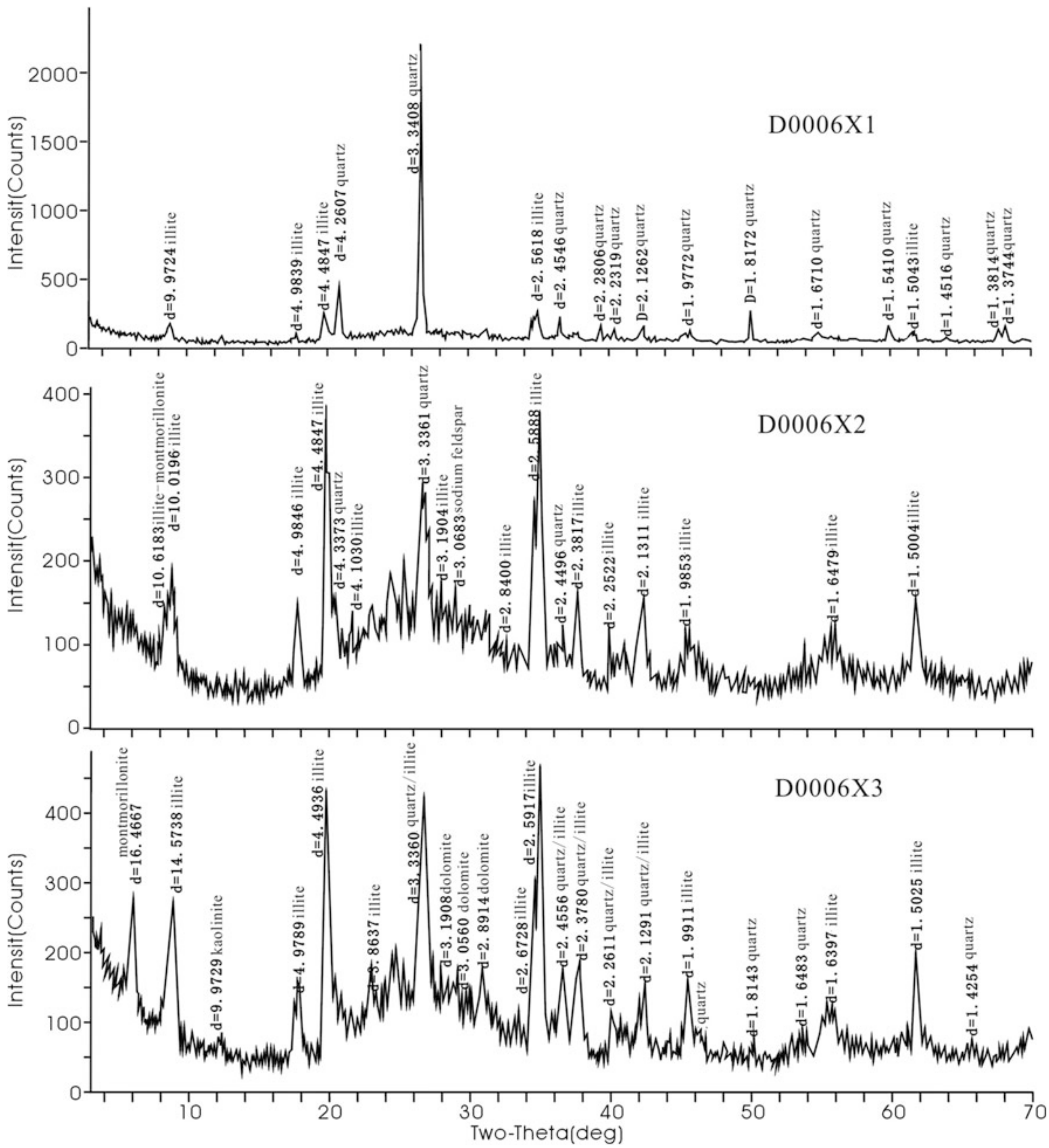


Fig. 2.53 X-ray diffraction pattern of K-bentonite

alteration of volcanic rocks, similar to the K-bentonite in Late Ordovician Wufeng Formation and Guanyinqiao Layer in Wangjiawan and Huanghuachang profiles in Yichang City, Hubei Province. However, the lithology varies among the six samples, suggesting that there may be two or more kinds of volcanic rocks.

2. **Major elements**

The respective content of the major elements in the K-bentonite is as follows. The SiO_2 content: 49.62–58.59%, indicating that the K-bentonite belongs to intermediate-basic rocks; σ (Rittman index): 3.57–12.40, indicating that the K-bentonite belongs to alkaline rocks–peralkaline rocks; K_2O content: generally high, 7.24–9.11%; ω (K_2O/Na_2O): >30, much higher than that of globally known Cambrian and Ordovician K-bentonite; Na_2O content: The maximum is only 0.22%, lower than that of globally known Cambrian and Ordovician K-bentonite; compared with the clastic rocks in Changwu Formation in the Area, the contents of Al_2O_3, MgO, K_2O, and TiO_2 are significantly higher; the consolidation index (SI) of the K-bentonite is 17.22–19.99, indicating a high differential degree. Therefore, the K-bentonite in Huangnigang Formation generally features high potassium (K_2O), high aluminum (Al_2O_3), high water (H_2O+), and low sodium (Na_2O), greatly different from normal sedimentary rocks.

In K_2O-SiO_2 illustration (Fig. 2.54), K-bentonite is all located in the shoshonite series. In Zr/TiO_2-Nb/Y illustration (Fig. 2.55), K-bentonite is mainly located in the areas of trachyte and rhyodacite, indicating that the original rocks contain rhyolitic and alkaline components.

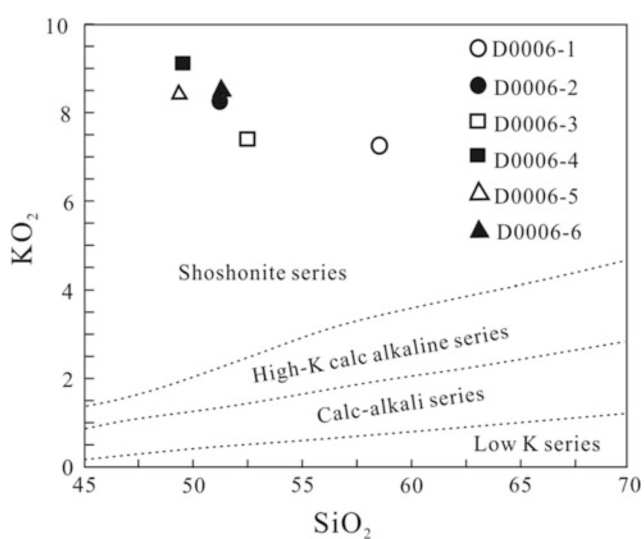


Fig. 2.54 K_2O-SiO_2 illustration of K-bentonite

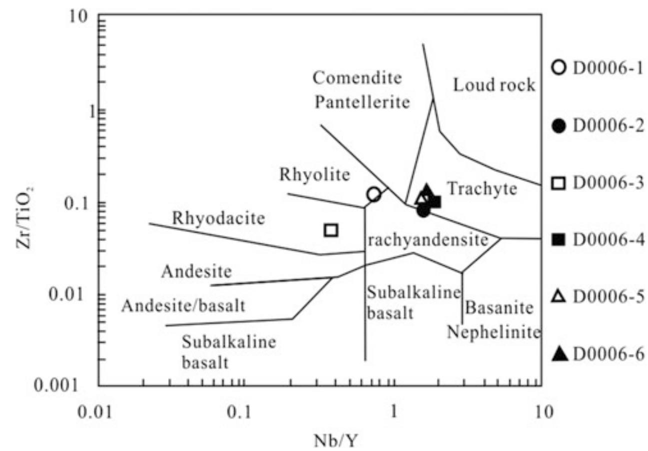


Fig. 2.55 Zr/TiO_2-Nb/Y bentonite of K-bentonite

3. **Rare-earth elements**

The total amount of rare-earth elements of K-bentonite (ΣREE) in the samples varies significantly with the range of (291.15–1452.51) × 10^{-6}, mainly in (1146.75–1452.51) × 10^{-6}. LREE is obviously enriched, and HREE is poor. The LREE/HREE ratio is 28.04–93.92, mainly in 87.60–93.92. The La_N/Yb_N ratio is 6.27–26.31, mainly in 16.45–26.31. δEu value is 0.53–0.68, indicating medium deficit. Although all samples feature quite different total amounts of REE, they enjoy relatively consistent LREE/HREE ratios, La_N/Yb_N values and δEu values. The diagenetic materials of K-bentonite in the Area should be consistent, given that the differences among the samples and experimental errors are excluded. The high contents of potassium, aluminum, and zircon are consistent with those of the upper crust, indicating that some materials may come from the part of the melting source areas of the upper crust. Low silicon is the characteristic of argillaceous and calcareous sedimentary rocks or lower crust rocks. Therefore, it can be inferred that the K-bentonite mainly comes from magmatic rocks and part of them are sedimentary rocks. The distribution curves of the rare-earth elements in K-bentonite are rightward generally (Fig. 2.56), showing similar distribution patterns. The distribution curves of rare-earth elements of the K-bentonite are slightly steeper than those of the K-bentonite of Late Ordovician Wufeng Formation and Guanyinqiao Bed in Wangjiawan and Huanghuachang profiles in Yichang City, Hubei Province.

4. **Trace elements**

The trace elements generally feature enriched large-ion lithophile elements such as Rb, Th, U, K, and Pb and poor high field strength elements such as Nb, P, and Ti (Fig. 2.57). In addition, the large-ion lipophilic elements Ba and Sr show strong negative anomaly, while the high field strong elements

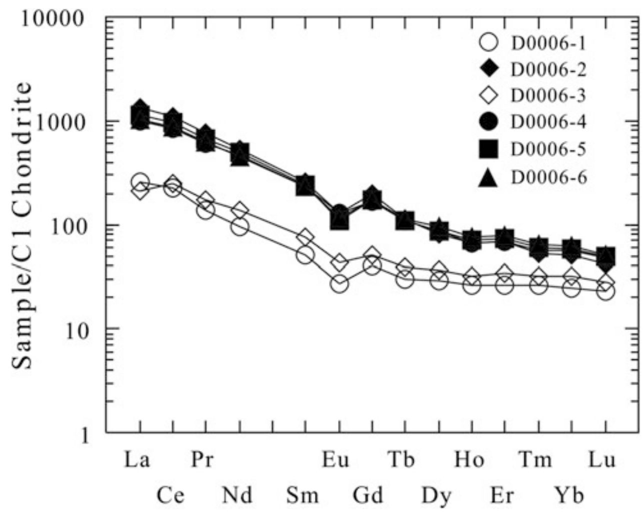


Fig. 2.56 Normalized pattern of rare-earth element chondrite of K-bentonite (Sun and McDonoungh 1989)

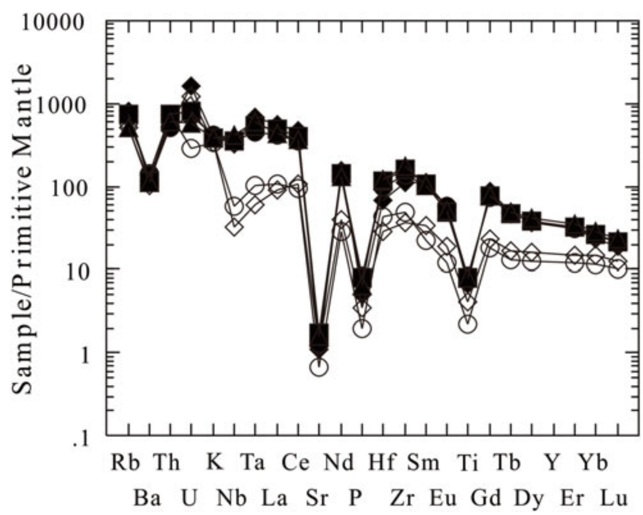


Fig. 2.57 Primitive mantle-normalized spidergram of trace elements of K-bentonite (Sun and McDonoungh 1989)

such as Zr and Hf show some positive anomaly. The Rb/Ba ratio is 0.44–0.77, far higher than that of the primitive mantle that is 0.088 (Hofmann 1988). The K/Rb ratio was 158.5–242, lower than that of normal magmatic rocks (242). In the primitive mantle-normalized spidergram of trace elements, Nb and Ti elements tend to show negative anomaly and Pb tends to show positive anomaly. The contents of Zr, Hf, Nb, Ba, Rb, Pb, Cu, Ag, and F in most K-bentonite in the Area are obviously 1–2 times higher than those in general clastic sedimentary rocks and claystone (Zhang et al. 1997).

5. **Zircon isotope chronology**

The zircon used to conduct zircon U-Pb dating was selected in the laboratory of Hebei Institute of Regional Geological and Mineral Resources Survey. In detail, the zircon was selected with binocular from 5 kg sample by crushing, heavy concentrate panning, and electromagnetic separation. The selected zircon was sent to Beijing Zircon Year Navigation Techonology Co., Ltd., where it was cemented into a sample target by using epoxy resin containing curing agent and then polished to reveal the center of zircon particles. Furthermore, cathode luminescence (CL) images and backscattering electron (BSE) imaging of zircon samples were analyzed, in order to study the internal structural characteristics. Zircon SHRIMP U-Pb isotope dating was done with the SHRIMP-II ion microprobe mass spectrometer of Institute of Geology, Chinese Academy of Sciences. The beam spot size is 30 μm, and the specific test conditions and workflow are described in the literature (Liu et al. 2006).

The zircon in K-bentonite is mostly irregularly columnar, with a length of about 80–120 μm and length/width ratio of about 1.5:1–1:1. Zonal structures developed in zircon (Fig. 2.58). The content of U in the zircon is (22–1643) $\times 10^{-6}$, the content of Th is (35–789) $\times 10^{-6}$, and the Th/U ratio is 0.28–4.17, indicating typical features of magmatic zircons (Hoskin and Schaltegger 2003). Most of the sample points were projected on or near the concordant curve (Fig. 2.59). Among the six samples of K-bentonite, the single-point age of $^{206}Pb/^{238}U$ is 482.1 ± 5–401.9 ± 8.2 Ma, except sample point D0006-2-1, of which the age of $^{206}Pb/^{238}U$ is 748.6 Ma, indicating possible captured zircon. The weighted mean ages of the six samples were 453 ± 4 Ma (MSWD = 1.7), 444.7 ± 3.3 Ma (MSWD = 1.6), 445.3 ± 2.6 Ma (MSWD = 0.48), 446 ± 4 Ma (MSWD = 1.5), 448 ± 8 Ma (MSWD = 3.2), and 449 ± 3 Ma (MSWD = 0.42), which were consistent within the error range. Therefore, the crystallization age of K-bentonite should be 453–444. 7 Ma.

6. **Comparison, genesis, and tectonic significance of regional distribution**

During the early Sandbian, a stratum interface with significant lithological difference developed between the Hule Formation and Yanwashan Formation in the Area. The part below the interface is the relatively stable abyssal deposition of graptolite-bearing siliceous argillaceous shale of the Early–Middle Ordovician Ningguo Formation and Hule Formation. The part above the interface is the carbonate deposition of neritic shelf of the Late Ordovician Yanwashan Formation. After stable abyssal subcompensational basin stage of the Early and Middle Ordovician, the crust uplifted rapidly. As a result, the Sandbian neritic shelf environment formed and sedimentary facies was changed from graptolite shale facies to shellfish facies. From Late Sandbian to Early Katian, the sedimentation was characterized by flat knotlike

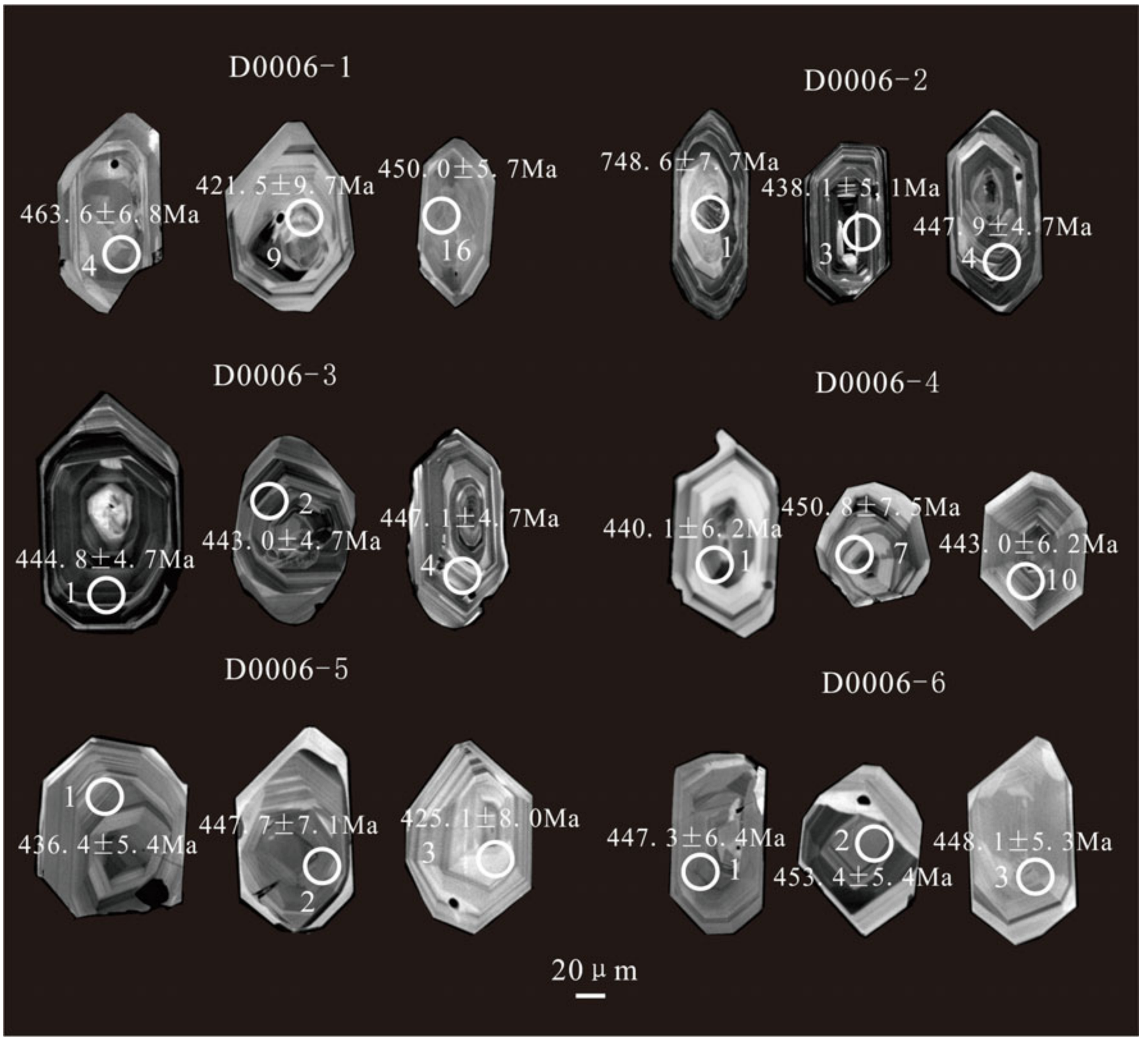


Fig. 2.58 Some CL images of zircon and analytical locations of K-bentonite samples

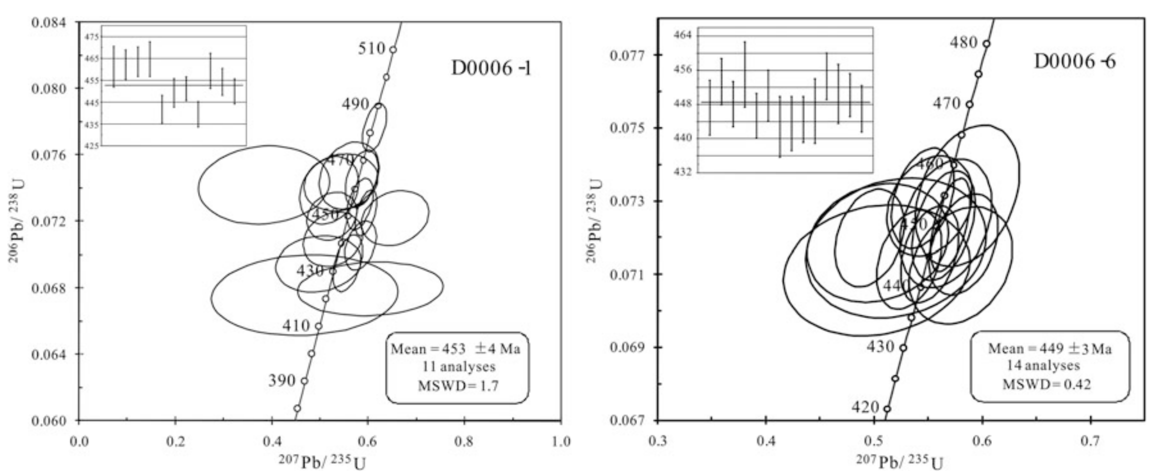


Fig. 2.59 SHRIMP U-Pb harmonic curve of zircon in K-bentonite

and banded limestone and marl of Yanwashan Formation, and lithofacies transition occurred in the siliceous calcareous ooze with the basin facies on the margin of the shallow shelf–bathyal basin facies of Huangnigang Formation. About 453–444.7 Ma, owing to the most intense crustal movement, the Yangtze landmass experienced internal or marginal tension. Consequently, dozens of layers of K-bentonite formed in the middle and upper parts of the Huangnigang Formation. In later Katian, with the rise of relative sea level, the deposition space increased rapidly; extremely thick flysch facies rocks of Changwu Formation were deposited in the boundary of Zhejiang Province and Anhui Province; the ancient organisms dominated by benthic shellfish changed to the ones mainly consisting of planktonic organisms such as pentolite; the sedimentary environment was changed to peripheral foreland basin from passive continent-edge basin.

The special characteristics of the event stratigraphy of Huangnigang Formation are as follows. In the Area, K-bentonite is visible in many outcrops in places such as Baofu Town in Hanggai map sheet. Besides, in the Huangnigang Formation in Liujia profile of Hecun Town, Tonglu County, which is about 83 km to the southwest of the Area, there are also 25 interbeds of K-bentonite. The Huangnigang Formation in Liujia profile is 34.2 m thick, and the lithologic association is similar to that of the Hanggai area. It can also be divided into two rhythm beds. The K-bentonite interbeds in the rhythm beds are pale gray, and the thickness of single layer is 1–4 mm, indicating the regional distribution of K-bentonite in Zhejiang Province. In the South Putangkou, Changshan County, the Jiangshan–Changshan–Yushan area along the border of Zhejiang Province and Jiangxi Province, the middle part of Huangnigang Formation is interbedded with a layer of dark gray blocky marl with thickness of 5.14 m, bears large scale of cross-bedding, slump structure, and slump breccia, and contains the fossils of brachiopoda and cephalopods. Upward from the middle part of the formation, there is a layer with the thickness of 18.53 m consisting of the interbeds of gray thin laminated calcareous mudstone and thin laminated mudstone-bearing pie-strip shaped and knotlike micritic limestone. Further upward, there is argillaceous limestone of the Sanqushan Formation (O_3s), with a thickness of more than 86 m and a large slump-fold structure developing. In the first member of the Sanqushan Formation (689 m thick) in the north of Yushan County and Changshan County of Jiangxi Province, 10 layers of slump-fold limestone and breccia developed in the argillaceous limestone and marl. It is generally believed that the origin of these slump structures is that the mud that is unconsolidated into rocks on the platform slid down and rolled down along the slope subjected to the seismic action. The contemporaneous multiple layers of K-bentonite in Hanggai and Liujia areas and seismic events in Jiangshan–Changshan–Yushan area indicate that northwest Zhejiang Province experienced regional tectonic movement and intense volcanic eruption in Early Katian.

Ordovician and Silurian K-bentonites are distributed globally. Since the 1970s, many scholars at home and abroad have conducted detailed studies on K-bentonite in sedimentary rocks (Huff et al. 1992, 1998; Huff et al. 2003; Huff 2008; Hu et al. 2008; 2009; Yang 2011; Xie et al. 2012a, b). In the areas such as Yichang City of Hubei Province, Tongzi County of Guizhou Province, and Haoping Town, Taoyuan County, Hunan Province, K-bentonite interbeds developed in Late Ordovician Linxiang–Wufeng Formation (corresponding to the Wenchang Formation in the Area). Along Hanggai of Zhejiang (453-444.7 Ma) → Wangjiawan–Huanghuachang of Hubei (445-442 Ma) (Hu et al., 2008) → Haoping, Taoyuan of Hunan (442 Ma) (Xie et al. 2012a, b) → Nanbazi of Guizhou (441 Ma), the age of K-bentonite tends to decrease and the total thickness of distribution also tends to reduce. In detail, the layer number and thickness are as follows. Hanggai of Zhejiang: 47 layers in total, total thickness: 60.7 cm, the maximum thickness of a single layer: 9 cm; Wangjiawan–Huanghuachang of Hubei: 11 layers in total, the maximum thickness of a single layer: 4.5 cm; Haoping, Taoyuan of Hunan: total thickness: 20 cm; Nanbazi of Guizhou: 12 layers in total, the maximum thickness of a single layer: 4 cm. In addition, foreign scholars also reported the research results of K-bentonite in North America, Britain, Sweden, and Estonia. Among these research results, 38 are about isotopic age dating by the K-Ar, U-Pb, Ar-Ar, and Sm-Nd methods of K-bentonite in Kentucky, Missouri, Alabama, and Tennessee, and the age is 462 ± 15–444 ± 20 Ma (Huff 2008). This can further confirm that the K-bentonite of the Sandbian-Hirnantian period is characterized by global distribution, and therefore, they may represent the global tectonic movement and volcanic activity events.

The distribution of the six K-bentonites in the Area in tectonic geochemical discrimination diagrams is as follows. In Rittmann-Gottiry diagram, they are all located in the alkaline and meta-alkaline rocks derived from the orogenic and anorogenic zones (Fig. 2.60). In Th-Hf-Ta diagram, they all fall in the alkaline intraplate basalt area and volcanic arc basalt area (Fig. 2.61). In Rb-Nb + Y diagram, most of them are located in the intraplate granite area (Fig. 2.62). In Th/Zr-Nb/Zr bilogarithmic diagram, they mainly fall in the tholeiite area of intracontinental rift and epicontinental rift types and in the basalt area in the continental collision zone (Fig. 2.63). The results show that the volcanic eruption is related to the intraplate or marginal tensile tectonic movement. The K-bentonite is mainly derived from the intraplate tectonic environment, and this is consistent with the previous conclusions of the early Paleozoic intraplate folding orogeny according to the lack of ophiolite and the presence of

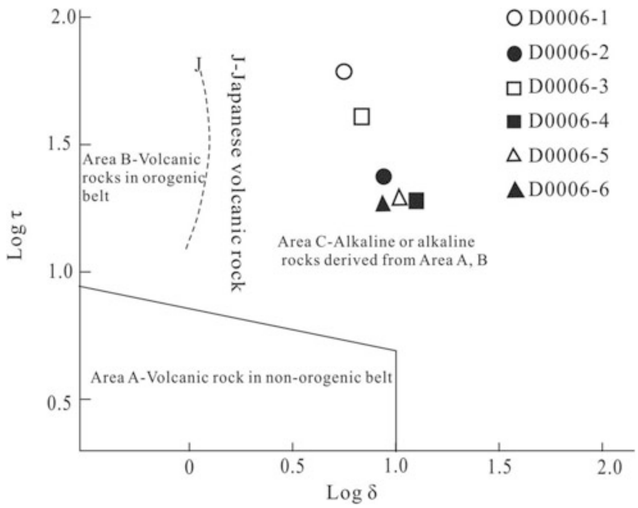


Fig. 2.60 Rittmann-Gottiry diagram of K-bentonite

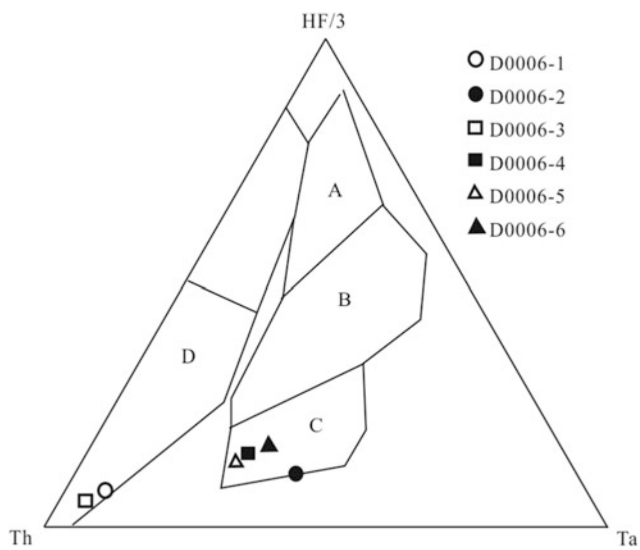


Fig. 2.61 Th-Hf-Ta tectonic setting discrimination diagram of K-bentonite (Pearce et al. 1984)

high-pressure metamorphic belt in South China in Caledonian period (Shu 2006, 2012).

Area A: N-type MORB; Area B: E-type MORB, and intracontinental tholeiites.
Area C: Alkaline intraplate basalt; Area D: volcanic arc basalt.

At present, there are two main viewpoints about the sources of the materials consisting of Late Ordovician bentonite. Most scholars believe that they are the production of volcanic ash deposition during submarine volcanic eruption, while a few scholars believe that it may be formed by lifting, denudation, transportation, sedimentation, and metamorphism of the

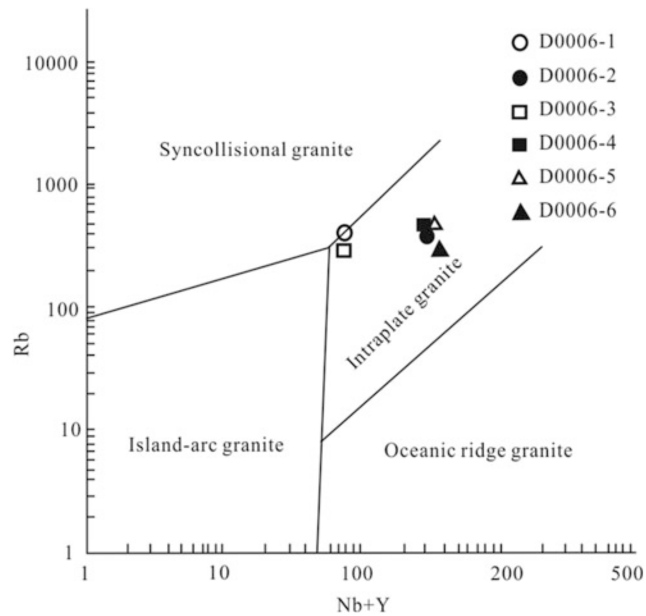


Fig. 2.62 Nb + Y-Rb tectonic setting discrimination diagram (Pearce et al. 1984)

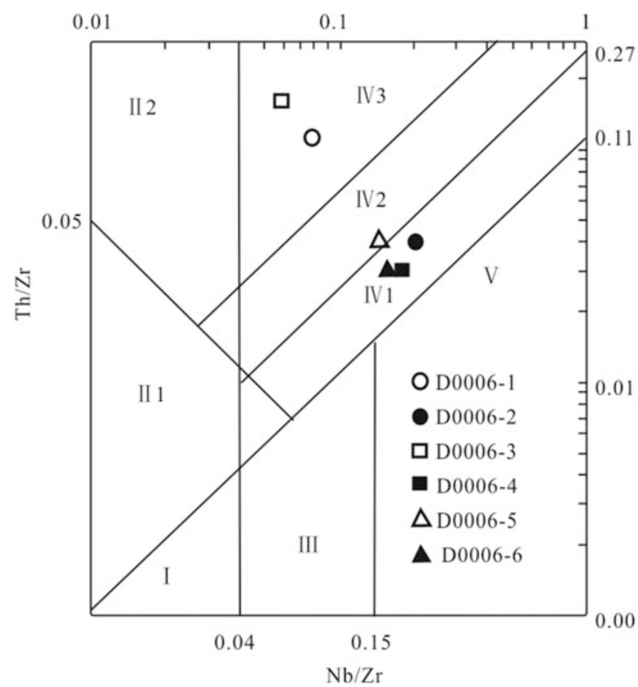


Fig. 2.63 Th/Zr-Nb/Zr bilogarithmic discrimination diagram (Sun et al. 2007) I. N-MORB area on the margin of divergent oceanic plate; II. convergent margin of plate (II_1. oceanic island arc basalts area; II_2. epicontinental island arc and continental volcanic basalt area); III. oceanic intraplate (oceanic island, seamount basalt area, T–MORB area, E–MORB area); IV. continental intraplate (IV_1. tholeiite area of intracontinental rift and epicontinental rift types; IV_2. basalt area in tension zone or (initial rift); IV_3. basaltic area in the continental collision zone); V. mantle plume basalt area

Caledonian intrusion. For the first point of view, on conducting the research of bentonite near the Ordovician–Silurian boundary in Hubei and Guizhou of the upper Yangtze landmass, the scholars believed that bentonite was widely distributed with small thicknesses. However, volcanic ash can drift in the air for a long distance and there are no enough corresponding magmatic activities in the interior of the Yangtze landmass, indicating that the materials consisting of these bentonite can only come from the periphery of the Yangtze landmass. This may be related to the volcanic eruption caused by plate subduction during the closing of Early Paleozoic Qinling palaeoocean in the north margin of the Yangtze landmass (Hu et al. 2009; Yang 2011; Xie et al. 2012a, b). However, some scholars believe that it is related to the converging of Cathaysia block toward Yangtze landmass (Su et al. 2009; Xie et al. 2012a, b). It may also be rated to the subducting of an ancient oceanic crust in the outside of the southeastern margin of the Early Paleozoic South China plate to the South China plate (Hu et al. 2009). According to the research results of *Jiangshan–Shaoxing Joint Belt Geological Structure Research Report* (2015) of Zhejiang Province, with the ultimate closing and extinction of the ancient South China Ocean in the end of the Early Paleozoic in the south of the Area (450 Ma), Wuyi block, respectively, converged and collided with the Yangtze landmass to the northwest and the southeast landmass to the southeast, and the tectonic evolution of the Jiangshan–Shaoxing joint zone entered the stage of continental collision (450–390 Ma). As a result, the Jiangshan–Shaoxing jointing zone formed owing to the northwest margin of Wuyi block converging and colliding with the southeastern margin of the Yangtze landmass, forming (450–420 Ma, Chencai subduction–accretionary complex), and Lishui–Yuyao jointing zone formed owing to the southeast margin of the Wuyi block converging and colliding with the northwest margin of the southeast landmass (Longyou tectonic melange).

According to relevant research, Caledonian magmatic activities are mainly distributed in two areas around the Yangtze landmass. One is the Qinling–Dabie area in the north margin of the Yangtze landmass, where intrusion and volcanic rocks are widely distributed. The other area is near the jointing zone on the southern margin of the Yangtze landmass, which is dominated by intermediate-acid intrusion and mainly distributed in Longyou, Zhejiang, from the southern section of the Jiangshan–Shaoxing jointing zone to Fujian (450–390 Ma) (Zhejiang Institute of Geological Survey 2015). At present, no magmatic activity in the northern part of the Jiangshan–Shaoxing jointing zone during that period has been reported. The possible reason is as follows. After the peak collision, the orogenic zone collapsed and stretched rapidly, and deep metamorphic rocks were uplifted out of the surface owing to strong post-orogeny. Among the metamorphic rocks, the garnet amphibolite (below 30 km) in the Longyou tectonic mélange area also turned back and emerged from the surface. All these indicate that a large number of magmatic activity products in the upper part may have been ablated and a large amount of sediments was provided for the later peripheral foreland basin deposition. After Yangtze landmass converged and collided with Wuyi block, the southeastern margin of the Yangtze landmass was transformed from a passive continental margin basin to peripheral foreland basin from the Late Ordovician and remained as peripheral foreland basin until the Early Devonian. As a result, the sedimentary environment and material deposition rate in the southeastern margin of the Yangtze landmass experienced great change. During this period, the terrigenous clasts in sedimentary strata increased significantly and thickened, and the sedimentary rate suddenly accelerated (the sedimentary rate of the Changwu Formation was even dozens of times higher than that of the Huangnigang Formation). Meanwhile, typical slump structure and reverse graded structure formed in the strata such as Huangnigang Formation and the Sanqushan Formation, reflecting the impact of collision orogeny on foreland basin.

In this Project, it is believed that just like the bentonite near the Ordovician–Silurian boundary of the upper Yangtze landmass, the Late Ordovician bentonite in the Area is also the products of volcanic ash deposition during the Caledonian collision and volcanic eruption, but not caused by the lifting, denudation, transportation, sedimentation, and metamorphism of the Caledonian intrusion. The main evidence is as follows:

(1) Material composition: The bentonite is mainly composed by montmorillonite, illite, kaolinite, illite–montmorillonite mixed-layer clay mineral, and quartz followed by a very small amount of albite. Compared with surrounding clastic rocks, bentonite is characterized by abrupt changes in color, composition, and structure. Furthermore, there is no obvious alteration in the clastic rocks. All these indicate that the bentonite and clastic rocks are sourced from different areas, and bentonite is not the products of metamorphism of clastic sediments.
(2) Geochemical evidence: The content of SiO_2, Na_2O, CaO, Fe_2O_3, FeO in bentonite is significantly lower than that in clastic rocks of the same period. The contents of Al_2O_3 and K_2O, as well as the K_2O/Na_2O ratio, are significantly higher than those in clastic rocks of the same period. The content of F (1549×10^{-6}) is also significantly higher than that in clastic rocks ($(596–1215) \times 10^{-6}$). All these indicate that the bentonite and clastic rocks are sourced from deposition of different materials.
(3) Zircon characteristics: According to CL image features of zircon, the zonal structure of zircon developed in the bentonite. Besides, the bentonite features obvious angular structure, indicating that the bentonite did not experience long-distance transportation.

(4) Chronological evidence: A total of 87 points were tested for the six zircon samples collected in this Project. Except for one point whose age is 748.6 Ma, the age of all the other points is 482.1–401.9 Ma and mainly 455–440 Ma. This indicates that the zircon in bentonite was from relatively uniform sources but was not transported from sedimentary rocks in different areas.

Therefore, the K-bentonite in the Area formed owing to large-scale magmatic intrusion and the disposition of volcanic ash (caused by volcanic eruption) in the peripheral foreland basin in the northwest during the collision and converging (450–420 Ma) between the Caledonian Yangtze landmass and the Cathaysian block. As a result, bentonite (sedimentary tuff) interbeds formed in the Late Ordovician Huangnigang Formation and Changwu Formation, and the interbeds in Huangnigang Formation were the most developed.

2.4.5.5 Analysis of Sedimentary Environment

The Huangnigang Formation is mainly composed of mudstone and knotlike limestone. In the mud, ancient organisms lack, and micro-fine horizontal bedding developed, indicating the anoxic quiet environment of deep shelf. The knotlike limestone is dominated by microcrystalline calcite and contains the fossils of benthic organisms, representing the oxygen-rich environment of shallow shelf.

According to two rhythm beds and the ancient organisms contained in Huangnigang Formation, it can be decided that the Huangnigang Formation experienced two similar rise and fall processes of the sea level. In the lower parts of the rhythm beds, the sediments are dominated by siliceous argillaceous matter interbedded with knotlike limestone layers. From bottom to top, the siliceous argillaceous matter gradually increases and the knotlike limestone interbeds gradually decrease, indicating a sedimentary environment with alternate vibration of abyssal and neritic and gradual rise of sea level. The upper parts of the rhythm beds only consist of siliceous argillaceous sediment, indicating that the Area was in the deep shelf environment near the stable redox zone after the maximum flooding. Within the Huangnigang Formation, there are a total of 47 layers of K-bentonite interspersed from the top of the first rhythm bed where siliceous mudstone-bearing knotlike limestone is distributed to the top of the second member of the Changwu Formation. Among these layers, 42 layers are interspersed in the Huangnigang Formation and five layers interspersed between the first and second members of the Changwu Formation. All these verify that frequent crustal movements and volcanic activities occurred in the middle and late sedimentary period of Huangnigang Formation, which affected the transformation of Middle and Late Ordovician sedimentary environment from closed basin to open basin. According to Zircon SHRIMP U-Pb isotope dating, the age of the K-bentonite is 453–445 Ma, basically consistent with the time of Guangxi movement (Chen et al. 2010, 2012, 2014). After experiencing strong Guangxi movement, the sedimentary environment in the Area gradually shifted from the shallow shelf to (bathyal) abyssal basin. Accordingly, the carbonate facies–siliceous-argillaceous facies of the shallow shelf–deep shelf in the Huangnigang Formation ended, and flysch sedimentation of abyssal slope began in Changwu Formation.

Regionally, Huangnigang Formation features slight lithofacies transition and mainly contains benthic ancient organisms, indicating that Zhejiang Province was in a stable and open shallow shelf environment during this period.

2.4.5.6 Trace Elements in Strata (Ore-Bearing)

In this Project, ten rock spectra were collected from the Huangnigang Formation of Xinqiao profile (PM001) and the statistics of the arithmetic mean values and concentration coefficients of the analysis results were made. According to the statistics, Huangnigang Formation is enriched in Bi, Pb, and W, among which Bi is extremely rich.

2.4.6 Changwu Formation (O_3c)

The name Changwu Formation (O_3c) was created by Lu et al. (1955) for Nanshan of Chengbei–Dongshan of Changwu area in Jiangshan City, Zhejiang Province. In 1937, Jie Xu discovered the Late Ordovician strata in Tashan Village, Yuqian Town, Lin'an City, and created the name "Yuqian System" for them. Zhejiang Regional Geological Survey Team (1965) plotted a complete Late Ordovician stratigraphic profile during regional geological survey of Jiande map sheet on a scale of 1:200,000. It divided the profile into three parts, i.e., the lower, middle, and upper parts. The former two parts were collectively called Changwu Formation, and the upper part was called Wenchang Formation. Zhejiang Regional Geological Survey Team (1967) divided the sedimentary strata into a southeast area and a northwest area during regional geological survey of Lin'an map sheet on a scale of 1:200,000. In the southeast area, Changwu Formation and Wenchang Formation were still adopted, while in the northwest area, the Yuqian System was divided into Yuqian Formation and Zhangcunwu Formation. In *Lithostratigraphy of Zhejiang Province* (1995), Yuqian Formation was renamed Changwu Formation and Zhangcunwu Formation was renamed Wenchang Formation. In this Project, the name Changwu Formation (O_3c) was still adopted given the lithological characteristics of Xinqiao profile (PM001) and Shangangshang map (PM002) in

Hanggai map sheet, Xiajia profile (PM030) and Maotan profile (PM041) in Xianxia map sheet, and the geological observation traverse.

2.4.6.1 Lithostratigraphy

Changwu Formation (O_3c) in the Area belongs to typical Ordovician flysch sedimentation in the Lower Paleozoic. It features basically the same outcrop range as Huangnigang Formation. That is, it mainly outcrops in the eastern part of the Hanggai map sheet and the south-central part of Xianxia map sheet. In addition, it is sporadically exposed in the southeast and northwest corners of the Chuancun map sheet. The total outcrop area is about 83.56 km^2, accounting for 6.57% of the bedrock area.

According to lithology and lithologic association, Changwu Formation (O_3c) is divided into the first member of Changwu Formation (O_3c^1), the second member of Changwu Formation (O_3c^2), and the third member of Changwu Formation (O_3c^3). They are in conformable contact with the underlying Huangnigang Formation and the overlying Wenchang Formation (Fig. 2.64).

The first member of Changwu Formation (O_3c^1): rhythm interbeds consisting of gray thick–medium laminated silt-fine sandstone, thin–medium laminated siltstone, and silicon-bearing mudstone; occasionally interspersed thick laminated K-bentonite; Bouma sequences such as ABE, ACE, ADE, AE, BE, and CE developing; from bottom to top, the sandstone gradually decreasing and the mudstone gradually increasing; the thickness of a single layer of silty-fine sandstone: 20–50 cm generally; the thickness of a single layer of silicon-bearing mudstone: 3–20 cm, varying greatly. The thickness of the member: 118.37–155.00 m.

The second member of Changwu Formation (O_3c^2): rhythm interbeds consisting of gray thin–medium laminated silt-fine sandstone, thin–medium laminated siltstone or argillaceous siltstone, thin–medium laminated silicon-bearing mudstone, and black micro-laminated carbonaceous mudstone; occasionally interbedded with thick laminated K-bentonite in the upper part; Bouma sequences such as ABE, ACE, ADE, AE, BE, and CE developing, dominated by CE followed by BCE, black micro-laminated graptolite-bearing carbonaceous mudstone visible in each sequence generally (the basis used to distinguish Bouma sequences of the member from the ones of the first and third member); from bottom to top, the sandstone gradually reducing, siltstone and mudstone increasing. The respective thickness of a single layer of siltstone and fine sandstone, siltstone or argillaceous siltstone, silicon-bearing mudstone, and black carbonaceous mudstone: 4–25 cm generally, 2–15 cm, 1–16 cm generally, and 0.2–3 cm generally. The thickness of the member: 95.70–201.48 m.

The third member of Changwu Formation (O_3c^3): the lower part: rhythm interbeds of gray thin–medium laminated feldspathic quartz silt-fine sandstone, siltstone or silty mudstone; the middle-lower part: rhythm interbeds consisting of thin–medium laminated argillaceous siltstone and mudstone; the middle-upper part: mainly rhythm interbeds consisting of feldspathic quartz silty-fine sandstone or sandstone and silty mudstone, interbedded with thick laminated mudstone. Generally, feldspathic quartz silty-fine sandstone constitutes the main body of the member, and the sandstone gradually increases upward. Graded bedding with thickness decreasing upward develops in small amounts of sandstones in the lower part of the layer; load casts develop at the bottom. The respective thickness of the single layer of silt-fine sandstone and siltstone: 10–30 cm generally and 5–15 cm. The thickness of the member: 161.39–167.45 m.

1. **Stratigraphic section**

The lithology of Changwu Formation is described by taking the example of Ordovician Changwu Formation (O_3c) profile in Xinqiao (Fig. 2.65) Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

Wenchang Formation — Total thickness: >3.93 m

59. Thick-bedded sandstone, no bedding developing, the thickness of a single layer: 50–60 cm. — 3.93 m

——— Conformable contact ———

The third member of Changwu Formation (O_3c^3) — Total thickness: 167.45 m

58. Interbeds consisting of khaki thin–medium laminated fine-silty sandstone and thick laminated silty mudstone after weathering; the fine-silty sandstone: cross-bedding developing, the thickness of a single layer: 8–25 cm; the thickness of a single layer of the mudstone: 5–10 cm. — 36.85 m

57. Khaki thin–medium laminated fine-silty sandstone after weathering. — 42.07 m

56. Rhythmic interbeds consisting of khaki medium laminated fine-silty sandstone and thick laminated silty mudstone after weathering. The respective thickness of a single layer of the fine-silty sandstone and the mudstone:

10–20 cm and 2–6 c 46.65 m

55. Khaki medium–thin laminated fine-silty sandstone interbedded with thick laminated mudstone after weathering. The fine-silty sandstone: cross-bedding developing, the thickness of a single layer: 5–12 cm; the thickness of a single layer of the mudstone: 3–6 cm. 5.33 m

54. Khaki thick laminated silty mudstone after weathering, occasionally interbedded with medium laminated fine-silty sandstone. 18.88 m

53. Gray medium laminated silt-fine sandstone interbedded with thick laminated silty mudstone. The silty-fine sandstone: mainly composed of feldspar and quartz, normal graded bedding developing. The rocks are usually khaki owing to weathering. 17.67 m

———————— Conformable contact ————————

The second member of Changwu Formation (O_3c^2) Total thickness: 201.48 m

52. Interbeds consisting of gray thick laminated sandstone, micro–thin laminated argillaceous siltstone, mudstone, and black carbonaceous mudstone. Bouma sequences BCE and CE developing, dominated by CE, BE visible occasionally. The sandstone (B): the thickness of a single layer: 4 cm; the argillaceous siltstone (C): cross-bedding developing, the thickness of a single layer: 2–9 cm; the mudstone (E): the thickness of single bed: 1–11 cm; The thickness of single layer of carbonaceous mudstone: 0.5–0.7 cm. Graptolite visible in the mudstone 25 cm away from the top; a layer of K-bentonite with a width of 2 cm respectively visible and 12 cm and 20 cm away from the top. 32.92 m

51. Interbeds consisting of gray thin–medium laminated sandstone, micro–thin laminated siltstone, mudstone, and black micro laminated carbonaceous mudstone, Bouma sequence BCE developing, gradual contact between the sandstone (B) and the siltstone (C) while the mudstone (E) in sharp contact with its underlying and overlying strata. The sandstone (B): parallel bedding developing, the thickness of a single layer: 3–12 cm; the siltstone (C): cross-bedding developing, the thickness of single bed: 1–4 cm; the mudstone (E) single-layer thickness 2–5 cm; the carbonaceous mudstone: the thickness of a single layer: 0.8–1 cm, containing graptolite, only appearing in the upper part. Producing Chitinozoa, *Belonechitina americana*(Taugourdeau, 1965), *Conochitina* aff. *dolosa* Laufeld, 1967, *Conochitina* sp. *Conochitina* sp. *Eisenackitina songtaoensis* Chen *et al*., 2009, and *Rhabdochitina gallica* Taugourdeau 1961. 12.46 m

50. Interbeds consisting of gray medium laminated fine-silty sandstone and thick laminated silty mudstone, Bouma sequences AE developing. The fine-silty sandstone (A): graded bedding developing, the thickness of a single layer: 17–25 cm; the silty mudstone (E): the thickness of single bed: 3–5 cm. 1.14 m

49. Interbeds consisting of gray thick laminated siltstone, thin–medium laminated silty mudstone, and black micro laminated carbonaceous shale. Bouma sequence CE developing. The siltstone (C): cross-bedding developing, the thickness of a single layer: 3–5 cm; the siltstone (E) the thickness of a single layer: 4–22 cm. Black carbonaceous mudstone, single layer 0.5–1 cm, containing graptolite. 15.48 m

48. Interbeds consisting of gray medium laminated sandstone, thick laminated siltstone, thick laminated mudstone, and black micro laminated carbonaceous mudstone, Bouma sequence ACE developing. The sandstone (A): the thickness gradually decreasing upwards, the thickness of a single layer: 10–25 cm generally and even 43cm (maximum); the siltstone (C): cross-bedding developing, the thickness of a single layer: 3–9 cm; gradual transition existing from A to C. The respective thickness of a single layer of the mudstone (E) and the black carbonaceous mudstone: 2–10 cm and 0.1–1 cm. 2.96 m

47. Interbeds consisting of gray thin–medium laminated sandstone, thick laminated siltstone, silty mudstone, and black micro laminated graptolite-bearing carbonaceous shale. The sandstone (B): parallel bedding developing, the grain size gradually decreasing upwards, the thickness of a single layer: 2–22 cm; the siltstone (C): small cross-bedding developing, the thickness of a single layer: 2–6 cm; the silty mudstone (E): the thickness of a single layer: 1–16 cm, massive bedding (homogeneous bedding) developing; the carbonaceous shale: horizontal bedding developing, graptolite visible, the thickness of the single bed: 0.2–3 cm. The sandstone (C): groove casts visible in the bottom with trending of 120°–300°, steep in the southeast and gentle in the northwest, indicating southeast water source. Chitinozoa, *Eisenackitina songtaoensis* Chen *et al*., 2009 produced. 7.74 m

46. Interbeds consisting of gray thin–medium laminated siltstone, mudstone, and micro laminated black shale, Bouma sequence CE developing. The siltstone (C): wavy or cross-bedding developing, the thickness of a single layer: 3–14 cm; the mudstone (E): massive bedding (homogeneous bedding), the thickness of a single layer: 3–16 cm; the black carbonaceous mudstone: micro-grained horizontal bedding developing, the thickness of a single layer: 0.3–1 cm. 17.79 m

45. Interbeds consisting of gray thick laminated siltstone, medium–thin laminated silicon-bearing mudstone, and micro laminated black carbonaceous mudstone, interbedded with medium laminated fine sandstone, Bouma sequence CE developing. The siltstone (B) in the upper part: sandstone with graded bedding visible locally, the thickness of a single layer: 10–20 cm; the siltstone (C): cross-bedding developing, the thickness of a single layer: 1–8 cm; the silicon-bearing mudstone (E): the thickness of a single layer: 4–11 cm. This layer is interbedded with graptolite-bearing micro laminated carbonaceous mudstone. 29.85 m

44. Interbeds consisting of gray thick laminated siltstone, silicon-bearing mudstone, and micro laminated black shale, Bouma sequence CE developing. The siltstone (C): cross-bedding developing, the thickness of a single layer: 2–8 cm; the silicon-bearing mudstone (E): the thickness of a single layer: 4–8 cm, massive bedding (homogeneous bedding) developing, the thickness of a single layer of carbonaceous mudstone: 1–4 cm. 21.37 m

43. Polycyclic interbeds consisting of gray thin–medium laminated fine sandstone, thick laminated siltstone, and thin–medium laminated mudstone, interbedded with black and micro laminated carbonaceous mudstone, Bouma sequence ACE developing. The fine sandstone (A): gray, scouring surface as the bottom, normal graded bedding developing; less obvious parallel bedding developing on the top, the thickness of a single layer: 5–20 cm; the siltstone (C): cross-bedding developing, the thickness of a single layer: 3–9 cm; the mudstone (E): the thickness of a single layer: 5–22 cm, massive bedding (homogeneous bedding) developing; the carbonaceous mudstone: the thickness of a single layer: 1–2cm, a small amount distributed in the bottom and stable in the upper part. 7.57 m

42. Rhythmic interbeds consisting of gray thin–medium laminated siltstone and mudstone, interbedded with micro laminated black shale, Bouma sequence CE developing. The siltstone (C): cross-bedding developing, uneven bottom, the thickness of a single layer: 3–11 cm; the mudstone (E): the thickness of a single layer: 7–12 cm, massive bedding (homogeneous bedding) developing. Black carbonaceous mudstone interbeds with a thickness of 1cm visible in the upper part. 10.06 m

41. Interbeds consisting of gray medium laminated fine-silty sandstone, thick laminated siltstone, medium–thin laminated mudstone, and black carbonaceous mudstone, Bouma sequence BCE developing. The gray fine-silt sandstone (B): normal graded bedding developing, the thickness of a single layer: 15–21 cm; the siltstone (C): cross-bedding developing, the thickness of a single layer: 2–4 cm; the respective thickness of a

single layer of the mudstone (E) and the carbonaceous mudstone: 6–15 cm and 1–3 cm. 10.1 m

40. Gray medium laminated siliceous mudstone, no bedding developing, the thickness of a single layer: 10–27 cm. 3.06 m

39. Interbeds consisting of gray medium laminated fine-silty sandstone and silty mudstone, interbedded with black thick laminated carbonaceous mudstone, Bouma sequences AE developing. The fine-silty sandstone (A): graded bedding developing, uneven bottom, the thickness of a single layer: 27–29 cm; the silty mudstone (E): no bedding developing, the thickness of a single layer: 14–25 cm; the black carbonaceous mudstone: horizontal bedding developing, the thickness of a single layer: 1–5 cm. 1 m

38. Interbeds consisting of gray thick laminated fine-siltstone and silicon-bearing mudstone, interbedded with black carbonaceous mudstone, two beds of fine sandstone with a thickness of 20cm of each layer interspersing in the middle and lower parts, one layer of iron oxide with a thickness of 8cm interspersing in the middle part, Bouma sequence CE developing. The fine-siltstone (C): cross-bedding developing, the thickness of a single layer: 3–3.5 cm; the respective thickness of single layer of the silicon-bearing mudstone (E) and the black carbonaceous mudstone: 3.5–4 cm and 1–2 cm. 6.1 m

37. Interbeds consisting of gray medium laminated fine sandstone, siltstone, and medium–thin laminated mudstone, Bouma sequences ABE developing. The fine sandstone (A): graded bedding developing, uneven bottom, the thickness of a single layer: 13–18 cm; the fine-sand siltstone (B): weak parallel bedding developing, the grain size gradually decreasing upwards, the thickness of a single layer: 7–16 cm; the mudstone (E): the thickness of a single layer: 7–15 cm. 8.21 m

36. Gray thin–medium laminated mudstone, interbedded with a layer of fine-silt sandstone with a thickness of 10cm in the middle part. The mudstone: silt visible occasionally, the thickness of a single layer: 10–15 m. 5.24 m

35. Interbeds consisting of grayish thick laminated siltstone and mudstone, interbedded with dark ash-black graptolite-bearing carbonaceous mudstone, Bouma sequences CE developing. The siltstone (C): cross-bedding developing, the thickness of a single layer: 3–7 cm; the mudstone (E): no bedding developing, the thickness of a single layer: 6–10 cm; the carbonaceous mudstone: graptolite visible, the thickness of a single layer: 0.5–3 cm. A layer of 0.5 cm thick K-bentonite visible in the middle-lower part of this bed. 6.22 m

——————— Conformable contact ———————

The first member of Changwu Formation (O_3c^1) Total thickness: 154.91 m

34. Interbeds of gray-caesious medium- to thick laminated fine-siltstone and dark gray thick laminated silicon-bearing mudstone, Bouma sequences AE and ABE developing. The fine-siltstone (A): graded bedding developing, the thickness of a single layer: 30–58 cm; the fine-silty sandstone (B): less obvious parallel bedding developing, the thickness of single bed: 40 cm; the siliceous mudstone (E): in sharp contact with its underlying and overlying strata, the thickness of a single layer: 4–7 cm. The top of this bed consisting of 12 cm thick K-bentonite. 1.67 m

33. Interbeds consisting of gray thin–medium laminated fine-silty sandstone and gray micro–thin laminated mudstone, Bouma sequence BE developing. The fine-silty sandstone (B): scour surface developing in the bottom, less obvious parallel bedding developing in the beds, the thickness of a single layer: 6–16 cm; the thickness of single layer of mudstone (E): 1–7 cm. 2.61 m

32. Interbeds consisting of gray thin–medium laminated fine sandstone and dark gray thin–medium

laminated silty mudstone, Bouma sequence BE developing. The fine sandstone (B): less obvious parallel bedding developing, grain size of the clastics decreasing gradually upwards, scour surface developing in the bottom, the thickness of a single layer: 6–23 cm; the silty mudstone (E): the thickness of a single layer: 4–13 cm, in sharp contact with B. The top of this bed: 30 cm thick siliceous mudstone, followed by 3 cm thick K-bentonite, bioturbation structures visible occasionally. 1.88 m

31. Interbeds consisting of gray medium laminated fine-siltstone and thin–medium laminated silicon-bearing mudstone, Bouma sequence AE developing. The fine-siltstone (A): gradually turning into silty sand from fine sand, from bottom to top (graded bedding developing), flute casts developing in the bottom, the thickness of a single layer: 15–47 cm. The thickness of a single layer of silicon-bearing mudstone (E): 8–26 cm. 15.17 m

30. Interbeds consisting of gray thin–medium laminated fine-silty sandstone, thick laminated siltstone, and silicon-bearing mudstone, Bouma sequences BCE and DCE developing dominated by BCE, C and E. The fine-silty sandstone (B): scour surface developing at the bottom, normal parallel bedding developing, the thickness of a single layer: 6–35 cm; the siltstone (C): fine sand with cross-bedding developing, in gradual contact with B, the thickness of a single layer: 2–5 cm; the siltstone (D): horizontal bedding developing, the thickness of a single layer: 3–8 cm; the silicon-bearing mudstone (E): bioturbation structures mostly developing in the upper part. 8.52 m

29. Interbeds consisting of gray medium- to thick laminated fine-silty sandstone, thin–medium laminated siltstone, and medium–thin laminated silicon-bearing mudstone, Bouma sequence AE developing in the lower part and Bouma sequences CE and BE developing upwards. The respective thickness of a single layer of the fine-silt sandstone (A), fine-silt sandstone (B), siltstone (C), and silicon-bearing mudstone (E): 23–110 cm,15–30 cm, 3–6 cm, and 4–15 cm. 6.27 m

28. Interbeds consisting of gray medium laminated fine-silty sandstone, gray – dark gray thin–medium laminated argillaceous siltstone, Bouma sequence BE developing. The fine-silty sandstone (B): parallel bedding developing, the grain size of the clastics gradually decreasing upwards, the thickness of a single layer: 13–18 cm. The argillaceous siltstone (E): no obvious bedding developing, the thickness of a single layer: 9–15 cm, 3–4 cm width (diameter: 7–8 cm) biological crawling trace developing near the top. 12.38 m

27. Interbeds consisting of gray medium- to thick laminated boulder silty-fine sandstone, fine-siltstone, dark gray medium–thin laminated silty mudstone, and siliceous mudstone; incomplete Bouma sequence ACDE developing, ACE distributed in the lower part and ADE mostly upwards. The sandstone (A): boulder clay visible in the bottom, the thickness of a single layer: 10–123 cm; the siltstone (C): small cross-bedding developing, the thickness of a single layer: 2–6 cm; the silty mudstone (D): parallel bedding developing, the thickness of a single layer: 3–15 cm; the siliceous mudstone (E): no bedding developing, the thickness of a single layer: 5–33 cm. 2.87 m

26. Interbeds consisting of medium laminated fine-silty sandstone and dark gray medium–thin laminated mudstone, Bouma sequence AE developing. The fine-silty sandstone (A): uneven scour surface developing in the bottom, the layer thickness gradually decreasing upwards, parallel bedding visible, the thickness of a single layer: 10–36 cm; the siliceous mudstone (E): horizontal bedding developing, the thickness of a single layer: 7–22 cm; bioturbation structures developing near the top. 11.59 m

25. Interbeds consisting of gray medium laminated boulder fine-silty sandstone, fine-silty sandstone, and dark gray thick laminated silty mudstone. Bouma sequence AE developing in the lower part, Bouma sequence

ADE developing in the upper part. The boulder fine-silty sandstone (A): grain size decreasing upwards, containing 5%–10% syngenetic boulder clay. The fine-silty sandstone(D): grain size decreasing upwards, parallel bedding developing. The silty mudstone (E): biological crawling trace visible. The respective thickness of a single of A in the upper part and the lower part: 7–14 cm and 10–100 cm; the thickness of a single layer of B in the upper part: 15–28 cm; the respective thickness of a single layer of E in the upper part: 4–13 cm and 3–6 cm. 7.36 m

24. Interbeds consisting of thin–medium laminated fine-silty sandstone, silty mudstone, and mudstone, Bouma sequence developing. The fine-siltstone (A): uneven scour surface developing in the bottom, the grain size gradually decreasing upwards, the thickness of a single layer: 7–35 cm; the siliceous mudstone (E): horizontal bedding developing, the thickness of a single layer: 7–22 cm; bioturbation structures visible near the top of this bed. 15.13 m

23. Rhythmic interbeds consisting of caesious medium- to thick laminated fine sandstone and gray thin–medium laminated siliceous mudstone, Bouma sequence AE developing. The fine sandstone (A): irregular syngenetic boulder clay visible occasionally, grain size: 1–5 cm and gradually decreasing from bottom to top, the thickness of a single layer: 50–80 cm generally and 20–30 cm locally; the siliceous mudstone (E): no bedding developing, the thickness of single bed: 5–30 cm. The top: 8 cm thick K-bentonite and 2 cm thick tan iron oxide layer downwards. 58.92 m

22. Interbeds consisting of caesious middle bedded fine sandstone, thin–medium laminated silty mudstone, and medium laminated mudstone, Bouma sequence ADE developing. The fine sandstone (A): gradually changing from fine sand to silt from bottom to top, the thickness of single bed: 10–30 cm; the silty mudstone (D): horizontal bedding developing, the thickness of a single layer: 5–10 cm; the grey mudstone (E): no bedding developing, the thickness of a single layer: 10–20 cm. 9.96 m

——— Conformable contact ———

Huangnigang Formation (O_3h) Total thickness: >2.14 m

21. Caesious medium laminated silicon-bearing mudstone, no bedding developing, the thickness of single bed: 30–50 cm generally. 2.14 m

The original stratigraphic lithologic association of the third member of Changwu Formation (O_3c^3) cannot be fully reflected from the above profile owing to strong weathering. The specific lithological characteristics of the third member can be shown in the third member of Changwu Formation (O_3c^3)–the middle and lower parts of Wenchang Formation (O_3w) profile (PM002) of Hanggai map sheet in Shangangshang, Hanggai Town, Anji County, Zhejiang Province.

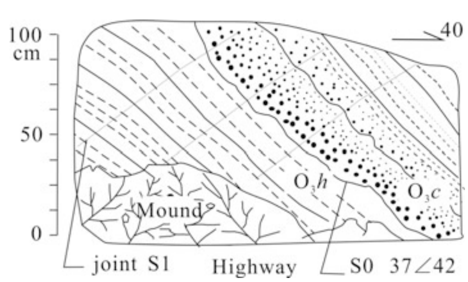


Fig. 2.64 Sketch of conformable contact between Changwu Formation and Huangnigang Formation of Xinqiao profile in Hanggai Town

2. **Lithological characteristics**

The lithology of the first member (O_3c^1) and the second member (O_3c^2) of Changwu Formation is mainly characterized by gray silt-fine sandstone, siltstone, silty mudstone or silicon-bearing mudstone, carbonaceous mudstone. Besides, there is a small amount of K-bentonite in the two members.

(1) The silty-fine sandstone: gray to caesious; composition: feldspar and quartz (80–85%), argillaceous material (15–20%), a small amount of detritus, and occasionally visible syngenetic boulder clay; the bottom: uneven

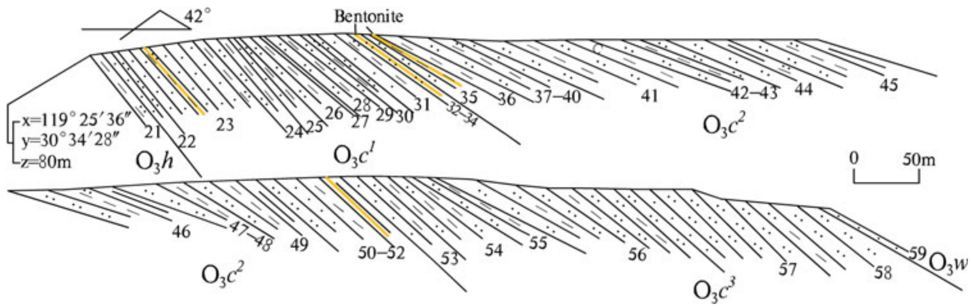


Fig. 2.65 Ordovician Changwu Formation (O_3c) profile in Xinqiao Village, Hanggai Town, Anji County, Zhejiang Province

sour surface; the thickness of a single layer: 15–50 cm generally; the siltstone: constituting A of Bouma sequences in case of normal graded bedding developing or constituting B of Bouma sequences in case of parallel bedding developing.

(2) The siltstone: gray; composition: feldspar and quartz (75–80%) and a small amount of argillaceous matter; constituting C of Bouma sequences in case of small cross-bedding, wavy bedding, or occasionally convolute bedding developing, or constituting D of Bouma sequences in case of parallel bedding developing; the thickness of single bed: 2–15 cm.

(3) The silicon-bearing mudstone: gray; composition: argillaceous matter (75–80%), siliceous matter (15–25%), and occasionally visible silt; no bedding developing generally; constituting C of Bouma sequences. However, biological disturbance relicts such as boring trace and crawling trace often visible in the upper part.

(4) The carbonaceous mudstone: dark gray–grayish black; composition: argillaceous matter and a small amount of silt and carbonaceous matter; horizontal bedding developing generally; graptolite fragments visible.

5) The K-bentonite: shallow gray yellow (green); tuff structure, blocky structure, and weak micro-bedding structure developing; composition: volcanic ash (90–95%) and a small amount of fine-grained angular feldspar (5–10%); the minerals mostly turning into kaolin owing to compression and hydrolysis, with weak waxy luster and soap-like slippery feeling, distinctly different from the upper and lower gray silicon-bearing mudstone and silty mudstone.

The lithology of the third member of Changwu Formation (O_3c^3) is mainly characterized by gray feldspathic quartz sandstone, feldspathic quartz silt-fine sandstone, silty mudstone, and mudstone.

(1) The feldspathic quartz sandstone: gray; composition: quartz and feldspar (5–80%) and silty argillaceous matter (20–25%); the feldspar and quartz: subangular to sub-well rounded; grain size: 0.05–0.4 mm, unevenly distributed, much distributed locally, mostly sub-well rounded.

(2) The feldspathic quartz silt-fine sandstone: gray; main component: quartz and a small amount of feldspar (75–80%), sub-well rounded; grain size: 0.05–0.1 mm; argillaceous matter: 20–25%.

(3) The silty mudstone: gray—dark gray, composition: argillaceous matter (50–90%) and a small amount of silt (10–50%), main components of the silt: quartz and feldspar.

(4) The mudstone: gray–dark gray; composition: argillaceous matter (80–90%) and occasionally visible silt and fine sand; part of the mudstone containing graptolite.

3. **Basic sequences**

In the first member (O_3c^1) of Changwu Formation, the basic sequences (Fig. 2.66) are consistent with the Bouma sequences. There are five types of basic sequences developing in this member, i.e., Bouma sequences ADE, AE, BE, CE, and ABE. The lower part of this member mainly consists of ADE and AE; the middle part is mainly composed of AE and BE followed by the small amount of CE; the upper part mainly includes AE, ABE, and BE. The thickness of the lower beds is greater than that of the upper bed. Therefore, these sequences belong to cyclic basic sequence with layer thickness generally decreasing upward.

(1) Bouma sequence ABE: composed of ① gray–caesious medium to thick laminated fine-silty sandstone, ② middle-bedded fine-silty sandstone, and ③ dark gray thick laminated silicon-bearing mudstone. The fine sandstone (A): graded bedding developing, the thickness of a single layer: 30–58 cm. The fine-silty sandstone (B): less obvious parallel bedding developing, in gradual contact with A, the thickness of a single layer: 40 cm. The silicon-bearing mudstone (E): no bedding developing; in sharp contact with its underlying and overlying strata, the thickness of a single layer: 4–7 cm.

(2) Bouma sequence ADE: composed of the interbeds of ① caesious middle-bedded sandstone, ② thick laminated silty mudstone, and ③gray middle-bedded mudstone. The fine sandstone (A): grayish–caesious, gradually changing from fine sand into silt from bottom to top, the

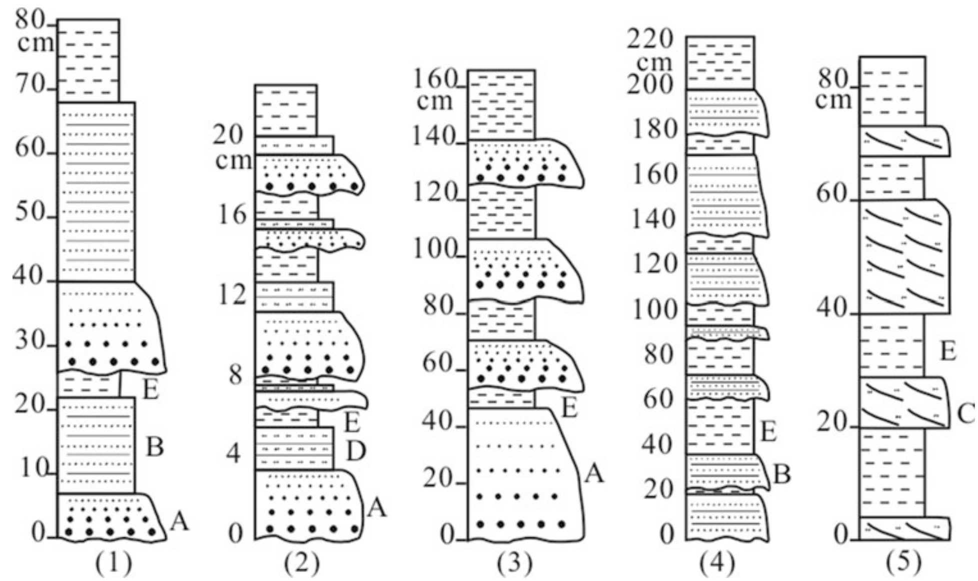


Fig. 2.66 Basic sequences of the first member of Changwu Formation (O_3c^1)

thickness of a single layer: 10–30 cm. The silty mudstone (D): horizontal bedding developing, the thickness of a single layer: 5–10 cm. The mudstone (E): no bedding developing, the thickness of a single layer: 10–20 cm.

(3) Bouma sequence AE: composed of rhythm interbeds of ① caesious medium to thick laminated fine sandstone and ② thin–medium laminated gray siliceous mudstone. The sandstone (A): 1–5 cm irregular syngenetic boulder clay visible occasionally, the grain size of the sand grain gradually decreasing from bottom to top, the thickness of a single layer: 20–80 cm. The siliceous mudstone (E): no bedding developing, the thickness of a single layer: 5–30 cm.

(4) Bouma sequence BE: consisting of ① gray thin–medium laminated fine sandstone and ② dark gray thin–medium laminated silty mudstone. The fine sandstone (B): parallel bedding developing, the grain size of the clastics gradually decreasing, scour surface developing in the bottom, the thickness of a single layer: 6–30 cm. The silty mudstone (E): the thickness of a single layer: 4–15 cm, in sharp contact with B, biological disturbance structures visible occasionally.

(5) Bouma sequence CE: consisting of ① gray thick laminated fine-silty sandstone and ② medium–thin laminated silicon-bearing mudstone. The fine sand siltstone (C): cross-bedding developing, convolute bedding developing locally, the thickness of a single layer: 3–6 cm. The siliceous mudstone (E): a small number of biological disturbance structures or crawling traces visible, the thickness of a single layer: 4–15 cm. Sharp contact between the two components.

The sediments in this member are mainly silt and fine sand, followed by siliceous and argillaceous matter. Crawling trace is visible in the upper part of the mudstone. The rock beds are thick, and scour structure generally developed in the bottom. All these reflect the sedimentary environment near oxidation–reduction zone with abundant terrigenous clastics sources and scarce ancient organisms. Therefore, this member belongs to turbidite facies of inner margin of bathyal basin slope.

In the second member of Changwu Formation (O_3c^2), the basic sequences (Fig. 2.67) are consistent with the Bouma sequences. There are five types of basic sequences developing in this member, i.e., Bouma sequences CE, ABE, AE, BCE, and ACE, dominated by CE. The lower part of this member mainly consists of CE, ABE, and AE, the middle part is mainly composed of CE, BCE, and ACE, and the upper part mainly includes CE, AE, and BCE. All these sequences belong to cyclic basic sequence with layer thickness and grain size decreasing from bottom to top.

(1) Bouma sequence ABE: consisting of ① gray medium laminated fine sandstone, ② thin–medium laminated fine-silty sandstone, ③ medium–thin laminated mudstone, and ④ black micro-laminated carbonaceous mudstone. The fine sandstone (A): normal graded bedding developing, uneven scour structure developing in the bottom, the thickness of a single layer: 13–25 cm. The fine-silty sandstone (B): weak parallel bedding developing, the grain size of clastics gradually decreasing upward, the thickness of a single layer: 3–20 cm. The mudstone (E): no bedding developing, the

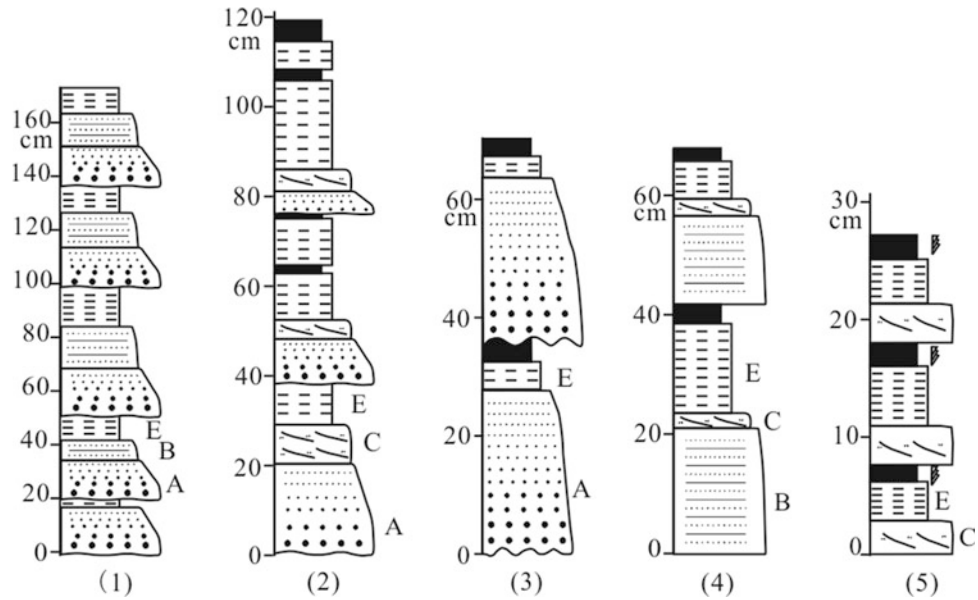


Fig. 2.67 Basic sequences of the second member of Changwu Formation (O_3c^2)

thickness of a single layer: 5–15 cm. The black micro-laminated carbonaceous graptolite-bearing mudstone: distributed in the upper part of this sequence, weak horizontal bedding visible occasionally.

(2) Bouma sequence ACE: consisting of ① gray thin–medium laminated fine sandstone, ② thick laminated siltstone, ③ thin–medium laminated mudstone, and ④ black micro-laminated carbonaceous mudstone. The fine sandstone (A): scour surface developing in the bottom, normal graded bedding developing, the thickness of a single layer: 5–20 cm. The siltstone (C): cross-bedding developing, the thickness of a single layer: 3–9 cm. The mudstone (E): the thickness of a single layer: 5–22 cm. The black carbonaceous mudstone: the thickness of a single layer: 1–2 cm, distributed in the upper part of the sequence.

(3) Bouma sequence AE: consisting of ① gray middle-bedded fine-silty sandstone, ② middle-bedded silty mudstone, and ③ black micro-laminated carbonaceous mudstone. The fine-silty sandstone (A): graded bedding developing, scour structure developing in the bottom, the thickness of a single layer: 27–29 cm. The silty mudstone (E): no bedding developing, the thickness of a single layer: 14–25 cm. The black carbonaceous mudstone: horizontal bedding developing, the thickness of a single layer: 1–5 cm. Sharp contact among the three components.

(4) Bouma sequence BCE: consisting of ① gray thin–medium laminated sandstone, ② thick laminated siltstone, ③ micro-thin laminated silty mudstone, and ④ black micro-laminated carbonaceous mudstone. The sandstone (B): parallel bedding developing, the thickness of a single layer: 3–12 cm. The siltstone (C): cross-bedding developing, the thickness of a single layer: 1–4 cm. The silty mudstone (E): the thickness of a single layer: 2–5 cm. Among them, sandstone (B) is in gradual contact with siltstone (C), while silty mudstone (E) is in sharp contact with its underlying and overlying strata. The black carbonaceous mudstone: the thickness of a single layer: 0.8–1 cm, containing graptolite, only distributed in the upper part.

(5) Bouma sequence CE: It consists of ① gray thick laminated siltstone and ② mudstone, often interbedded with ③ dark gray–black thick laminated graptolite-bearing carbonaceous mudstone. The lower siltstone (C): cross-bedding developing, the thickness of a single layer: 3–7 cm. The mudstone (E): no bedding developing, the thickness of a single layer: 6–10 cm. The black carbonaceous mudstone: graptolite commonly visible, the thickness of a single layer: 0.5–3 cm, mostly distributed above the mudstone; sharp contact among the three components.

The sediments in this member are mainly siliceous and argillaceous matters followed by silt and fine sand. Graptolites are common in black carbonaceous mudstone. Therefore, the second member belongs to the turbidite facies of outer margin of bathyal basin slope–abyssal basin.

There are three types of basic sequences (Fig. 2.68) developing in the third member of Changwu Formation (O_3c^3).

(1) Basic sequences in the lower part of the third member. Consisting of rhythm interbeds of ① thin–medium laminated feldspathic quartz silt-fine sandstone and ② silty mudstone. The silty-fine sandstone: mainly

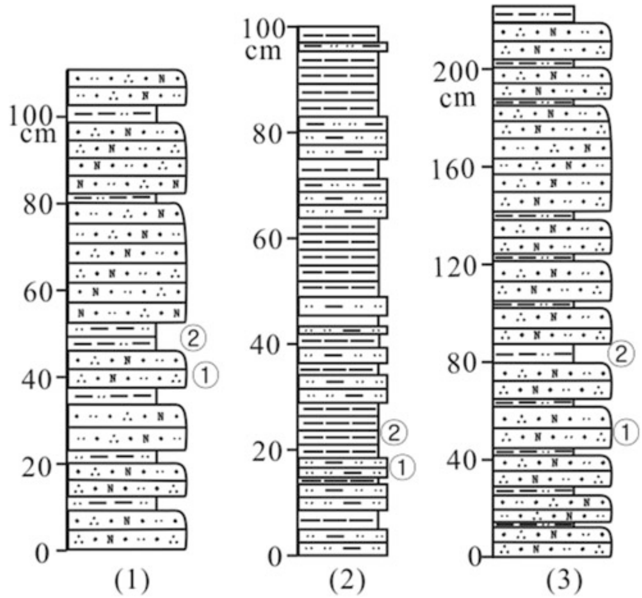


Fig. 2.68 Basic sequences of the third member of Changwu Formation (O_3c^3)

composed of quartz followed by feldspar, subangular–sub-well rounded, top and bottom mostly even, uneven scour surface developing in the bottom visible occasionally, normal graded bedding developing in the beds, the thickness of a single layer: 5–20 cm generally or even up to 40 cm locally. The silty mudstone: mainly composed of quartz and feldspar, sedimentary structure not obvious, horizontal bedding developing in a small amount of the silty mudstone, graptolite obtained in partial mudstone, the thickness of a single layer: 5–15 cm generally and 25–30 cm locally. Sandstone is approximately 1–2 times silty mudstone.

(2) Basic sequences in the middle part of the third member. Composed of rhythm interbeds of ① thin–medium laminated argillaceous siltstone and ② mudstone. The argillaceous siltstone: mainly consisting of feldspar and quartz with low maturity, the thickness of a single layer: 5–15 cm generally, the sedimentary structure not obvious. The mudstone: the thickness of a single layer: generally 5–25 cm, accounting for similar proportion to that of the argillaceous siltstone, distributed in the middle and lower parts.

(3) Basic sequences in the upper part of the third member. Consisting of rhythm interbeds of ① medium laminated feldspathic quartz silt-fine sandstone and ② thin–medium laminated silty mudstone. The silty-fine sandstone: mainly composed of quartz and feldspar, subangular–sub-well rounded, even top and bottom, print casts developing in the bottom, the thickness of a single layer: 10–25 cm generally and up to 40 cm locally. The silty mudstone: mainly composed of quartz and feldspar, sedimentary structure not obvious, horizontal bedding developing locally, the thickness of a single layer: 2–15 cm generally and 25–30 cm locally. The sandstone is about 3–10 times of silty mudstone.

Compared with the lower two lithological members, there is no Bouma sequence developing in the third member (O_3c^3) of Changwu Formation generally, and only the sequences similar to Bouma sequences developed locally. Furthermore, there is only a small amount of grapholite-bearing mudstone. Therefore, the third member is of flyschoid facies of inner margin of shallow shelf slope, and the clastic rock association belongs to non-cyclic basic sequence with width and thickness of beds increasing upward generally.

2.4.6.2 Sequence Stratigraphy

According to the characteristics of the lithology, paleontology, lithofacies association, and sequence boundary Xinqiao profile in Hanggai map sheet, there is one third-order sequence Sq23 in Changwu Formation (O_3c), which belongs to the second-order sequence SS8 (Fig. 2.69).

***Third-order sequence Sq*23**

It consists of the transgressive systems tract (TST), starved section (CS), and highstand systems tract (HST). The bottom is the interface between the sandstone of the first member of Changwu Formation and the siliceous mudstone of Huangnigang Formation. Although the interface is uneven owing to sour of the turbidity current, there is only a short sedimentation interval between them. Therefore, they are still in conformable contact with each other. The top is the

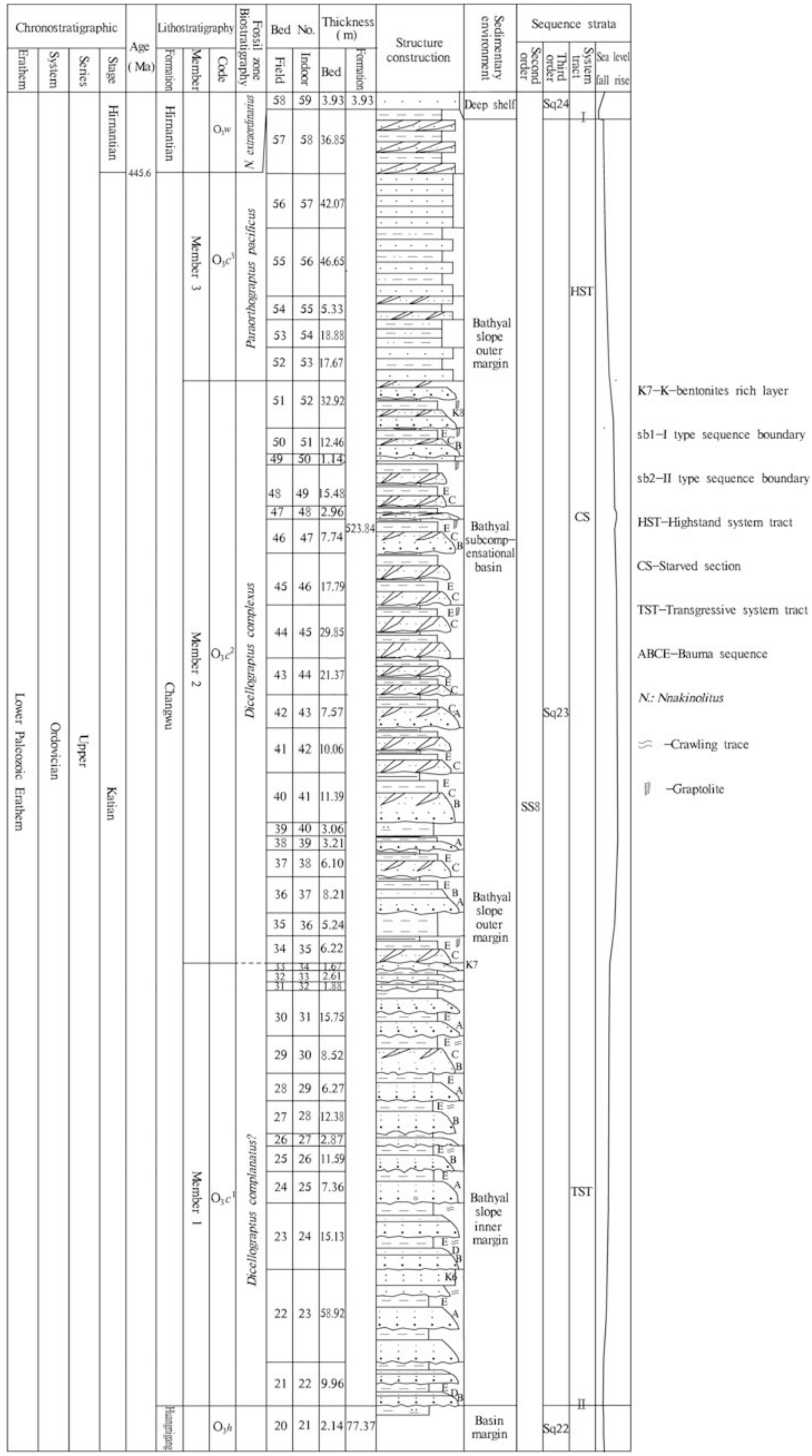


Fig. 2.69 Sequence of stratigraphic framework of Ordovician Changwu Formation in the area

conformity interface between the medium laminated silty mudstone of the third member of Changwu Formation and the thick laminated sandstone of the Wenchang Formation. Both the bottom and the top are of type-II sequence boundary.

Transgressive systems tract (TST) is located in the first member and the lower part of the second member of Changwu Formation. The sediments in TST are mainly terrigenous feldspathic quartz sand grains, silt, and argillaceous matter, followed by carbonaceous argillaceous matter. Typical Bouma sequences AE, ABE, ADE, ACE, BE, BCE, and CE developed from bottom to top. The sandstone (constituting A and B) is medium laminated (30–45 cm) mainly in the lower part and changes into thin–medium laminated shape upward, and the layer thickness and the grain size of the clastics decrease upward. However, the thick laminated siltstone (constituting D and C) and mudstone (constituting E) increases upward. All these indicate that the sea level of the sedimentary basin in the Area rose gradually, and consequently, the supplies of the terrigenous clastics gradually decreased and the hydrodynamic force gradually weakened.

In the middle and upper parts of the second member of Changwu Formation, the transgression reached the maximum, i.e., the maximum flooding surface. Owing to that, these parts are located in the outer margin of abyssal basin slope far away from the continent. The sediments are scarce and mainly include fine sand and silt, argillaceous matter, and carbonaceous argillaceous matter. Typical Bouma sequence CE developed in these parts, accompanied by graptolite-bearing carbonaceous shale. Therefore, these parts constitute the starvation section (CS) with the most deficient sediments.

The highstand systems tract (HST) is located from the upper part of the second member to the third member of Changwu Formation. The sediments in the second member mainly include terrigenous feldspathic quartz sand, silt, argillaceous matter, and carbonaceous argillaceous matter. Typical Bouma sequences CE, ACE, BE, and BCE developed in this member, accompanied by graptolite-bearing carbonaceous shale. The sediments in the third member are mainly terrigenous feldspathic quartz sand grains, silt, and argillaceous matter. No Bouma sequences developed in this member. All these indicate that the sea level of the sedimentary basin in the Area gradually fell, and accordingly, the supplies of the terrigenous clastics gradually increased and the hydrodynamic force increased.

To sum up, the third-order sequence (Sq23) experienced a relatively complete transgression–regression process and is a sequence of retrogradation–progradation type.

2.4.6.3 Biostratigraphy and Chronostratigraphy

After experiencing the Late Ordovician tectonic–volcanic events, the Area entered the abyssal slope environment. The ancient organisms in the Area mainly included planktonic graptolites, ancient microorganisms, and benthic mollusca, and the fossils were only preserved in mudstone or carbonaceous shale. At present, the biostratigraphic division of the Changwu Formation in China is still mainly based on graptolite zones and the study on chitinozoan is in its initial stage. There are three graptolite zones in Changwu Formation, which are *Dicellograptus complanatus* zone, *Dicellograptus Complexus* zone, and *Paraothograptus pacificus* zone, respectively. According to the *Stratigraphic Chart of China* (2014), all these three zones in Changwu Formation belong to the Late Ordovician Katian Stage.

In this Project, only a small number of graptolite fragments and biological crawling traces were found in the first member of Changwu Formation in the Area, and *Dicellograptus Complexus* zone and *Paraothograptus pacificus* zone were identified in the second and third members, respectively. The details are as follows:

1. ***Dicellograptus complexus* zone**

Dicellograptus complexus zone is located in the second member of Changwu Formation (O_3c^2). Abundant graptolites are obtained in the micro-laminated carbonaceous shale in the third layer of the second member of Changwu Formation in Shangangshang profile (PM002), including *Amplexograptus disjunctus yangtzensis* Mu et Lin, *Amplexograptus suni* (Mu) *Appendispinograptus supernus* (Elles and Wood), *Appendispinograptus venustus* (Hsu), *Climacograptus hastatus* (Hall 1902), *Yinograptus disjunctus* (Yin et Mu), *Paraplegmatograptus uniformis* Mu, and *Leptograptus extremus* Mu et Zhang. No standard fossil of *Dicellograptus Complexus* zone was obtained. However, the above fossils are the main molecules of *Dicellograptus complexus* zone, indicating the *Dicellograptus complexus* zone. The above fossils may be corresponding to the upper part of the zone (Figs. 2.70 and 2.71m).

2. ***Paraothograptus pacificus* zone**

Paraothograptus pacificus zone is located in the third member of Changwu Formation (O_3c^3). A few genera of graptolites were found in Layer 6 and Layer 7 of the third member of Changwu Formation (O_3c^3) in Shangangshang profile (PM002) including: *Paraothograptus pacificus* (Ruedemann), *Paraothograptus angustus* Mu et Lee 1977, *Amplexograptus disjunctus yangtzensis* Mu et Lin,

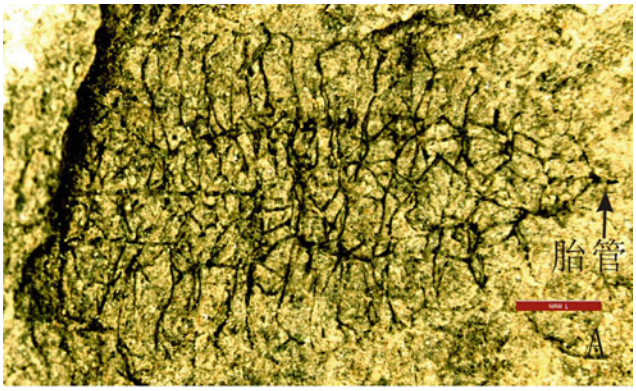


Fig. 2.70 *Paraplegmatograptus uniformis Mu(A)*

Climacograptus chiai Mu 1949 (= Amplexograptus hubeiensis Mu et al.), *Amplexograptus* sp. indet., *Appendispinograptus supernus* (Elles & Wood), and amplexograptid gen. et sp. indet. (Fig. 2.72).

In addition, 16 chitinozoan samples were collected from the first and the second members of Changwu Formation of Xinqiao profile (PM001) and four chitinozoan samples were taken from the third member of Changwu Formation of Shangangshang profile (PM002). Only three of these samples contain chitinozoan fossils. The following chitinite fossils were obtained from the samples collected from the Layer 47 and Layer 50 of the second member of Changwu Formation in Xinqiao profile: *Belonechitina americana* (Taugourdeau 1965), *Conochitina aff. dolosa* (Laufeld 1967), *Conochitina* sp. 1, *Conochitina* sp. 2, *Eisenackitina songtaoensis* (Chen et al. 2009), and *Rhabdochitina gallica* (Taugourdeau 1961). The chitinozoan fossil *Eisenackitina songtaoensis* Chen et al. 2009 was obtained from Layer 20 in the third member of Changwu Formation in the Shangangshang profile. All these chitinozoan fossils obtained belong to E. *Songtaoensis* zone (Fig. 2.73), which is corresponding to *Didymograptus complanatus* zone–*Nemagraptus extraordinarius* zone. The time of these chitinozoan fossils is the Late Katian–Late Ordovician.

2.4.6.4 Event Stratigraphy

There are five interbeds of K-bentonite developing in the first and the second members of Changwu Formation of Hule Formation ($O_{2\text{-}3}h$)–Changwu Formation (O_3c)

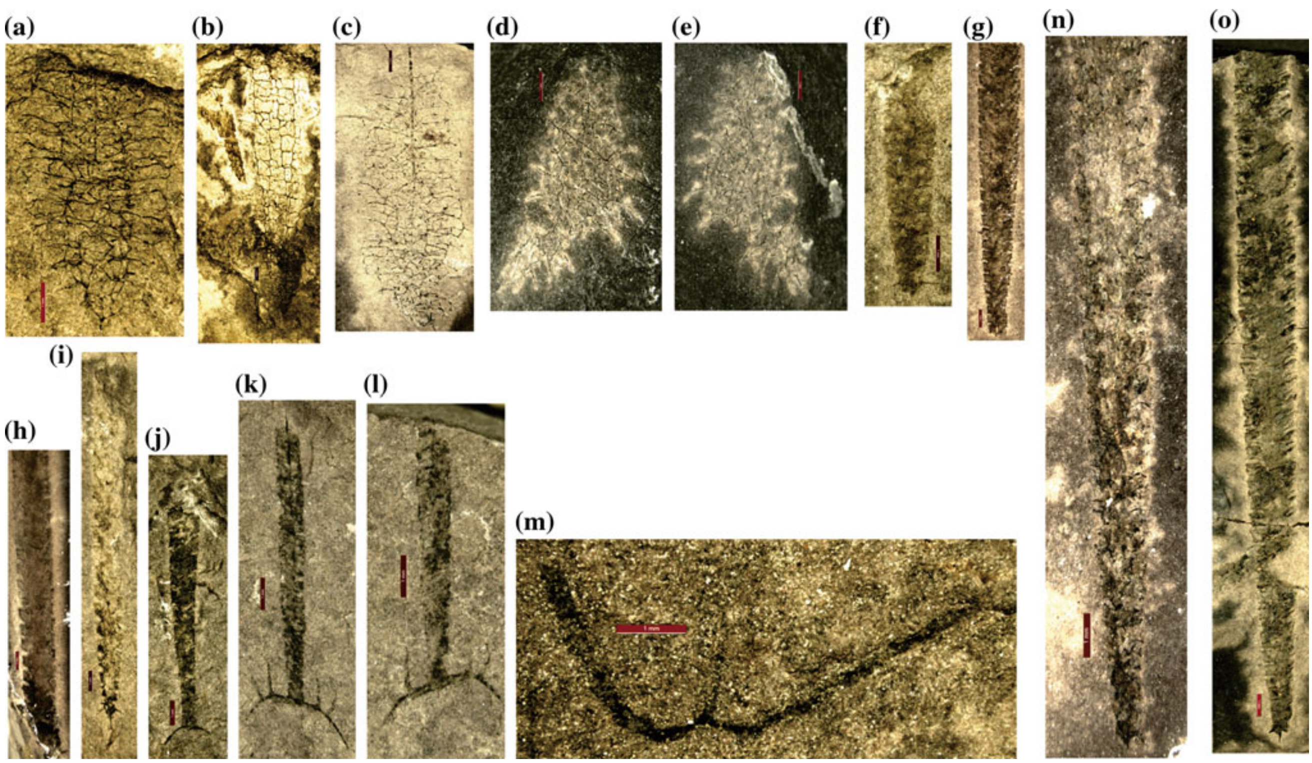


Fig. 2.71 Graptolite fossils in Dicellograptus complexus zone of the second member of Changwu Formation (O3c2): **a** *Paraplegmatograptus uniformis* Mu (Pm002-38a-21-1); **b** *Paraplegmatograptus uniformis* Mu (Pm002-38a-41); **c** *Yinograptus brevispinus* Mu(Pm002-38a-55a); **d** *Reteograptus geinitzianus* Hall (Pm002-38a-12-1); **e** *Reteograptus geinitzianus* Hall (Pm002-38a-11-2); **f** *Climacograptus hastatus* (Hall 1902) (Pm002-38a-10); **g** *Amplexograptus disjunctus yangtzensis* Mu et Lin, Pm002-Hb38b-6; **h** *Amplexograptus suni* (Mu) (Pm002-Hb38-6a); **i** *Diplograptus palaris* Lin (Pm002-38a-13-1); **j** *Appendispinograptus supernus* (Elles and Wood) (Pm002-38a-24-1); k-*Appendispinograptus venustus* (Hsu) (Pm002-38a-17); **l** *Appendispinograptus venustus* (Hsu) (Pm002-38a-18); **m** *Leptograptus extremus* Mu et Zhang (Pm002-38a-43-1); **n** *Amplexograptus suni* (Mu) (Pm002-Hb38a-18a); **o** *Amplexograptus suni* (Mu) (Pm002-38a-48-2)

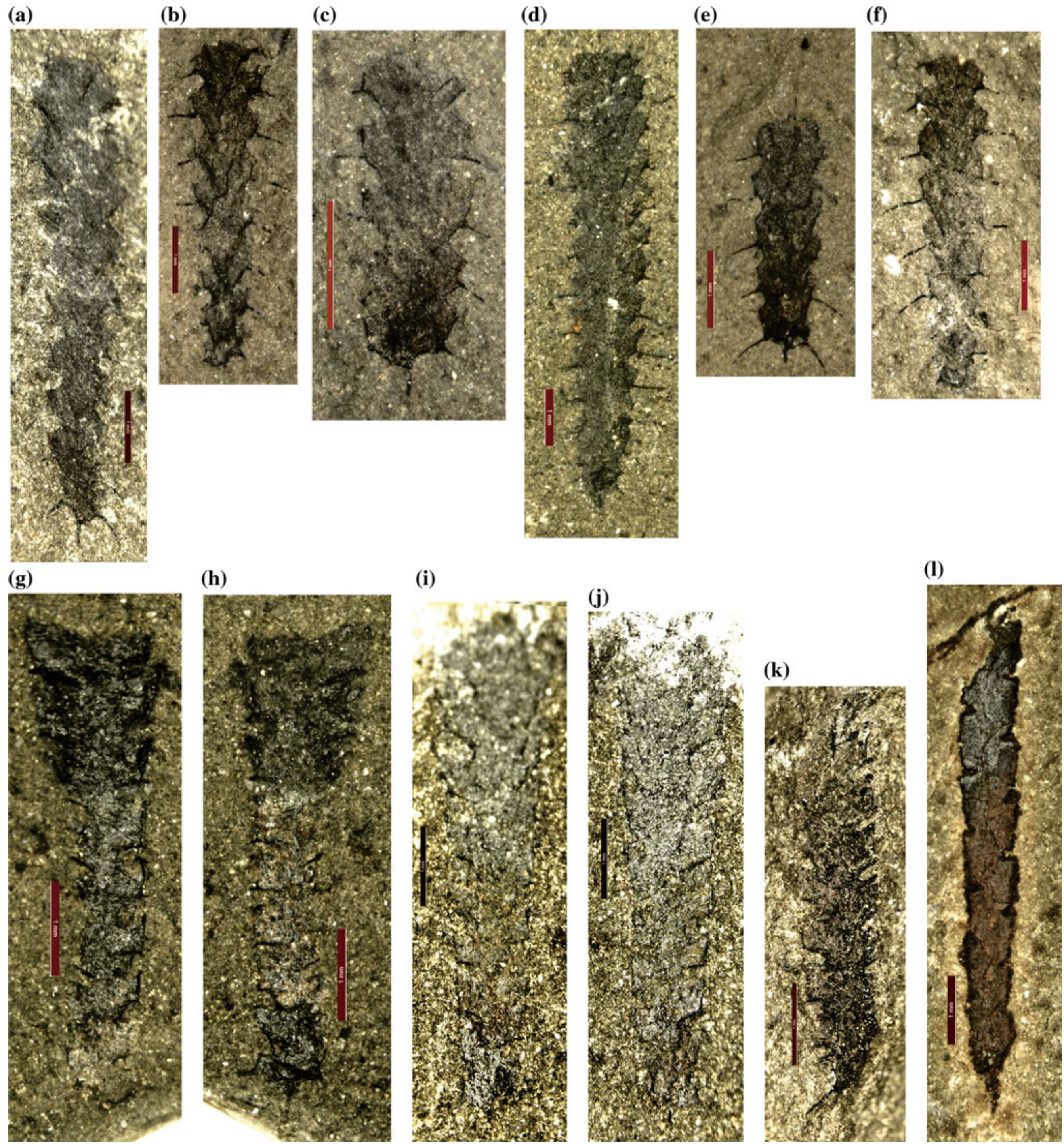


Fig. 2.72 Graptolite fossils in *Paraothograptus pacificus* zone of the third member of Changwu Formation (O_3c^3): **a** *Paraothograptus pacificus* (Ruedemann) (Pm002-Hb6-2a); **b** *Paraothograptus pacificus* (Ruedemann) (Pm002-7-1-2-2); **c** *Paraothograptus pacificus* (Ruedemann) (Pm002-7-1-2-3); **d** *Paraothograptus pacificus* (Ruedemann) (Pm002-7-1-19); **e** *Paraothograptus pacificus* (Ruedemann) (Pm002-7-1-23-3); **f** *Paraothograptus angustus* (Pm002-7-1-3-3); **g** *Amplexograptus disjunctus yangtzensis* Mu et Lin (Pm002-7-1-7); **h** *Amplexograptus disjunctus yangtzensis* Mu et Lin (Pm002-7-1-8); **i** *Amplexograptus disjunctus yangtzensis* Mu et Lin (Pm002-7-1-40a); **j** *Amplexograptus disjunctus yangtzensis* Mu et Lin (Pm002-7-1-41); **k** A*mplexograptus hubeiensis* Mu et al. (Pm002-7-1-23-1); **l** *Amplexograptus disjunctus yangtzensis* Mu et Lin (Pm002-Hb6-1a)

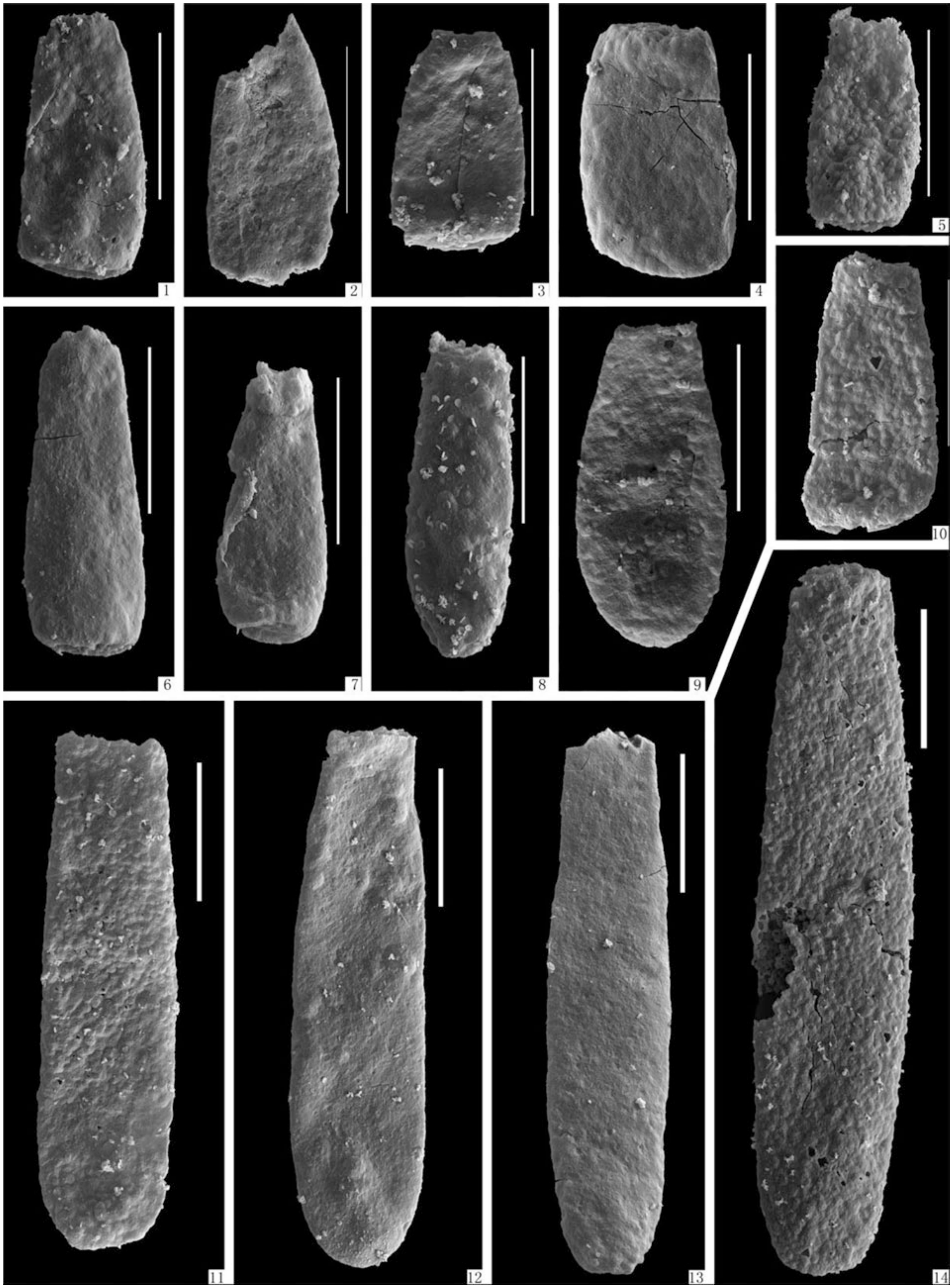


Fig. 2.73 Chitinozoa fossil zone of Changwu Formation in Late Ordovician 1, 6, 7, 10. *Belonechitina americana* (Taugourdeau 1965), sample No. : 12ZAX40(PM001WH50); 2-5. *Eisenackitina songtaoensis* (Chen et al. 2009), sample No. of (2)(4) : 12ZAX38 (PM001WH46), sample No.of (3)(5):12ZAX40 (PM001WH50); 8. *Conochitina* sp. 1, sample No. : 12ZAX40 (PM001WH50); 9. Conochitina sp. 2, sample No. : 12ZAX40 (PM001WH50); 11. *Rhabdochitina gallica* (Taugourdeau 1961), sample No. : 12ZAX40 (PM001WH50); 12-14. *Conochitina aff. dolosa* (Laufeld 1967), sample No. : 12ZAX40 (PM001WH50). The white scale representing 100 μm

stratigraphic profile (PM001) in Xinqiao Village, Hanggai Town. All these interbeds concentrate on three K-bentonite enrichment cycles (K_6–K_8). A detailed study of the event stratigraphy is described in "2.4.5.5 Huangnigang Formation (O_3h)–Late Ordovician Volcanic Event Stratum."

2.4.6.5 Characteristics of Stable Isotopes

A total of seven samples were collected from the gray–dark gray mudstone of the Changwu Formation of Shangangshang profile (PM002) to conduct whole-rock stable isotope test and analysis of $\delta^{13}C$ and $\delta^{34}S$. The $\delta^{13}C$ value is from −30.99 to −29.45‰, with a small variation range and an average value of −30.07‰. This is consistent with the content range $\delta^{13}C$ (−35 to −30‰) of organic carbon in normal shale, indicating the normal reduction deep shelf sedimentary environment. Owing to the relatively low sulfur content in the samples, there is no $\delta^{34}S$ detected in four samples and the range of $\delta^{34}S$ value in the three effective samples was 4.70‰–20.60‰, with an average value of 12.33‰, indicating slightly positive excursion compared with the $\delta^{34}S$ content range (−10 to 10‰) in normal shale. This may be caused by partial isotope fractionation caused by sulfur-reducing bacteria.

2.4.6.6 Analysis of Sedimentary Environment

After Guangxi movement, the sedimentary environment in the Area changed from carbonate lithofacies–siliceous-argillaceous facies of shallow shelf–deep shelf of Huangnigang Formation period to the flysch-flyschoid facies of deepwater slope–deep shelf of Changwu Formation period.

In the first member of Changwu Formation, the Bouma sequences mainly include AE, ABE, ADE, and BE, followed by a small amount of CE. The thickness of the sandstone beds gradually decreases from 35 to 45 cm to less than 20 cm. The mudstone accounts for a small proportion while the crawling trace of mollusca can only be visible in the mudstone. All these indicate the sedimentation of the inner margin of abyssal slope near the continent. Owing to abundant sources of terrigenous clastics, frequent turbidity current is unfavorable to the survival of organisms and the preservation of fossils. Therefore, there are very few paleontological fossils in this member.

In the second member of Changwu Formation, the Bouma sequences mainly include CE followed by AE, ABE, BCE, and ACE. Furthermore, this member is often interbedded with black micro-laminated graptolite-bearing carbonaceous shale, which is mostly thick laminated mostly. All these indicate the sediments are deposited in the outer margin of abyssal slope far away from the continent with relative scarce sources of terrigenous clastics.

In the third member of Changwu Formation, the sediments mainly include thin–medium laminated sand and silt, followed by argillaceous matter. No graded bedding developed in the sandstone, and no diagonal bedding and convolute bedding developed in the siltstone. A small amount of gray mudstone contains planktonic graptolites. All these belong to a flyschoid formation and indicate a hypoxic deep shelf sedimentary environment.

According to the identification and analysis of the fine-silty sandstone samples collected from the first member and the second member of Changwu Formation, the main clastics in the sandstone is sub-well rounded feldspar followed by quartz, with a total content of 80%. Besides, the clastics feature good sorting and argillaceous–siliceous cementation. Therefore, the clastics belong to the graywacke with medium quartz content. The content of SiO_2 in the clastics is 65.03–68.97%, with a small change range. Besides, the content of other components is as follows: $Fe_2O_3 > FeO$, $K_2O > Na_2O$. All these indicate that the clastics come from relatively mature and stable platform. It is inferred that the main body of this member is granite and high-grade metamorphic rocks, followed by part of the product coming from the denudation area of low-grade metamorphic rock and sedimentary rocks.

To sum up, the sedimentary environment of the Area is the abyssal slope and its adjacent areas near the discontinuous zone of the geosphere at the boundary between active continental crust and oceanic crust. Regionally, the sedimentary environment of Changwu Formation varies greatly. In Xianlin area, Yuhang, carbonaceous shale is missing in the second member of Changwu Formation, indicating that the water body became shallower. In Jiangshan–Changshan–Yushan area, the upper and middle parts of Changwu Formation feature lithofacies transition and consist of mud and patch of Sanqushan Formation, belonging to the sedimentary environment of inner margin of the slope.

2.4.6.7 Trace Elements in Strata (Ore-Bearing)

Thirty-seven rock spectra were systematically collected from Changwu Formation of Xinqiao profile (PM001) including 17 collected from the first member and 20 from the second member. Besides, 19 rock spectra were collected from the third member of Changwu Formation of Shangangshang profile (PM002). Analysis was made on 14 trace elements, and statistics were made on the arithmetic mean values and

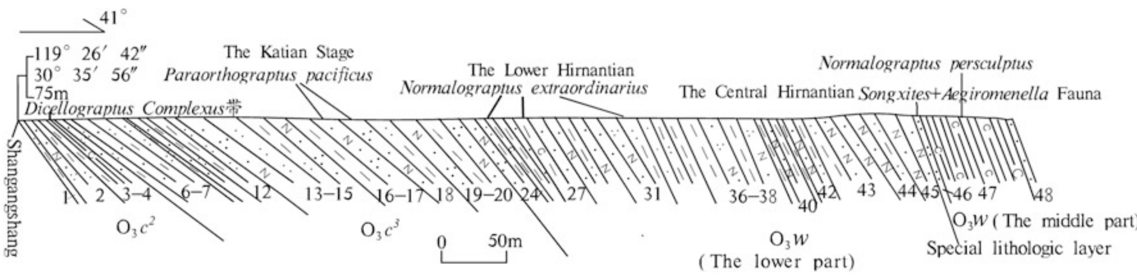


Fig. 2.74 Third member of Changwu Formation (O_3c^3)–middle and lower parts of Wenchang Formation (O_3w) profile in Shangangshang, Hanggai Town, Anji County, Zhejiang Province

concentration coefficients. The enriched elements of the three members of Changwu Formation vary slightly. The enriched trace elements in the first member are Bi and Pb, while those in the second member are Bi, Pb, and Zn. These two members share basically similar content of common enriched elements and other elements. The enriched elements in the third member are Bi, Sb, and Sn, and the content of other elements in the third member varies at a certain degree, indicating the influence of sedimentary environment on the distribution of trace elements in sediments.

2.4.7 Wenchang Formation (O_3w)–Standard Section of Lower Yangtze Region in the Upper Ordovician (Hirnantian)

The name Wenchang Formation (O_3w) was created by Zhejiang Regional Geological Survey Team (1965) in the south of Tantou Village, Wenchang Town, Chun'an County, Zhejiang Province. It was used by the preparation group of regional stratigraphic table of Zhejiang Province (1979). Wenchang Formation used by *Regional Geology of Zhejiang Province* (1989) referred to the former Wenchang Formation and the Yankou Formation collectively (including *Diplograptus bohemicus* and *Dalmanitina* cf. *mucronata* horizons and pebbled sandstone). Yankou Formation (including Zhangcunwu Formation and Yankou Formation) was adopted in the north Zhejiang. Late Ordovician Wenchang Formation was used in *Lithostratigraphy of Zhejiang Province* (1995) and northwest Zhejiang. In this Project, the name Wenchang Formation (O_3w) was still adopted according to the lithological characteristics of Shangangshang profile (PM002, Saoshe profile (PM008), and Zhuwukou profile (PM013) in Hanggai map sheet, and the geological observation traverse.

2.4.7.1 Lithostratigraphy

As the topmost Ordovician strata in the Area, Wenchang Formation (O_3w) is mainly distributed in the eastern part of Hanggai map sheet and the south-central part of Xianxia map sheet. In addition, it is sporadically exposed in the southeast and northwest corners of the Chuancun map sheet. The outcrop area is about 50.97 km^2, accounting for 4.01% of the bedrock area.

The characteristics of the lithology and lithologic association of Wenchang Formation (O_3w) are as follows. The lithology and lithologic association of the lower part: medium–thick laminated feldspathic quartz silty-fine sandstone interbedded with thin–medium laminated silty mudstone or their interbeds, and a small amount of grayish black micro-thin laminated graptolite-bearing silty mudstone. The lithology and lithologic association of the middle part: from bottom to top, 3-m-thick grayish siliceous nodule siltstone-bearing benthos fossils, and 8–10-m-thick black carbonaceous shale-bearing graptolites and sponge fossils. The lithology and lithologic association of the upper part: gray medium–thick laminated (blocky locally) medium-fine feldspathic quartz sandstone interbedded with gray–dark gray thin laminated graptolite-bearing silty mudstone. From bottom to top, the grain size: Rock clasts change from medium → fine → medium. The thickness of this formation is 363.04 m.

1. **Stratigraphic section**

The lithology of the lower and middle parts of Wenchang Formation (O_3w) is described by taking the example of the third member of Changwu Formation (O_3c^3)–the middle and lower parts of Wenchang Formation (O_3w) profile (Fig. 2.74) of Hanggai map sheet in Shangangshang, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

The upper part of Wenchang Formation Total thickness: >2.00 m

48. Khaki medium–thick laminated fine-silty sandstone owing to weathering. 2.00 m

Conformable contact

Special lithologic layer in the middle part of Wenchang Formation Total thickness: 11.76 m

47. Grayish black thin laminated carbonaceous shale, the thickness of a single layer: 2–6 cm generally, very thin horizontal bedding developing, 7–8 kinds of sponges produced, aboundant graptolite fossils obtained including: *Normalograptus persculptus* (Elles and Wood, 1907), *Normalograptus mirneyensis* (Obut and Sobolevskaya, 1967),*Normalograptus aff. indivisus* (Davies, 1929),*Normalograptus rhizinus* (Li and Yang, 1983), *Normalograptus madernii* (Koren and Mikhaylova, 1980), *Neodiplograptus* sp. nov. (= *Normalograptus* aff. *tamariscus* Nicholson, 1868), and *Normalograptus laciniosus* (Churkin and Carter, 1970). 8.77 m

46. Light grayish-yellow siltstone, interbedded with one siliceous mudstone nodule layer in the middle part with nodule size of 7–81 to 5–22 cm, rich in fossils such as brachiopodas, crinoid stems, trilobites and gastropods as well as *Aegiromena planissima* (Reed,1915) and *Mucronaspis* (Songxites) *wuning-ensis* (Lin). 3.09 m

Conformable contact

The lower part of Wenchang Formation Total thickness: 226.15 m

45. Grayish-yellow thick bedded–blocky quartz arkose, boulder clay visible locally, interbedded with a layer of silt with the thickness of about 1m in the middle-lower part. 30.88 m

44. Interbeds consisting of grayish yellow medium laminated quartz arkose and thin–medium laminated silty mudstone. The arkose: spherical weathering developing, the thickness of a single layer: 10–50 cm generally, argillaceous bands visible locally. The thickness of a single layer of the mudstone: 4–17 cm generally. 13.82 m

43. Grayish yellow thick laminated blocky lithic quartz sandstone, interbedded with 2 layers of silty mudstone with the thickness of a single layer of about 30 cm at the bottom. 32.67 m

42. Interbeds consisting of grayish yellow thin–medium laminated quartz arkose and silty mudstone. The arkose: globular weathering of φ =5–10cm developing, the thickness of a single layer: 8–23cm generally and 90cm locally. The silty mudstone: horizontal bedding developing, the thickness of a single layer: 1–30cm. 10.63 m

41. Weathering is brownish yellow mudstone with horizontal bedding, the thickness of a single layer: 2–5 cm thick and thin laminated siltstone interbedded with on top. 1.87 m

40. Interbeds consisting of brownish yellow thin–medium laminated quartz arkose and mudstone owing to weathering. The thickness of a single layer of the arkose: 8–25 cm. The mudstone: horizontal bedding developing, the thickness of a single layer: 2–12 cm. 6.95 m

39. Brownish yellow silty mudstone owing to weathering, interbedded with two layers of fine-silty sandstone upwards with respective thickness of 10 and 20 cm. The silty mudstone: horizontal bedding developing. 2.78 m

38. Two cycles constituting of gray thin–medium laminated, fine- to medium-grained, fine quartz arkose interbedded with mudstone. The respective thickness of a single layer of the arkose and the mudstone: 6–20 cm and 2–15cm. The ratio of the arkose to mudstone: ≈ 20:1. 19.27 m

37. Rhythmic interbeds consisting of caesious medium laminated quartz feldspathic silty-fine sandstone and thin–medium laminated mudstone. The sandstone: the thickness of a single layer: 12–40 cm, less obvious argillaceous micro-thin bands visible only on the top of local sandstone. The thickness of a single layer of the mudstone: 2–35 cm thick. 7.39 m

36. Interbeds consisting of ①caesious medium–thick laminated fine- to medium- grained quartz arkose and ②gray medium laminated fine sandstone and thin-to medium laminated mudstone, containing 8 cycles. The arkose: the thickness of a single layer: 10–115 cm. The fine sandstone; cross-bedding developing locally. The mudstone: the thickness of a single layer: 6–17 cm, horizontal bedding developing. 15.4 m

35. Gray thin–medium laminated quartz feldspathic fine sandstone, interbedded with silty mudstone. The fine sandstone: the thickness of a single layer: 10–17 cm generally and 70cm locally. The mudstone: the thickness of a single layer: 5–16 cm, tidal bedding and cross bedding developing. 9.77 m

34. Interbeds consisting of gray thin–medium laminated quartz arkose with thin laminated mudstone. The arkose: the thickness of a single layer: 7–18cm. The mudstone: containing a small amount of silt, no obvious bedding developing, the thickness of a single layer: 2–6 cm. 2.16 m

33. Caesious blocky quartz arkose. 2.54 m

32. Interbeds consisting of silty sandstone and silty mudstone are gray thin–medium laminated quartz feldspar silty sand. Silty-fine sandstone, the thickness of a single layer: 4–11cm thick, a small amount being 40cm. The silt in silty mudstone is fine banding with the thickness of a single layer: 2–20 cm. 2.22 m

31. Rhythmic interbeds consisting of caesious thick blocky–laminated quartz arkose, medium–thin laminated sandstone, and thin laminated silty mudstone, with a blocky–laminated sandstone as the upper part. The sandstone: the thickness of a single layer: 8–10cm generally and 150cm locally. The silty mudstone: the thickness of a single layer: 3–5cm. 8 rhythms totally. Fossils of chitinozoan *Belonechitina americana* (Taugourdeau, 1965) and the fossils of the flowing graptolite obtained: *Normalograptus extraordinarius* (Sobolevskaya 1974), *Normalograptus ojsuensis* (Koren et Mikhailova) (graptolite), and a small amount of *Normalograptus mirnyensis* (Obut et Sobolevskaya) and *Normalograptus normalis* (Lapworth). 27.36 m

30. Interbeds consisting of gray thin–medium laminated quartz arkose and silty mudstone. The arkose: the thickness of a single layer: 5–48 cm; The mudstone: containing many silty strips, which constitute flaser bedding, the thickness of a single layer: 1–8 cm generally and 12–20 cm locally. 2.58 m

29. Gray thick laminated quartz arkose, the thickness of a single layer: greater than 50 cm. 1.46 m

28. Gray medium–thick laminated quartz arkose intercalated with thin laminated silty mudstone. The arkose: medium–thick laminated in the lower part and thin–medium laminated in the upper part, the thickness of a single layer: 6–130 cm thick. The silty mudstone: the thickness of a single layer: 1–9 cm, the amount increasing upwards, fine-banded in the upper part. 8.18 m

27. Consisting of black carbonaceous mudstone, feldspathic quartz sandstone and silty mudstone, three cycles in total. The carbonaceous mudstone: graptolite visible. The lithic sandstone: containing syngenetic boulder clay locally, distributed in flat manner along the layer, length × width: (1–2) cm × (0.1–0.2) cm. The silty mudstone: fine strips of silt developing. Graptolite visible about 3m above the bottom of this layer. Chitinozoa *Belonechitina Americana* (Taugourdeau, 1965) and graptolite *Normalograptus extraordinarius* (Sobolevskaya, 1974) obtained. 7.77 m

26. Gray thick laminated quartz arkose, no sedimentary structure developing. 1.75 m

25. Interbeds consisting of thin–medium laminated sandstone and thin laminated mudstone, interbedded with a small amount of black thin laminated carbonaceous mudstone. The respective thickness of a single layer of the sandstone, the mudstone, and the carbonaceous mudstone: 6–22 cm, 1–7 cm, and 0.5–1 cm. 5.48 m

24. Interbeds consisting of dark gray thin–medium laminated carbonaceous mudstone and thin laminated quartz feldspathic fine sandstone and silty mudstone. The respective thickness of a single layer of the carbonaceous mudstone, the fine sandstone, and the silty mudstone: 2–19cm, 4–8cm, and 4–10cm. The upper part: interbeds consisting of caesious thin laminated silty mudstone and fine-silty sandstone, interbedded with carbonaceous mudstone, the respective thickness of a single layer of the sandstone and the mudstone: 2–7 cm and 2–6 cm. A large number of graptolite fossils visible in the black shale in the lower part of this layer including *Normalograptus extraordinarius* (Sobolevskaya, 1974), *Normalograptus ojsuensis* (Koren et Mikhailova), diplograptids gen. et sp. indet. *Neodiplograptus charis* (Mu et Ni 1983), and *Amplexograptus* sp. Indet. Chitinozoan fossil obtained such as *Belonechitina americana* (Taugourdeau, 1965)and *Eisenackitina songtaoensis* Chen et al. 2009. 2.91 m

--- Bottom of Hirnantian Stage

23. Gray thick laminated fine- to medium-grained quartz arkose, the thickness of a single layer: greater than 50 cm. 0.87 m

22. Rhythmic interbeds consisting of gray thin–medium laminated fine- to medium-grained quartz arkose and thin laminated mudstone. The arkose: the thickness of a single layer: 8–28 cm generally and 90cm locally. The mudstone: horizontal bedding developing, the thickness of a single layer: 2–10 cm. The ratio of the sandstone to the mudstone: (2–4):1 approximately. 6.25 m

21. Brownish yellow thick laminated fine- to medium-grained quartz arkose, intercalated with a layer of 5cm thick mudstone in the middle; horizontal bedding developing. 3.19 m

———————— Conformable contact ————————

The third member of Changwu Formation Total thickness: 161.39m

20. Three cycles of interbeds consisting of gray medium–thin laminated fine- to medium-grained and fine-grained quartz arkose and mudstone, the respective thickness of single layer of the arkose and the mudstone: 5–13cm and 2–14cm. The fossils of chitinozoan *Eisenackitina songtaoensis* Chen *et al*., 2009 obtained. 9.39 m

19. Brownish yellow thin laminated feldspathic quartz fine-grained sandstone owing to weathering, intercalatede with mudstone. The sandstone: diagonal bedding developing, the thickness of a single layer: 5–10 cm. The mudstone: no obvious bedding developing, the thickness of a single layer: 1–3 cm, flaky owing to weathering. The ratio of the sandstone to the mudstone: (3–10):1 approximately. The top: medium laminated sandstone intercalated thin laminated mudstone, the respective thickness of a single layer of the sandstone and the mudstone: 10–20 cm and 2–5 cm. 29.88 m

18. The upper and lower parts of this layer: interbeds consisting of gray medium laminated feldspathic

quartz fine sandstone and dark gray medium laminated silty mudstone. The fine sandstone: diagonal bedding visible locally, the thickness of a single layer: 11–18 cm. The mudstone: no obvious horizontal bedding developing, the thickness of a single layer: 10–34 cm. The middle part of this layer: interbeds consisting of thin laminated sandstone and mudstone, the respective thickness of a single layer of the sandstone and the mudstone: 5–9 cm and 2–7 cm. The 2–3 cm thick dark gray shale 2m above the bottom of this layer producing the following graptolites: the species possibly in the lower part of *Paraorthograptus pacificus* zone including *Paraorthograptus pacificus* (Ruedemann), *Paraorthograptus angustus* Mu et Lee 1977, *Amplexograptus disjuctus yangtzensis* Mu et Lin, and *Climacograptus chiai* Mu, 1949 (= *Amplexograptus hubeiensis* Mu et al.), as well as common species in *Dicellograptus complexus* zone including *amplexograptid gen.* et sp. indet. and *diplograptid gen.* et sp. Indet. No *Tangyagraptus* and *Diceratograptus* visible. 10.61 m

17. Dark gray medium–thin laminated mudstone intercalated with thin laminated feldspathic quartz fine sandstone. The fine sandstone: less obvious normal graded bedding developing upwards, cross bedding developing on the top locally, the thickness of a single layer: 3–10 cm. The mudstone: less obvious horizontal bedding developing, the thickness of a single layer: 4–10 cm generally and 22–40 cm locally, thin laminated carbonaceous mudstone constituting the top locally. The ratio of the mudstone to the sandstone: (2–4):1 approximately. Carbonaceous mudstone producing *Amplexograptus disjuctus yangtzensis* Mu et Lin and *Paraorthograptus pacificus* (Ruedemann), corresponding to the lower part of *Paraorthograptus pacificus* zone of the Wufeng Formtion in Yangtze Region. 5.71 m

16. Gray medium laminated feldspathic quartz silty-fine sandstone, intercalated with dark gray thin laminated mudstone. The silty-fine sandstone: dominating the lower part, the thickness of a single layer: 12–18 cm. The mudstone: the thickness of a single layer: 2–3 cm. The ratio of the sandstone to the mudstone: 20:1 approximately and 2:1 at the top. 16.61 m

15. Interbeds consisting of dark gray medium laminated silty mudstone and thin laminated feldspathic quartz sandstone. The silty mudstone: horizontal bedding developing locally, the thickness of a single layer: 11–22 cm. The sandstone: sedimentary structure uncertain, the thickness of a single layer: 5–10 cm. The ratio of the mudstone to the sandstone: (2–4):1 approximately. A layer of 20 cm thick sandstone intercalating in the middle part of the layer. 4.92 m

14. Rhythmic interbeds consisting of dark gray thin–medium laminated siltstone and gray feldspathic quartz fine sandstone. The siltstone and the mudstone mainly consisting the lower part and the upper part of a single rhythm respectively. The siltstone: the thickness of a single layer: 5–15 cm. The mudstone: horizontal bedding developing, the thickness of a single layer: 5–30 cm. The ratio of the sandstone to the mudstone: 1:1.5 approximately. 19.02 m

13. Interbeds consisting of gray medium laminated feldspathic quartz silty-fine sandstone and thin laminated silty mudstone. The silty-fine sandstone: graded bedding and less obvious parallel bedding developing, the thickness of a single layer: 16–32 cm. The silty mudstone: blocky, no bedding developing, the thickness of a single layer: 5–10 cm. The ratio of the sandstone to the mudstone: (3–5):1 approximately. 24.98 m

12. Interbeds consisting of yellow medium–thin laminated mudstone and argillaceous siltstone owing to weathering. The respective thickness of a single layer of the argillaceous siltstone and the mudstone: 5–25 cm and 5–12 cm. The ratio of the mudstone to the siltstone: 1.2:1 approximately. 13.45 m

11. Interbeds consisting of gray medium–thin laminated silty mudstone and feldspathic quartz silty-fine

sandstone. The silty-fine sandstone: no bedding developing, diagonal bedding visible occasionally, the thickness of a single layer: 6–20 cm. The silty mudstone: composed of argillaceous matter and a small amount of silt, the thickness of a single layer: 5–20 cm. The ratio of the silty-fine sandstone and the mudstone: 1:1 approximately. 0.75 m

10. Dark gray thin laminated silty mudstone intercalated with micro laminated feldspathic quartz sandstone. The silty mudstone: no obvious bedding developing. The sandstone: diagonal bedding developing, the thickness of a single layer: 1–2 cm. The ratio of the silty mudstone and the siltstone: 20:1 approximately. 1.13 m

9. Interbeds consisting of gray thin laminated silty mudstone and feldspathic quartz silty-fine sandstone. The sandstone bottom is in a soothing wave shape, with occasional oblique bedding and the single layer of the rock layer is 2–5 cm thick. The ratio is about 1. 5.73 m

8. Gray thin laminated silty mudstone intercalated with micro laminated siltstone. The silty mudstone: the thickness of a single layer: 3–5 cm, very thin horizontal bedding developing. The siltstone: the thickness of a single layer: 1–2 cm. The ratio of the mudstone to the siltstone: (30–50):1 approximately. 2.64 m

7. Interbeds consisting of gray thin–medium laminated feldspathic quartz fine sandstone and thin–medium laminated silty mudstone. The respective thickness of the fine sandstone and the silty mudstone: 5–24 cm and 2–17 cm. The ratio of the fine sandstone to the silty mudstone: 2:1. 16.07 m

6. Interbeds consisting of gray medium laminated feldspathic quartz silty-fine sandstone and thin laminated mudstone. The silty-fine sandstone: the thickness of a single layer: 23–40 cm. The mudstone: no bedding developing, the thickness of a single layer: 6–10 cm. The ratio of the sandstone and the mudstone: 2–3:1. Differential weathering and costate landform shown in the surface, the siltstone protruding from the surface. 2.02 m

5. Interbeds consisting of gray thin–medium laminated argillaceous siltstone and thin laminated mudstone. The argillaceous siltstone: the thickness of single bed: 7–14 cm, undulating uneven bottom, groove and gravity casts developing. The thickness of a single layer of the mudstone: 3–10 cm. The ratio of the argillaceous siltstone to the mudstone: (1–2):1. 4.43 m

4. Interbeds consisting of gray thick–medium laminated feldspathic quartz silty-fine sandstone and thick–medium laminated mudstone. The thickness of a single layer of the silty-fine sandstone: 16–63 cm. The mudstone: horizontal bedding visible locally, the thickness of a single layer: 5-18cm. The ratio of the silty-fine sandstone to the mudstone: (2–3):1. 4.16 m

——————— Conformable contact ———————

The second member of Changwu Formation Total thickness: > 15.73 m

3. Gray - dark gray thin–medium laminated mudstone intercalated with thin laminated feldspathic quartz fine sandstone and black micro laminated carbonaceous shale. The mudstone: very thin horizontal bedding developing. The fine sandstone: the thickness of a single layer: 2–5 cm, The ratio of the mudstone to the sandstone: 3–5:1. The carbonaceous shale: the thickness of a single layer: 0.2–8 cm, rich in abundant graptolites of *Dicellograptus complexus* zone including *Amplexograptus disjunctus yangtzensis* Mu et Lin, *Amplexograptus suni* (Mu), *Appendispinograptus supernus* (Elles and Wood), *Appendispinograptus venustus* (Hsu), *Climacograptus hastatus* (Hall, 1902), *Yinograptus disjunctus* (Yin et Mu), *Paraplegmatograptus uniformis* Mu, and *Leptograptus extremus* Mu et Zhang *et al*. 7.41 m

2. Interbeds consisting of grayish thin–medium laminated silty mudstone and thin–medium laminated

feldspathic quartz silty-fine sandstone. The silty-fine sandstone: the thickness of a single layer: 6-12 cm. The silty mudstone: the thickness of a single layer: 7–20 cm, very thin horizontal bedding visible locally. The ratio of the silty-fine sandstone to the silty mudstone is 1:(2–3). 6.52 m

1. Interbeds consisting of gray thin–medium laminated silty mudstone and thin laminated feldspathic quartz silty-fine sandstone. The respective thickness of a single layer of the silty-fine sandstone and the silty mudstone: 2–7 cm and 8–28 cm. The ratio of themis 1:(2–3). 2.80 m

The lithology of the special lithological layer in the middle part of Wenchang Formation (O_3w) is described by taking the example of the profile of the special lithological layer in the middle of the Late Ordovician Wenchang Formation (O_3w) of Zhuwukou, Hanggai Town, Anji County, Zhejiang Province (Fig. 2.75). The details are as follows:

The upper part of Wenchang Formation (O_3w) Total thickness: ＞5.42 m

6. Gray thick laminated blocky fine-grained quartz arkose intercalated with thin laminated siltstone. The thickness of a single layer: 100–200 cm. The thickness of a single layer of the siltstone: 1–2 cm. 5.42 m

Special lithological layer of Wenchang Formation (O_3w) Thickness: 10.88 m

The second special lithological bed Thickness: 10.43 m

5. Black thin laminated carbonaceous siliceous silty mudstone, taxitic after weathering with a small amount of black mudstone remaining, very thin horizontal bedding developing, rich in graptolite fossils fragments.2.13 m

4. Gray medium laminated fine-grained quartz arkose. 0.36 m

3. Interbeds consisting of gray medium laminated fine-grained quartz arkose and thin–medium laminated silicon-bearing silty mudstone. The thickness of a single layer of the arkose: generally 10–20 cm. The silicon-bearing silty mudstone: the thickness of a single layer: generally 2–15 cm, very thin horizontal bedding developing. The two components featuring similar proportion. 0.80 m

2. Black thin laminated carbonaceous siliceous silty mudstone, very thin horizontal bedding developing, rich in graptolite fossils and sponges followed by a small amount of chitosan. 7.14 m

Graptolites: *Nomalograptus angustus* (Pemer)

Sudburigraptus? Similaris Chen (*in press*)

Chitinozoan: *Eisenackitina rectangularis Zaslavskaya* 1983

The first special lithological bed Total thickness: 0.45m

1. Grayish cataclastic siltstone after diagenesis, brachiopoda fragments visible. ＞ 0.45 m

——————— Conformable contact ———————

Lower part of Wenchang Formation (O_3w) Total thickness: ＞5.00 m

0. Gray medium–thick laminated medium- to fine-grained feldspar lithic sandstone intercalated with thin laminated silty mudstone. The respective thickness of a single layer of the sandstone and the silty mudstone: 38–150 cm and 1–3 cm. 5.00 m

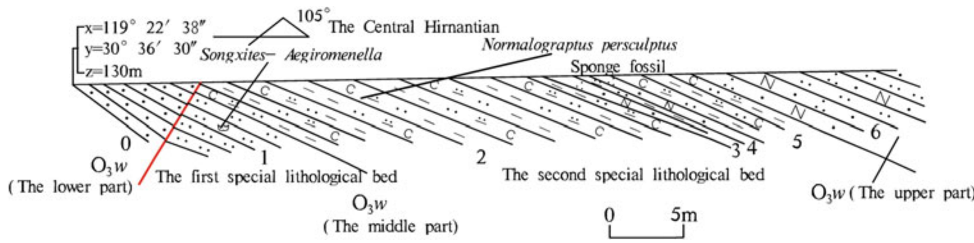


Fig. 2.75 Profile of the special lithological layer in the middle part of the Late Ordovician Wenchang Formation (O_3w) in Zhuwukou, Hanggai Town, Anji County, Zhejiang Province

The lithology of the upper part of Wenchang Formation (O_3w) is described by taking Ordovician Wenchang Formation (O_3w) profile (Fig. 2.76) of Hanggai map sheet in Saoshe Village, Hanggai Town, Anji County, Zhejiang Province. The details are as follows:

The first member of Xiaxiang Formation Total thickness: >64.20 m

65. Covering, black carbonaceous shale visible on the slopes about 200m to the southwest. 18.58 m

64. Gray medium–thick laminated feldspathic quartz fine sandstone. 32.99 m

63. Interbeds consisting of gray thin–medium laminated sand-bearing shale and black carbonaceous siliceous mudstone. The mudstone: the thickness of a single layer: 5–20 cm, very thin horizontal bedding developing. 6.69 m

62. Gray medium–thick laminated feldspathic quartz fine sandstone. The thickness of a single layer: 40–150 cm. One layer of medium laminated sandstone respectively intercalating in the top and bottom of the layer; 2–10 cm thick shale intercalating between the sandstone. 5.37 m

61. Interbeds consisting of black thin laminated carbonaceous silty mudstone and grayish shale. The carbonaceous silty mudstone: the thickness of a single layer: 1–3 cm, abundant fossils of graptolite obtained includes: *Akidograptus ascensus* Davies 1929, *Normalograptus laciniosus* (Churkin and Carter, 1970), *Normalograptus rhizinus* (Li and Yang, 1983), and *Nomalograptus ojsuensis*, *Normalograptus angustus* (Perner, 1895). 0.57 m

--- Ordovician - Silurian Boundary

——— Conformable contact ———

The upper part of Wenchang Formation Total thickness: 125.03m

60. Gray blocky–laminated feldspathic quartz sandstone intercalated with micro laminated shale. A single layer of sandstone: the thickness: >200cm, less obvious parallel bedding developing, intercalated with a layer of 18cm thick black shale in the middle part. The shale: very thin horizontal bedding developing. 16.19 m

59. Gray medium laminated feldspathic quartz fine sandstone intercalated with micro–thin laminated siltstone or silty mudstone. The thickness of a single layer of the fine sandstone: 10–40 cm. The siltstone or silty mudstone: very thin horizontal bedding developing, the thickness of a single layer: 3–30 mm. 9.14 m

58. Dark gray thin laminated silty mudstone containing a small amount of micro laminated carbonaceous

matter and pyrite, very thin horizontal bedding developing. The fossils of the graptolites of *Normalograptus persculptus* zone at the end of Hirnantian obtained includes: *Normalograptus persculptus* (Elles & Wood), *Normalograptus avitus* (Davies, 1929), *Normalograptus ojsuensis* (Koren and Mikhailova, 1980), *Normalograptus rhizinus* (Li and Yang, 1983), *Normalograptus angustus* (Perner, 1895, *Normalograptus* cf. *minor* Huang 1982, *Normalograptus laciniosus*, *Normalograptus* (Koren and Melchin, 2000), *Glyptograptus* aff. *tamariscus* (Nicholson, 1868) sensu Koren and Melchin 2000, *Normalograptus zhui* (Yang, 1964), *Sudburigraptus? angustifolius* Chen et Lin 1978, *Normalograptus normalis* Lapworth 1877 and *Normalograptus persculptus, Atavograptus* sp. nov. etc. No *Akidograptus ascensu* is visible owing to abundant N. *avitus*. The age is belonging to the final Hirnantian *Normalograptus persculptus* graptolite belt. 2.06 m

57. Gray–purple-gray thick blocky–laminated feldspathic quartz fine sandstone intercalated with medium–thin laminated siltstone or silty mudstone. The thickness of a single layer of the fine sandstone: 100–200 cm. The siltstone: the thickness of a single layer: 3–15 cm, very thin horizontal bedding developing. 12.05 m

56. Interbeds consisting of gray thin–medium laminated feldspathic quartz fine sandstone and black micro laminated carbonaceous shale. Parallel bedding developing in the fine sandstone. The shale: mostly 1–2 mm thick, containing carbon. 1.41 m

55. Gray blocky–laminated feldspathic quartz silty-fine sandstone, the thickness of a single layer: > 1 m. 4.66 m

54. Interbeds consisting of gray thin laminated fine-silty sandstone and micro laminated black carbonaceous siliceous mudstone. The fine-silty sandstone: very thin horizontal bedding developing, carbon and pyrite cast distributed along the bedding. The mudstone: containing carbonized graptolites, the following fossils obtained: *Normalograptus mirneyensis* Obut et Sobolevskaya and *Normalograptus laciniosus* Churkin et Carter, *Sudburigraptus angustifolius* Chen et Lin. 6.11 m

53. Gray thick laminated fine sandstone interbedded with silicon-bearing silty mudstone. Less obvious parallel bedding developing in the sandstone. 1.62 m

52. Gray thin laminated feldspathic quartz fine sandstone intercalated with micro laminated carbonaceous shale. The fine sandstone: the thickness of a single layer: 1–3 cm thick, very thin horizontal bedding developing, a small amount of pyrite casts distributed along the bedding surface. The carbonaceous shale: containing graptolite fossil fragments, the thickness of a single layer: 1–3 mm. 1.44 m

51. Gray blocky–laminated feldspathic quartz sandstone intercalated with micro–thin laminated mudstone. The sandstone: less obvious parallel bedding developing, the thickness of a single layer: > 2 m. 43.02 m

50. Gray medium laminated feldspathic quartz sandstone with the thickness of a single layer of 30–40 cm. A single layer of the sandstone: intercalated with thin strips and lenses of siltstone 10–20 cm above the bottom, then the sandstone becoming pure upwards. 3.00 m

49. Interbeds consisting of gray thin–medium laminated argillaceous siltstone, and black shale bearing thin laminated siliceous carbonaceous matter and gray siltstone. The argillaceous siltstone: the thickness of a single layer: 5–15 cm, horizontal bedding developing. The shale: the thickness of a single layer: 3–10 cm, rich in graptolites, horizontal bedding developing. *Monograptid* gen. & sp., *Normalograptus* sp. obtained. 2.06 m

48. Gray thick laminated feldspathic quartz fine-silty sandstone intercalated with gray - dark gray thin laminated argillaceous siltstone and shale. The fine-silty sandstone: the thickness of a single layer: 50–150 cm, smooth layer surface. The argillaceous siltstone: the thickness of a single layer: 0.5–5 cm, very thin horizontal

bedding developing. The fossils of the following graptolites obtained in the shale at the bottom: *Normalograptus avitus* (Davies), *Normalograptus* cf. *avitus* (Davies 1929, *Normalograptus* cf. *laciniosus* (Churkin and Carter), and *Normalograptus mirneyensis* (Obut and Sobolevskaya). The fossils of the following graptolites obtained in the shale on top: Normalograptus rhizinus (Li and Yang), Normalograptus avitus (Davies, 1929), Normalograptus cf. avitus (Davies), Normalograptus laciniosus (Churkin & Carter), and Normalograptus mirneyensis (Obut & Sobolevskaya), Neodiplograptus sp. 22.27 m

———————— Conformable contact ————————

Special lithological layer in the middle part of Wenchang Formation Total thickness: >7.28 m

47. Grayish-black thin laminated carbonaceous shale, in which micro-grain horizontal bedding is developed, rich in graptolites. 7.28 m

2. **Lithological characteristics**

The lithology of Wenchang Formation (O_3w) is mainly characterized by medium–thick laminated feldspathic quartz sandstone, feldspathic quartz fine-silty sandstone, followed by thin–medium laminated silty mudstone, thin laminated argillaceous siltstone, silty siltstone, and carbonaceous mudstone.

(1) The feldspathic quartz sandstone: gray, composition: quartz (45–55%), feldspar (10–25%), and detritus (10–25%), subangular to sub-well rounded, grain size: 0.1-0.5 mm, argillaceous cementation.
(2) The feldspathic quartz fine-silty sandstone: gray, the main components: quartz and feldspar (55–80%), subangular to sub-well rounded, grain size: 0.05–0.1 mm generally and 0.1–0.2 mm locally, argillaceous cementation, the thickness of a single layer: 10–40 cm and 50–150 cm, layer surface: even.
(3) The argillaceous siltstone: gray–dark gray, composition: quartz and feldspar (60–75%) and argillaceous matter (25–40%), thickness of a single layer: 0.5–8 cm, horizontal bedding developing generally, cross-bedding developing locally.
(4) The silty mudstone: grayish gray; composition: argillaceous matter (40–60%) and a small amount of silt (20–40%); composition of silt: feldspar and quartz; grain size: 0.01–0.05 mm, subangular to sub-well rounded; horizontal bedding developing.
(5) The carbonaceous shale: black, composition: argillaceous matter (75–80%), silt (10–15%), and carbonaceous matter (5–15%), the thickness of a single layer: 2–6 cm generally, very thin horizontal bedding developing, rich in graptolite fossils and sponge.

3. **Basic sequences**

There are five types of basic sequences developing in Wenchang Formation (O_3w) (Fig. 2.77).

(1) Composed of ① gray thick laminated feldspathic quartz sandstone and ② rhythmic interbeds of thin–medium laminated silty mudstone, intercalated with ③ thin–medium laminated fine-silty sandstone. The sandstone: mainly composed of quartz and feldspar, low maturity, subangular to subrounded, the thickness of a single layer: 50–80 cm generally. The fine-silty sandstone and silty mudstone: 4–12 cm thick generally and 15–20 cm thick locally per single bed, horizontal bedding generally or micro-fine-silty strips developing in silty mudstone. The thickness of the thick laminated sandstones is 2–5 times that of the rhythmic layers generally. Therefore, the basic sequences of this type are common basic sequences.
(2) Distributed in the middle-lower and upper parts in Wenchang Formation (O_3w), composed of the interbeds of ① gray thin–medium laminated silty-fine sandstone and ② thin laminated silty mudstone, intercalated with

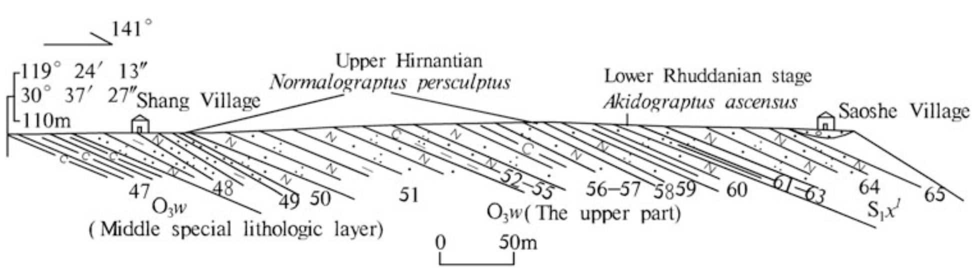


Fig. 2.76 Profile of the upper part of Ordovician Wenchang Formation (O_3w) in Saoshe Village, Hanggai Town, Anji County, Zhejiang Province

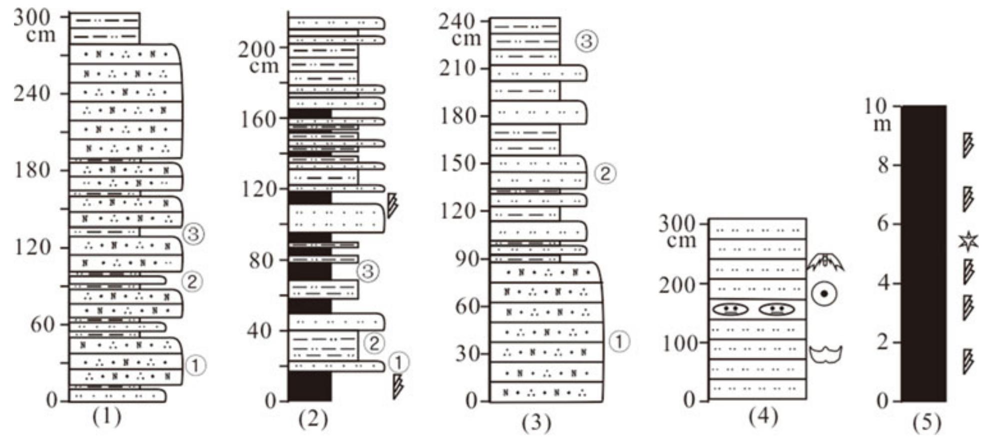


Fig. 2.77 Basic sequences of Wenchang Formation (O_3w)

black thin laminated silicon-bearing carbonaceous shale. The silty-fine sandstone: mainly composed of feldspar and quartz (60–85%), and argillaceous matter (15–40%), the thickness of a single layer: 5–15 cm. The carbonaceous shale: composed of argillaceous matter (70–75%) and a small amount of carbonaceous matter (10–15%) and silt (10%), the thickness of a single layer: 3–10 cm, rich in graptolites, very thin horizontal bedding developing. The ratio of the silty-fine sandstone and the mudstone is 1–5:1 approximately.

(3) Developing in the lower and middle-upper parts of Wenchang Formation (O_3w), composed of ① gray thick blocky–laminated medium-grained feldspathic quartz sandstone, and rhythmite consisting of ② thin–medium laminated fine-silty sandstone and ③thin–medium laminated silty mudstone. The sandstone: mainly composed of quartz and feldspar, low maturity, subangular to subrounded. The thickness of single layer of medium-grained sandstone: 50–200 cm generally. The fine-silty sandstone and silty mudstone: the clasts mainly composed of feldspar and quartz, the thickness of single bed: 2–15 cm generally, horizontal bedding or less obvious bedding developing in silty mudstone. The thickness of the thick blocky–laminated sandstone is generally 3–10 times that of the rhythmic bed.

(4) Developing in the middle part of Wenchang Formation (O_3w), composed of ① grayish medium laminated siltstone and ② silicon-bearing mudstone nodule layers, the main components: feldspar, quartz silt followed by a small amount of argillaceous matter, rich in benthic organisms including trilobites, deepwater brachiopoda, pteropods, and gastropods. The nodules: (5–9) × (15–25) cm in size, circle structures developing. Therefore, the basic sequences of this type are of non-cyclic monotonous type.

(5) Developing in the middle part of Wenchang Formation (O_3w), composed of black silicon-bearing carbonaceous mudstone, rich in graptolites and sponge fossils, belonging to monotonous basic sequences.

The main sediments of Wenchang Formation (O_3w) are thick blocky–laminated feldspathic quartz silt and fine sand, followed by thin–medium laminated silt and fine sand, all of which are terrigenous clasts. Part of the silt is rich in benthos fossils. All these indicate clastic sedimentary rock facies of shallow shelf in weak oxidization environment. The graptolite-bearing carbonaceous shale in the lower and upper parts of Wenchang Formation (O_3w) features positive excursion of stable isotopes of organic carbon and monotonous graptolite species, indicating subcompensational basin facies of bathyal stagnant reduction environment in Hirnantian global glacial period. The 8–10-m-thick black carbonaceous graptolite-bearing shale in the middle part of Wenchang Formation (O_3w) features no positive excursion of the stable isotopes of organic carbon and many kinds of sponges and graptolites, indicating subcompensational basin facies of bathyal reduction environment in normal climate.

2.4.7.2 Sequence Stratigraphy

According to the characteristics of the lithology, paleontology, lithofacies association, and sequence boundary of Shangangshang profile (PM002) and Saoshe profile (PM008) in Hanggai map sheet, there is one third-order sequence Sq24 (Fig. 2.78) in Wenchang Formation (O_3w), which belongs to the second-order sequence SS8.

***Third-order sequence Sq*24**

It includes transgressive systems tract (TST), starved section (CS), and highstand systems tract (HST). The bottom of the sequence is the conformity interface between thick laminated sandstone of Wenchang Formation and the silty mudstone of the third member of Changwu Formation. The top of the sequence is the conformity interface between thick laminated sandstone of Wenchang Formation and carbonaceous silty mudstone of Xiaxiang Formation. The bottom and top are both type-II boundaries.

TST is located in the lower part of Wenchang Formation, with the thick blocky–laminated feldspathic quartz

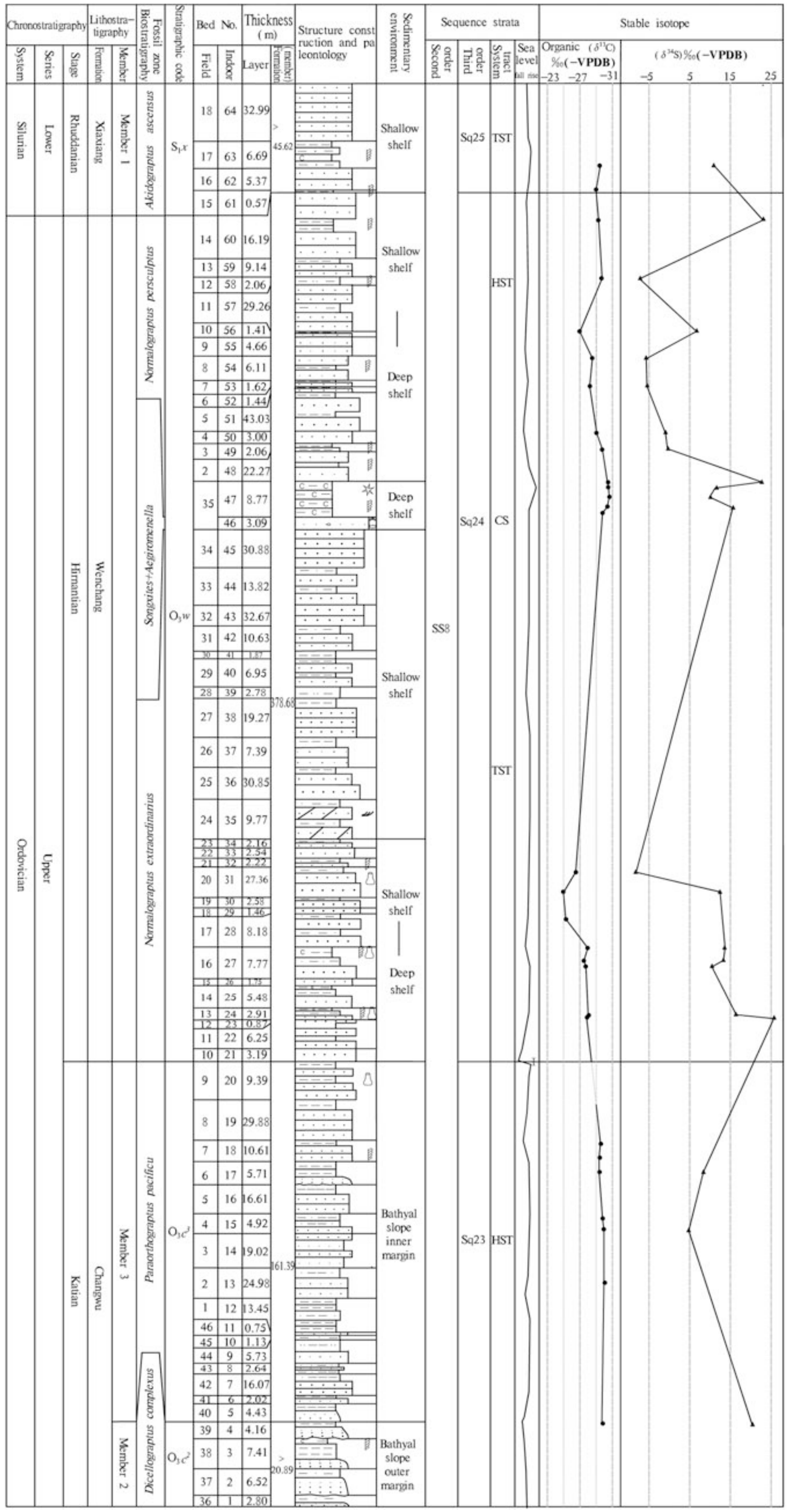


Fig. 2.78 Sequence of stratigraphic framework of Ordovician Wenchang Formation in the area

sandstone as its main component and the medium laminated fine-silty sandstone and carboniferous mudstone-bearing graptolite and chitinozoan, which are distributed alternatively as its minor components. The main component is of the clastic sedimentary rock facies of shallow shelf with abundant sources of terrigenous clasts. The minor components are of deepwater mudstone facies. All these indicate the two kinds of sedimentary environment. The positive drift of $\delta^{13}C‰$ in the carbonaceous mudstone indicates that the Area was affected by the global glacial events in the Late Ordovician. The monotonous genera and species of the graptolites obtained in the multilayers of the shale also indicate that glacier climate is unfavorable for the evolution of the genera and species of organisms. TST of Sq24 features frequent oscillation of the sea level owing to the glaciation.

CS is located in the middle part of Wenchang Formation and consists of siltstone and carbonaceous mudstone, belonging to the shallow shelf–deep shelf facies of siliceous-argillaceous matter-bearing terrigenous clasts. The lower part of CS is composed of grayish siltstone intercalated with a layer of siliceous mudstone nodules. It is rich in the fossils of brachiopoda, trilobites, cephalopods, and crinoid but features monotonous genera and species and small figure of the organisms, indicating the sedimentation above the oxidation zone of shallow shelf. The upper part of the CS is composed of carbonaceous silty mudstone and contains abundant graptolites and well-preserved sponges of 7–8 genera and species in the middle part. Furthermore, the carbonaceous shale in the upper part of CS features no positive excursion of $\delta^{13}C‰$. All these indicate the mudstone facies between the oxidation and reduction zones of deep shelf. Therefore, the CS indicates that there was a rapid sea level rise and the maximum transgression reached during the interglacial period, when the low-velocity sedimentary strata were strongly scarce.

HST is located in the upper part of Wenchang Formation and mainly composed of medium–blocky–laminated fine-silty sandstone, thin–medium laminated siltstone, and carbonaceous mudstone. The mudstone contains graptolite, with horizontal bedding developing. HST features similar rock association with the lower part of Wenchang Formation. Besides, the carbonaceous mudstone also features positive excursion of $\delta^{13}C‰$. Therefore, HST is similar to the lower part of Wenchang Formation.

To sum up, the third-order sequence (Sq24) formed in shallow shelf–the deep shelf. It was controlled by the Hirnantian glacier event and the crustal movement, and the product is subjected to both climate and crustal stress field. Furthermore, it is a sequence of aggradation type.

2.4.7.3 Biostratigraphy and Chronostratigraphy

Wenchang Formation was deposited during the Late Ordovician Hirnantian global glacial period and experienced two major glacial periods and one interglacial period. As a result, a different biocenosis formed. In this Project, two fossil zones and one shellfish fauna were identified, i.e., *Normalograptus extraordinarius* graptolite zone, *Songxites–Aegiromenella* fauna, and *Normalograptus persculptus* graptolite zone from bottom to top. Among them, chitinozoan fossils were found in *Normalograptus extraordinarius* graptolite zone, no graptolite was discovered in *Songxites–Aegiromenella* fauna, and sponge fossils were found in *Normalograptus persculptus* graptolite zone.

1. ***Normalograptus extraordinarius* zone**

Normalograptus extraordinarius graptolite zone is located in the lower part of Wenchang Formation. The large fossils and microfossils obtained are graptolite fossils and chitinozoan fossils, respectively, and they are produced in the thin laminated black carbonaceous shale. The graptolite fossils obtained include main fossils of *Normalograptus extraordinarius* (Sobolevskaya 1974) (Figs. 2.79 and 2.80) and associated graptolites including *Normalograptus ojsuensis* (Koren and Mikhailova, 1980), *Normalograptus mirnyensis* (Obut and Sobolevskaya, 1967), *Normalograptus normalis* (Lapworth), *Neodiplograptus charis* (Mu and Ni 1983), *Paraclimacograptus innotatus, and Normalograptus laciniosus* (Churkin and Carter 1970). Among them, *Normalograptus* cf. *persculptus* (Elles and Wood, 1907) is small in figure. The chitinozoan fossils obtained include

Fig. 2.79 *Normalograptus extraordinarius* graptolite (Sobolevskaya 1974)

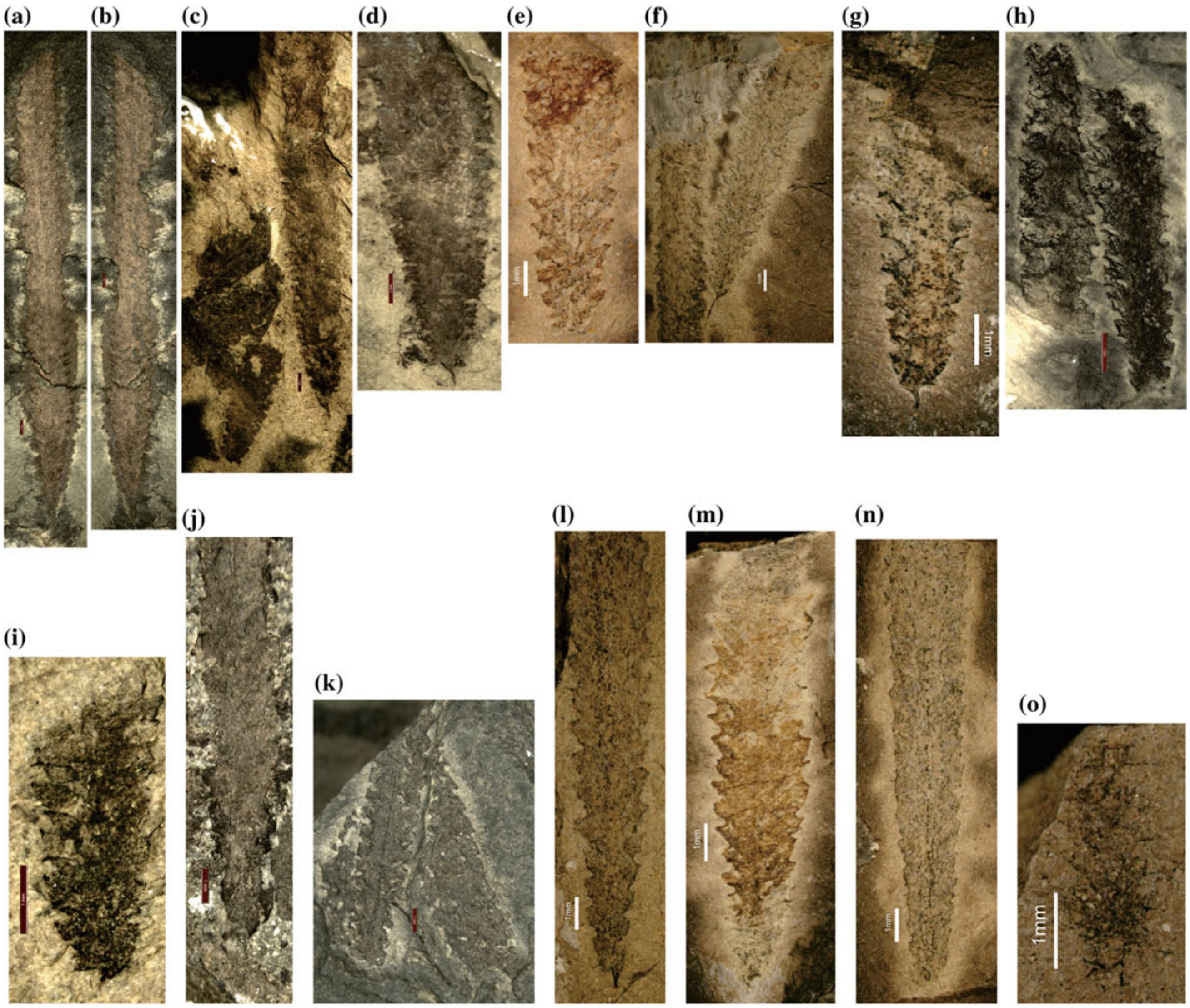


Fig. 2.80 *Normalograptus extraordinarius* graptolite zone in the lower part of Wenchang Formation (O_3w): **a** *Normalograptus extraordinarius* (Sobolevskaya 1974) (Pm002-20-5a); **b** *Normalograptus extraordinarius* (Sobolevskaya 1974) (Pm002-20-6-1a); **c** *Normalograptus extraordinarius* (Sobolevskaya 1974) (Pm002-20-13-3); **d** *Normalograptus extraordinarius* (Sobolevskaya, 1974) (Pm002-20-18-3); **e** *Normalograptus extraordinarius* (Sobolevskaya, 1974) (Pm002-wh 13-11-1a); **f** *Normalograptus extraordinarius* (Sobolevskaya 1974) (Pm002-wh13-1); **g** *Normalograptus ojsuensis* (Koren et Mikhailova) (Pm002-wh13-15); **h** *Normalograptus ojsuensis* (Koren et Mikhailova) (Pm002-20-8-4a); **i** *Normalograptus ojsuensis* (Koren et Mikhailova) (Pm002-20-23); **j** *Normalograptus mirnyensis* (Obut et Sobolevskaya) (Pm002-20-8-2); **k** *Normalograptus normalis* (Lapworth) (Pm002-20-26-2); **l** *Neodiplograptus charis* (Mu et Ni, 1983) (Pm002-wh13-45); **m** *Neodiplograptus charis* (Mu et Ni,1983) (Pm002-wh13-71); **n** *Neodiplograptus charis* (Mu et Ni, 1983) (Pm002- wh13-60); **o** *Paraothograptus pacificus* (Ruedemann) (Pm002-wh13-50)

Belonechitina americana (Taugourdeau 1965) and *Eisenackitina songtaoensis* Chen et al., which belongs to *Eisenackitina songtaoensis* chitinozoan zone. Since the chitinozoan zone features a time span, it can only be used for reference in chronostratigraphy.

2. ***Songxites–Aegiromenella* fauna**

Songxites–Aegiromenella fauna is located in the first special lithological bed in the middle part of Wenchang Formation, and the large fossils obtained are all the fossils of benthic shellfish including *Mucronaspis* (*Songxites*) *wuningensis* (Lin) (Fig. 2.81d, e) and *Aegiromena* (*Aegiromenella*) *planissima* (Reed 1915) (Fig. 2.81a, b, c), as well as gastropod and crinoid stem. The age of this fauna is between the ages of *Normalograptus extraordinarius* zone and *Normalograptus persculptus* graptolite zone. This fauna is called Hernantabean faunain in the Upper Yangtze Region and formed in the age of the lower part of *Normalograptus persculptus* graptolite zone. This fauna corresponds to the

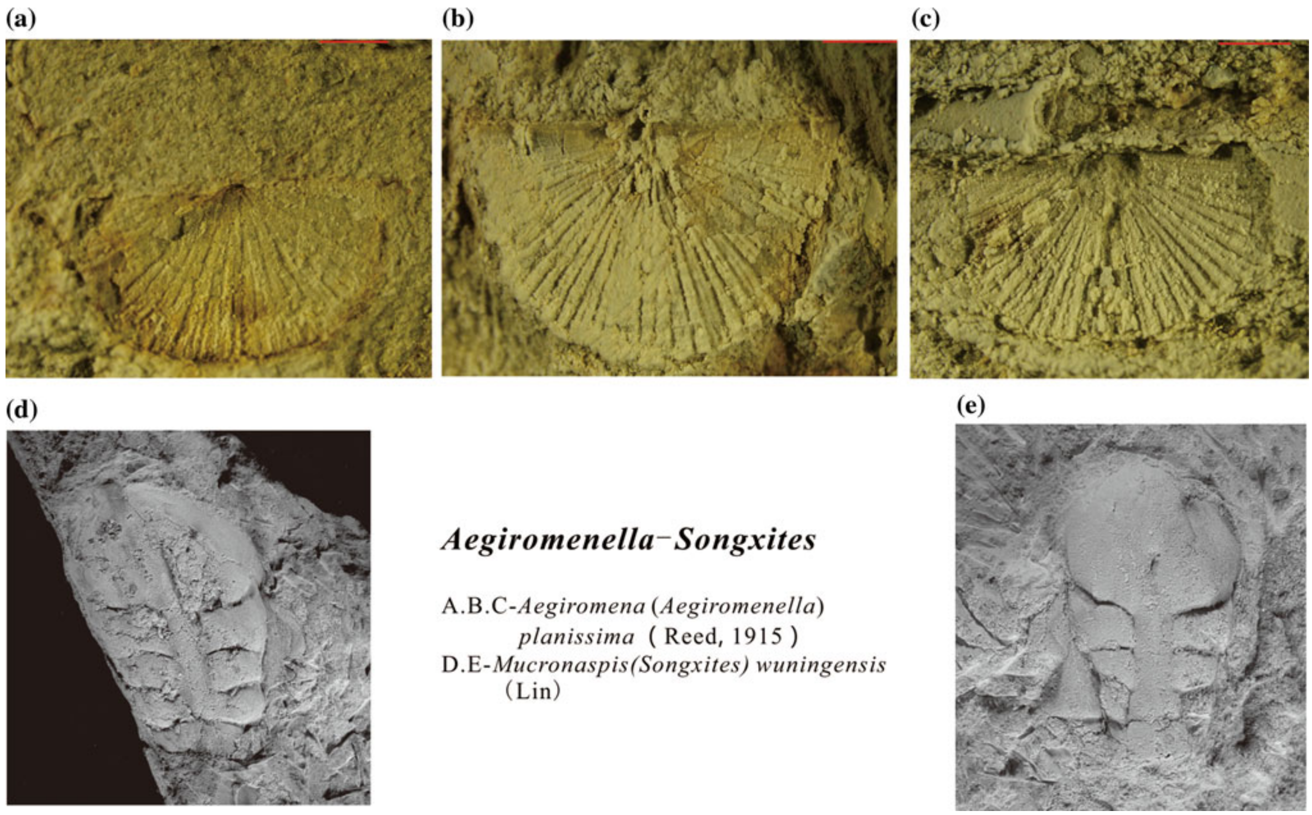


Fig. 2.81 *Songxites–Aegiromenella* fauna in the first special lithological bed in the middle part of Wenchang Formation (O_3w)

Guanjianqiao bed in the Wangjiawan profile of Hubei Province and is the product of the life explosion during the sea level rise period in Hirnantian interglacial period.

3. ***Normalograptus persculptus*** **graptolite zone**

Normalograptus persculptus graptolite zone is located in the upper part and the second special lithological bed in the middle part of Wenchang Formation, and the large fossils obtained are mainly graptolite fossils, which are all produced in the micro-thin laminated black carbonaceous shale. The 10-m-thick black shale in the second special lithological bed in the middle part of Wenchang Formation features the most abundant fossils including the main graptolite fossils of *Normalograptus persculptus* (Elles and Wood E M 1907, Fig. 2.82a) and associated graptolites such as *Normalograptus parvulus* (Lapworth), *Normalograptus laciniosus* (Churkin and Carter 1970), *Normalograptus angustus* (Perner 1895), *Neodiplograptus charis* (Mu et Ni 1983), *Normalograptus rhizinus* (Li and Yang 1983), *Neodiplograptus shanchongensis* (Li 1984), *Normalograptus aff. indivisus* (Davies 1929), *Normalograptus mirneyensis* (Obut and Sobolevskaya 1967), *Normalograptus zhui* (Yang 1964), *Normalograptus* aff. *tamariscus Nicholson*, 1868, *Normalograptus acceptus* (Koren and Mikhaylova 1980), "*Glyptograptus*" *jerini* Koren and Melchin 2000, and *Normalograptus madernii* (Koren and Mikhaylova 1980) (Figs. 2.82 and 2.83). The genera and species of the fossils decrease upward. Especially in carbonaceous shale with a positive excursion of $\delta^{13}C‰$, the graptolite fossils feature monotonous genera and species and increased individual figure. This may be affected by glaciation.

4. **First-ever global discovery of fossil sponges of Late Ordovician**

The fossils of the sponge of multiple genera and species were first discovered (Fig. 2.84) in the Late Ordovician Wenchang Formation in the Area. This is of great significance in the following three aspects. (1) They are the ones firstly discovered in this period. (2) They are of the Burgess Shale type, and the sponges of this type were previously believed to have already been extinct during the first main extinction event in the early stage of the Late Ordovician Hirnantian. The sponge in the Area developed together with the *Normalograptus persculptus* graptolite zone at the end of the Hirnantian Stage, indicating that the sponge extended to the late stage of the Hirnantian Stage. (3) The sponge fossils should have developed in an oxygen-rich environment, while the sponge in the Area developed in an anoxic

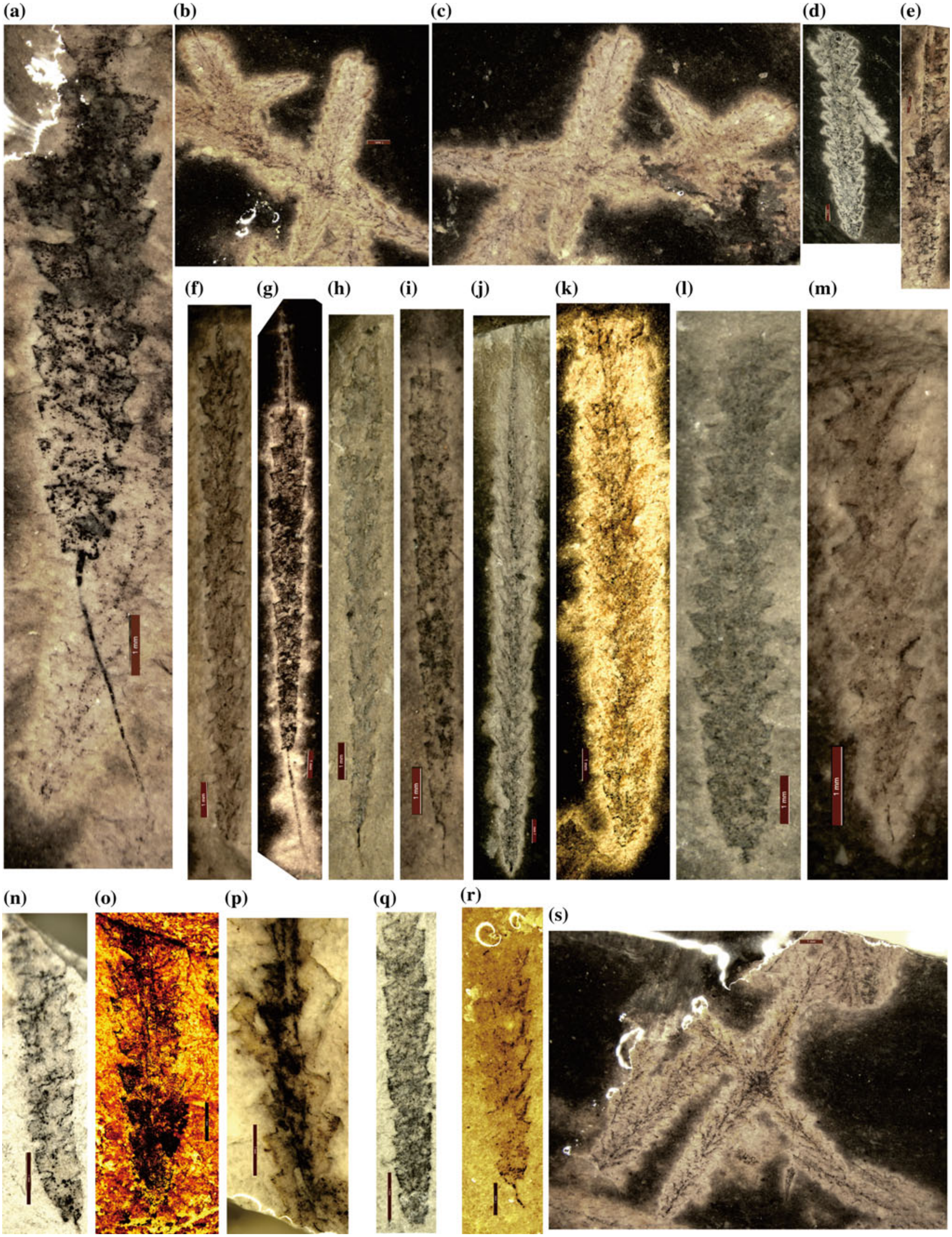

(a)
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Fig. 2.82 *Normalograptus persculptus* graptolite zone in the middle and upper parts of Wenchang Formation (O_3w): **a**, **b**, **c** *Normalograptus persculptus* (Elles and Wood 1907) (Pm002-Hb35-4-2b, 2d, 3b); **d**, **e** *Normalograptus laciniosus* (Churkin and Carter 1970) (Pm002-35-4-4, -4-3a); **f**, **g** *Normalograptus rhizinus* (Li et Yang 1983) (Pm002-35-4-9-1, -4-4a); **h**, **i** *Normalograptus angustus* (Perner 1895) (Pm002-35-4-5, -4-13-1); **j**, P-*Normalograptus* aff. *tamariscus Nicholson* (1868 Pm002-35-4-7, -15a); **k** *Neodiplograptus charis* (Mu et Ni 1983) (Pm002-35-4-8); **l** *Neodiplograptus shanchongensis* (Li 1984) (Pm002-35-4-11-1); **m** *Normalograptus* aff. *indivisus* (Davies 1929) (Pm002-35-4-12); **n** *Normalograptus mirneyensis* (Obut and Sobolevskaya 1967) (Pm002-35x-2a); **o** *Normalograptus zhui* (Yang 964) (Pm002-35x-10a); **p** *Normalograptus acceptus* (Koren and Mikhaylova 1980) (Pm002-35x-16a); **q** "*Glyptograptus*" jerini Koren et Melchin (2000) (Pm002-35x-21a); **r** *Normalograptus parvulus* (Lapworth) (Pm002-Hb35-4-2a1); scale length: 1 mm

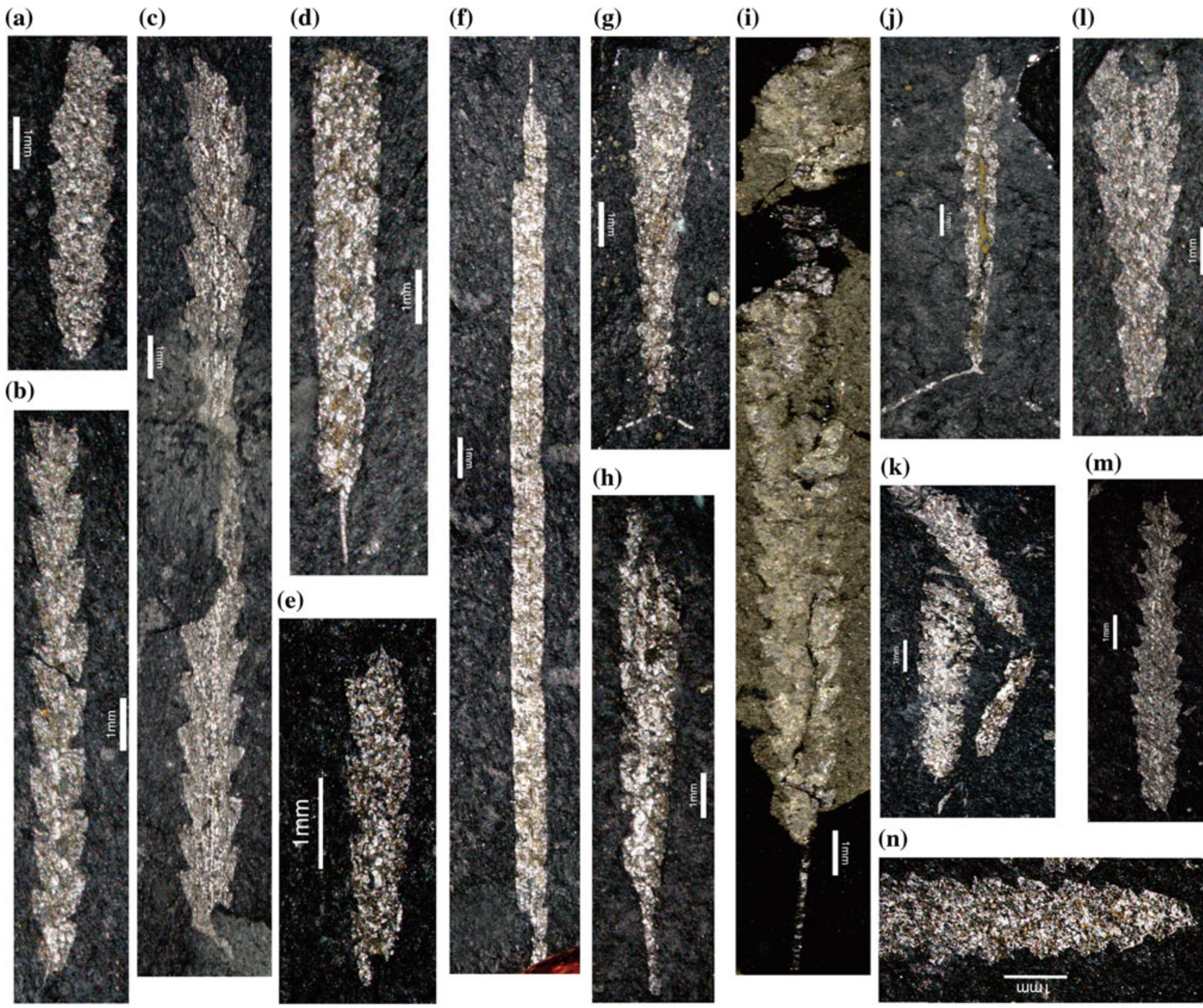


Fig. 2.83 *Normalograptus persculptus graptolite* zone in the upper part of Wenchang Formation (O_3w): **a** *Normalograptus* (Koren and Melchin 2000) (Pm008-Hb12-9); **b**, **c** *Glyptograptus* aff. *tamariscus* (Nicholson 1868) sensu Koren and Melchin 2000 (Pm008-Hb12-15, 12a); **d**, **e**, **f** *Normalograptus angustus* (Perner 1895) (Pm008-Hb12-13, 19, 14a); **g** *Normalograptus* cf. *minor* (Huang 1982) (Pm008-Hb12-11a); **h** *Normalograptus rhizinus* (Li and Yang 1983) (Pm008-Hb12-7); **i** *Normalograptus ojsuensis* (Koren and Mikhaylova in Apollonov et al. 1980) (Pm008-Hb12-32a); **j** *Normalograptus zhui* (Yang 1964) (Pm008-Hb12-23); **k**, **l** *Normalograptus avitus* (Davies 1929) (Pm008-Hb12-35a Volume 1, 26); *Normalograptus normalis* (Lapworth 1877) (Pm008-Hb12-35a Volume 2); **m** *Normalograptus laciniosus* (Pm008-Hb12-38b); **n** *Normalograptus persculptus* (Pm008-Hb12-30b)

environment such as carbonaceous shale, indicating that the Area was in a very special paleogeographic environment and thus significant in the research of paleoecology, biological paleogeography, and evolutionary paleontology.

To sum up, the age range of Wenchang Formation is basically consistent with that of Hirnantian Stage. The Hirnantian global glaciation exposed huge impact on organisms and caused two significant events of biological extinction,

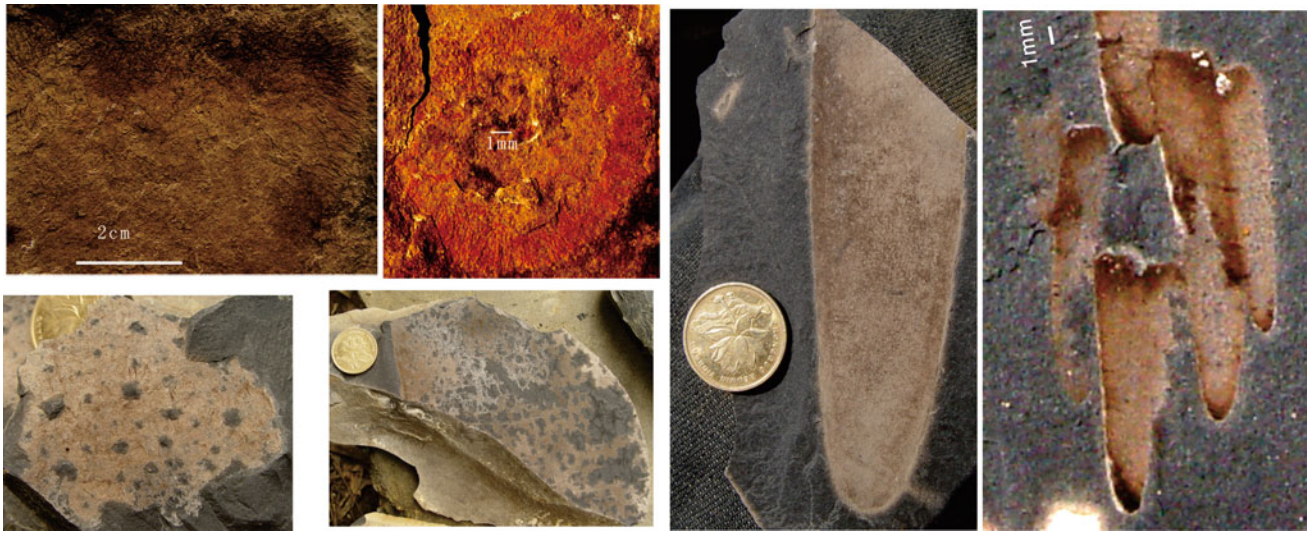


Fig. 2.84 Sponge fossils of *Normalograptus persculptus* zone in the middle part of Wenchang Formation (O_3w)

i.e., the extinction of graptolite fauna of Katian *Paraothograptus pacificus* zone and the extinction of the vast majority of graptolites of *Normalograptus extraordinarius* zone. *Songxites–Aegiromenella* fauna was also extinct.

2.4.7.4 Characteristics of Stable Isotope

A total of 29 mudstone (shale) samples were collected from Shangangshang profile (PM002), the Saoshe profile (PM008), and Zhuwukou profile (PM013) to conduct whole-rock stable isotope analysis of $\delta^{13}C$ and $\delta^{34}S$.

In the lower part of the Wenchang Formation, the $\delta^{13}C$ value is from −28.09 to −24.96‰ with an average of −26.99‰, and the $\delta^{34}S$ value is −2.1‰–25.7‰ with an average of 12.83‰. Compared with the $\delta^{13}C$ value (−35 to 30‰) and $\delta^{34}S$ value (−10 to 10‰) of normal argillaceous shale, they feature weak positive excursion, indicating shallow shelf sedimentary environment. In addition, the $\delta^{13}C$ value and the $\delta^{34}S$ value of the samples PM002C17 and PM002C20-1 feature the relatively obvious positive excursion, proving that the Area may experience a short glacial age in the Early Hirnantian. The reason is that a large number of organisms (including plants, animals, and microorganisms) died and were buried and deposited in the Area in the short cooled glacial environment, leading to the enrichment of $\delta^{13}C$ in the sediments and highlighting the positive anomaly. This anomaly is completely comparable with the Wangjiawan profile in Yichang City, Hubei Province, of the same period.

In the middle part of Wenchang Formation of Zhuwukou profile, the $\delta^{13}C$ value is from −31.00‰ to 30.76‰ with an average of −30.89‰, and the $\delta^{34}S$ value is 5.5‰–13.7‰ with an average of 10.36‰. In the middle part of the Wenchang Formation of Shangangshang profile and Saoshe profile, the $\delta^{13}C$ value is from −30.64 to −29.71‰ with an average of −30.22‰, and the $\delta^{34}S$ value is from 9.3 to −22.7‰ with an average of 14.92‰. Compared with the values of normal argillaceous shale, they feature weak negative excursion. The possible reason is that after the early Wenchang period, the climate in the Area gradually warmed up, the Area entered into a short interglacial period, and the sedimentary environment evolved into the deep shelf sedimentation.

In the upper part of Wenchang Formation, the $\delta^{13}C$ value is from −29.73 to −26.96‰ with an average of −28.91‰, and the $\delta^{34}S$ value is from −7.0 to 23.3‰ with an average of 1.54‰, showing a weak positive anomaly in general. The values of PM008C10 sample feature relatively obvious positive excursion. All these may indicate that during the Late Hirnantian, the Area experienced glacial period again after the short interglacial period, and the sedimentary environment evolved into shallow shelf facies. Therefore, the Area experienced two short glacial periods and one interglacial period during the whole Wenchang Formation period.

2.4.7.5 Analysis of Sedimentary Environment

The sediments in the lower and upper parts of Wenchang Formation are mainly thick blocky–laminated feldspathic quartz sand grains followed by medium laminated fine-silty sandstone, indicating the sedimentary environment of shallow shelf with abundant sources of terrigenous clasts. The interbedded graptolite and chitinozoan fossils-bearing carbonaceous argillaceous layer within Wenchang Formation represent the quiet deep shelf sedimentary. All these indicate that two kinds of sedimentary environment frequently alternate, suggesting varied sedimentary environment and frequent crust movements. The positive excursion of $\delta^{13}C$ in the carbonaceous mudstone shows that the sedimentary environment is related to the Late Ordovician global glacial events, and this is basically consistent with the characteristics of Wangjiawan stratigraphic profile in Yichang City, Hubei Province.

There are two different sedimentary strata in the middle part of Wenchang Formation. The lower stratum is composed of grayish siltstone intercalated with a layer of siliceous mudstone nodules. It is rich in the fossils of brachiopoda, trilobites, cephalopods, and crinoid but features monotonous genera and species and small figure of the organisms, indicating the sedimentation above the oxidation zone of shallow shelf. In the upper stratum, the carbonaceous mudstone with the thickness of about 10 m is rich in graptolites, representing the quiet reduction environment of deep shelf. However, there are well-preserved sponge fossils of 7–8 genera and species associated with the graptolites. Since sponges are benthic sessile organisms and lived in seawater containing enough oxygen and there is no excursion of $\delta^{13}C$‰ in the carbonaceous shale, it is inferred that there was an interglacial period during Hirnantian period.

Regionally, the lithology of Wenchang Formation and the sedimentary environment reflected change greatly. In Jiangshan–Changshan area, amaranthine sandstone appears in the middle and upper parts of Wenchang Formation, suggesting a locally hot and dry shallow shelf environment. In Wenchang, Chun'an County–Tonglu–Fuyang–Huangshi Village, Anji County area, tidal bedding developed in the sandstone of Wenchang Formation, and the strata located between *Songxites–Aegiromenella* fauna and *Normalograptus persculptus* graptolite zone are intercalated with the gravels, with quartz as main component and good rounding, indicating a sedimentary environment of fluvial facies during glacial period.

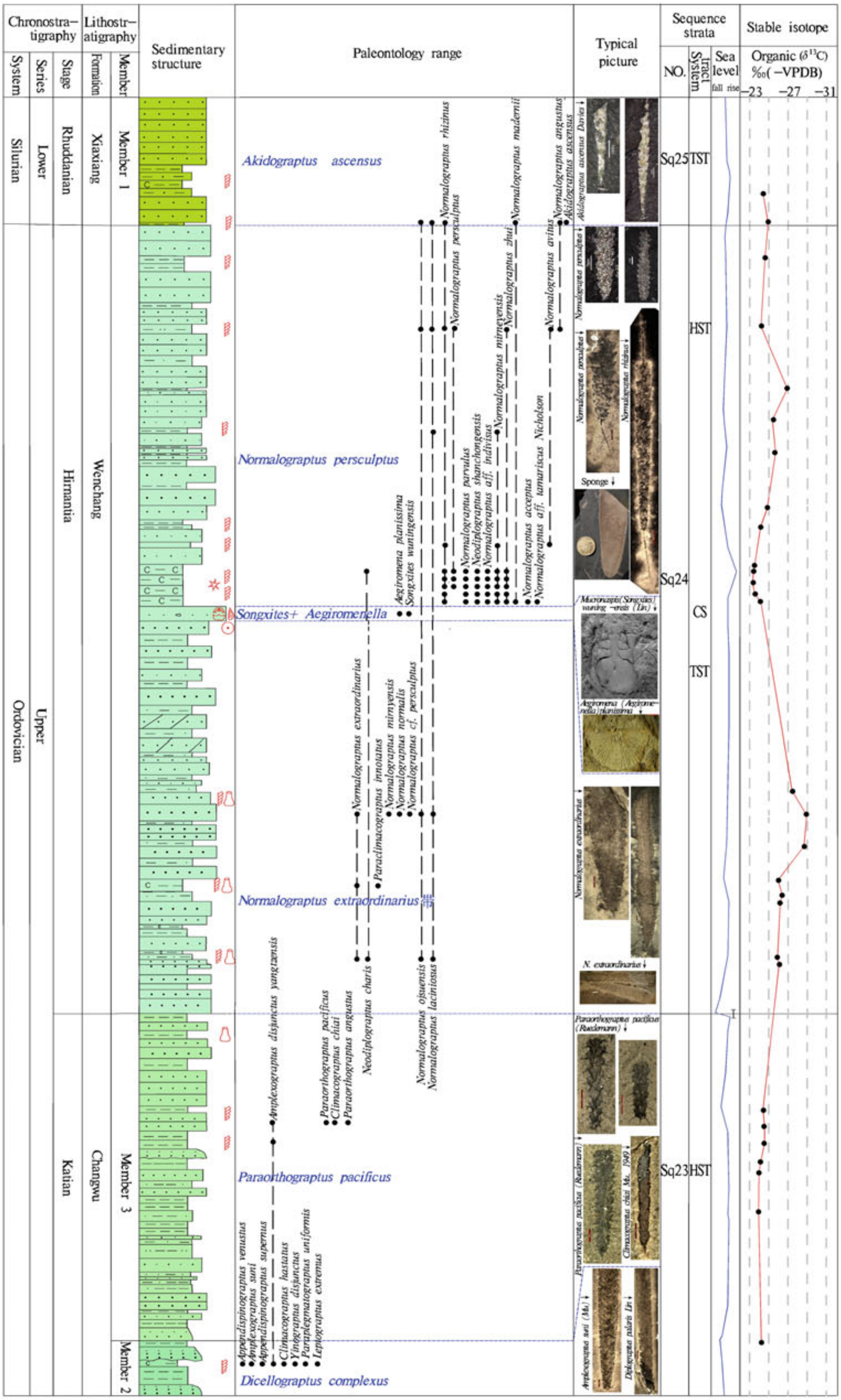
2.4.7.6 Trace Elements in Strata (Ore-Bearing)

A total of 28 rock spectra were collected from the Wenchang Formation of Shangangshang profile (PM002), including 27 systematically collected in the lower part and one collected from about 10–m-thick carbonaceous shale in the middle part. Furthermore, 16 rock spectra were collected from the Wenchang Formation of Saoshe profile (PM008), including one collected from about 10-m-thick carbonaceous shale in the middle part and 15 systematically collected in the upper part. Statistics were made on the arithmetic mean values and concentration coefficients of 14 main trace elements. According to spectral analysis and statistics, the lower part of Wenchang Formation is enriched in Be, Sb, and Sn; the middle part is enriched in Be, Sb, Pb, W, Mo, and Ag, especially Sb; the upper part is enriched in Sb, Mo, and Sn, indicating weak glacial chemical weathering resulting in less enriched elements. During the interglacial period, the quantity and quality of deposited elements from terrigenous supplies increased sharply with the increase of oxidation, reflecting that the climate exposed great influence on the distribution of trace elements in sediments.

2.4.7.7 Standard Section of Lower Yangtze Region in the Upper Ordovician Hirnantian

The Hirnantian Stage refers to an informal but widely recognized stratum with an age range of less than 2 Ma at the end of the Ordovician (Cooper and Sadler 2004; Gradstein et al. 2004). It is of great significance in spite of short age range since it records the second largest biological extinction event in geological history. This extinction event is related to the cooling of climate and the rise of global sea level caused by the expansion of Antarctic ice sheet, resulting in the extinction of about 85% of the species (Sheehan 2001). Furthermore, these events left unique records on lithostratigraphy, biostratigraphy, sedimentary rocks, and chemostratigraphy in the Area. All China Commission of Stratigraphy organized competent experts to conduct a field investigation and demonstration for the "Upper Ordovician Wenchang Formation Profile of Hanggai Town, Anji County, Zhejiang Province." All the experts unanimously agreed to rank the profile as the "Standard Section of Lower Yangtze Region in the Upper Ordovician Hirnantian" (Fig. 2.85) and believed that the profile obtained the following innovative achievements:

1. Hirnantian Stage and Ordovician—Silurian boundary are exposed completely in Hanggai profile in Anji County, Zhejiang Province. Besides, about 360-m-thick cyclic sedimentation consisting of graptolite-bearing shale and clastic rocks developed in the profile. According to chemostratigraphical studies of carbon isotopes, no structural damage was observed near the major boundary, and the geological events and biological sequences were well recorded. Therefore, Hanggai profile is qualified to be established as the Standard Section of Lower Yangtze Region in the Upper Ordovician Hirnantian.
2. Well-preserved fossils have been discovered in the profile. Among them, six graptolite zones and one shellfish fauna were determined in successive strata in Upper Ordovician Katie Stage–Hirnantian Stage and Lower Silurian Rhuddanian Stage, i.e., *Dicellograptus complexus*, *Paraothograptus pacificus, Normalograptus extraordinarius*, *Normalograptus persculptus*, *Akidograptus ascensus*, *Parakidograptus acuminatus* graptolite zones and *Songxites–Aegiromenella* shellfish fauna. In addition, the fossils of diverse graptolites,



Note: the section was approved as "Standard Section of Lower Yangtze Region of Upper Ordovician Hirnantian Stage" by All China Commission of Stratigraphy

Fig. 2.85 Histogram and paleontology range of the standard section of Lower Yangtze Region in the Upper Ordovician (Hirnantian) in the area

chitinozoans, sponges, trilobites, gastropods, brachiopoda, cephalopods, etc., have been identified in the successive strata.
3. Abundant sponge fauna (involving more than 10 genera and species) was first discovered in the Hirnantian strata, opening an important window to the further understanding of the global biosphere of the Hirnantian period and the sponge evolution after the Cambrian life explosion.

2.4.8 Xiaxiang Formation (S_1x)

As the only exposed Silurian stratum in the Area, Xiaxiang Formation is mainly distributed in the Fushi Reservoir in the eastern part of Hanggai map sheet and sporadically exposed in Ma'anshan area in the southern part of the Xianxia map sheet. The distribution area is about 21.98 km^2, accounting for 1.73% of the bedrock area.

The name Xiaxiang Formation (S_1x) was created by the 317 Geological Team of Bureau of Geology and Mineral Exploration of Anhui Provincial (1965) on the side of the railway near Xiaxiang Village, which lies about 5 km to the north of Hulesi Town, Ningguo County, Anhui Province. In Zhejiang Province, Xiaxiang Formation was originally known as Anji Formation, which was created by Regional Geological Survey Team of Geological Exploration Bureau of Zhejiang Province (1967) in Xiaofeng Town, Anji County, Zhejiang Province. When the name was created, the bottom of conglomerate and pebbled sandstone was taken as the bottom of Anji Formation. The preparation group of regional stratigraphic table of Zhejiang Province (1979) divided the conglomerate, pebbled sandstone, and

Xiaxiang Formation Total thickness: > 493.18 m

The second member of Xiaxiang Formation Total thickness: 414.91 m

Top: undiscovered

31. Gray blocky–laminated quart-feldspar silty-fine sandstone, the thickness of a single layer: greater than 1 m. 53.99 m

30. Gray thick laminated silty mudstone, micro-very thin horizontal bedding developing, the thickness of a single layer: 0.6–1 m. 1.87 m

29. Gray thick bedded-blocky silty-fine sandstone, main components: sub-well-rounded quartz and feldspar, argillaceous cement, the thickness of a single layer: 0.5–1.5 m, micro horizontal bedding developing. 16.72 m

28. Gray thick laminated silty mudstone, the thickness of a single layer: 0.5–1 m, no bedding developing. 0.89 m

27. Gray thick laminated argillaceous silty-fine sandstone, main components: quartz and feldspar, argillaceous cement, the thickness of a single layer: 0.5–1 m. 16.01 m

26. Khaki thick laminated argillaceous silty-fine sandstone owing to weathering, main components: quartz and feldspar, argillaceous cementation, the thickness of a single layer: 0.5–1 m, very thin horizontal bedding developing. 2.92 m

25. Dark grayish–grayish-yellow thick laminated argillaceous siltstone, mainly composed of quartz-feldspar sand, argillaceous cement, pyrite and mica visible occasionally, the thickness of a single layer: 0.5–1 m, very thin horizontal bedding developing. 26.98 m

24. Gray argillaceous siltstone, main components: quartz and feldspar followed by a small amount of argillaceous matter, very thin horizontal bedding developing, containing a small amount of pyrite grains 4.57 m

23. Gray medium laminated argillaceous siltstone, mainly composed of quartz-feldspar sand, thickness of a single layer: 0.2–0.4 m, horizontal bedding developing. 3.27 m

22. Gray thick laminated argillaceous silty-fine sandstone, main components: quartz-feldspar sand followed by a small amount of argillaceous matter, the thickness of a single layer: 0.8–1.5 m, parallel bedding developing. 4.68 m

21. Gray thick laminated silty-fine sandstone, main components: quartz and feldspar followed by a small

amount of argillaceous matter, clear horizontal bedding developing, the bottom: a layer of mudstone with the thickness of about 50 cm. 11.73 m

20. Gray thick bedded-blocky quartz arkose, main components: quartz and feldspar followed by a small amount of argillaceous matter, the thickness of a single layer: 1–1.2 m, parallel bedding developing. 21.40 m

19. Gray medium laminated fine siltstone; main components: quartz and feldspar followed by argillaceous matter; the fine sandstone: locally concentrating, micro-fine banded; the thickness of a single layer: 30–40 cm; horizontal bedding developing. 15.26 m

18. Gray thick laminated argillaceous siltstone, with a few fine sand bands, developed horizontal bedding, local cross-bedding. 10.58 m

17. Covering. 25.40 m

16. Gray thick laminated argillaceous siltstone, intercalated with micro laminated silty mudstone; pyrite grains visible occasionally, horizontal bedding developing, cross-bedding developing locally. 113.29 m

15. Gray-caesious argillaceous fine sandstone, parallel bedding developing, spheroidal weathering. 34.15 m

14. Gray-caesious silty-fine sandstone, pyrite visible occasionally, parallel bedding developing. 33.06 m

13. Gray argillaceous siltstone; very thin horizontal bedding developing; the silt: micro-fine banded (1–2 mm), spheroidal weathering locally. 18.13 m

12. Gray silty mudstone intercalated with thin laminated of argillaceous siltstone. The thickness of a single layer of the argillaceous siltstone: 2–3 cm, spherical weathering, horizontal bedding developing. 8.78 m

———————— Conformable contact ————————

The first member of Xiaxiang Formation Total thickness is 78.27 m

11. Gray silty mudstone, very thin horizontal bedding developing. 34.88 m

10. Covering. 8.10 m

9. Gray silty mudstone, graptolite visible. 10.43 m

8. Gray thick laminated quartz feldspar fine sandstone, main mineral components: quartz and feldspar clasts followed by a small amount of argillaceous matter, no bedding developing. 2.09 m

7. Gray silty mudstone, major component: argillaceous matter, minor components: clasts of quartz and feldspar. 2.41 m

6. Gray thick laminated siltstone interbedded with mudstone. 3.76 m

5. Gray silty mudstone, main mineral components: argillaceous mater followed by clasts of quartzy silt. 1.32 m

4. Gray thick laminated argillaceous silty-fine sandstone, main mineral components: clasts of quartz and feldspar followed by a small amount of argillaceous. 1.74 m

3. Gray thin laminated siliceous carbonaceous shale, main mineral component: argillaceous matter, graptolites visible. 2.10 m

2. Interbeds consisting of gray thick–medium laminated argillaceous siltstone and micro laminated carbonaceous shale; the argillaceous siltstone: composed of clasts of quartz and feldspar followed by argillaceous matter, the thickness of a single layer: 25–55 cm; the carbonaceous shale: the thickness of a single layer: 0.5–1 cm, graptolites visible. 2.67 m

———————— Conformable contact ————————

Wenchang Formation Total thickness: >14.79 m

1. Khaki thick laminated silty-fine sandstone. 10.39 m

0. Grayish yellow thick sandstone interbedded with argillaceous siltstone. 4.40 m

the horizon producing *Dalmanitina* cf. *mucronata Mucronaspis* (*Songxites*) *wuningensis* (Lin) from Anji Formation and collectively named them Yankou Formation, and accordingly the Anji Formation only referred to the sandstone and mudstone-bearing *Normalograptus* (*Glytograptus*) *persculptus* and the strata upward in Anji Formation. This kind of division was adopted in *Regional Geology of Zhejiang Province* (1989). In *Lithostratigraphy of Zhejiang Province* (1995), Anji Formation was renamed Xiaxiang Formation. In this Project, according to the characteristics of the lithologic association, sedimentary structures, fossils, and geological observation traverse of Fushi Reservoir profile (PM009) of Hanggai map sheet in the Area, the strata dominated by thick blocky–laminated sandstone and intercalated with shale containing *Normalograptus* (*Glytograptus*) *persculptus* in the profile were classified under Wenchang Formation (O_3w), while the strata consisting of dark gray–black thin laminated carbonaceous shale containing *Akidograptus ascensus* and medium laminated fine-silty sandstone in the profile were classified as Xiaxiang Formation (S_1x).

2.4.8.1 Lithostratigraphy

According to the lithology and lithologic association, Xiaxiang Formation is divided into the first member (S_1x^1) and the second member (S_1x^2), which are in conformable contact with the underlying Ordovician Wenchang Formation.

The first member of Xiaxiang Formation (S_1x^1): grayish–grayish black thin laminated graptolite-bearing siliceous carbonaceous shale intercalated with gray medium laminated feldspathic quartz silty-fine sandstone or rhythmic interbeds constituting of them. The siliceous carbonaceous shale: micro-texture horizontal bedding developing, bearing micro-fine-grained pyrite, and rich in graptolites.

The second member of Xiaxiang Formation (S_1x^2): interbeds consisting of gray thick blocky–laminated silty-fine sandstone and gray–caesious medium laminated argillaceous siltstone, interbedded with a small amount of silty mudstone and mudstone. The silty-fine sandstone gradually increases, and the rock layers gradually thicken upward. The top of this member is not discovered in the Area.

1. **Stratigraphic section**

The lithology of Xiaxiang Formation is described by taking the example of Xiaxiang Formation (S_1x) profile (Fig. 2.86) of Hanggai map sheet in Fushi Reservoir, Anji County, Zhejiang Province. The details are as follows:

2. **Lithological characteristics**

The lithology of the first member of Xiaxiang Formation (S_1x^1) is mainly characterized by thin laminated silicon-bearing carbonaceous shale and medium–thick laminated feldspathic quartz silty-fine sandstone.

(1) Silicon-bearing carbonaceous shale: dark gray–grayish black; composition: argillaceous matter (65–70%), silt (10–20%), cryptocrystalline siliceous matter (10–15%), and carbonaceous matter (5–10%), micro-fine-grained pyrite visible occasionally along the bedding (0–5%); very thin horizontal bedding and many carbonized graptolite fossils developing.
(2) Feldspathic quartz silty-fine sandstone: gray; main component: feldspar and quartz (80–85%); grain size: 0.1–0.2 mm generally and 0.05–0.1 mm for a small amount, sub-well rounded; argillaceous cementation; argillaceous content: 15–20%.

The lithology of the second member of Xiaxiang Formation (S_1x^2) is mainly argillaceous siltstone, silty-fine sandstone, and silty mudstone.

(1) Silty-fine sandstone: gray–caesious; silty-fine sandstone structure; medium–thick laminated structure dominated by thick laminated structure; main component: quartz–feldspar sand (80–85%), sub-well rounded; grain size: 0.01–0.1 mm; minor component: a small amount of argillaceous matter (15–20%).
(2) Argillaceous siltstone: gray; silty structure; medium–thick laminated structure dominated by the medium laminated structure; main component: quartz–feldspar sand (60–80%), sub-well rounded; grain size: 0.01–0.05 mm; minor component: argillaceous matter (20–40%); pyrite grains visible occasionally; clear horizontal bedding developing.
(3) Silty mudstone: gray; thin laminated structure; main component: argillaceous matter (65–70%); minor component: quartz–feldspar sand (30–35%); grain size: 0.01–0.06 mm, sub-well rounded.

3. **Basic sequences**

There are two types of basic sequences developing in the first member of Xiaxiang Formation (S_1x^1) (Fig. 2.87).

(1) Mainly distributed in the upper part of Xiaxiang Formation, mainly composed of medium laminated silty mudstone, main component of the silt: quartz, horizontal bedding developing, belonging to monotonic basic sequences.

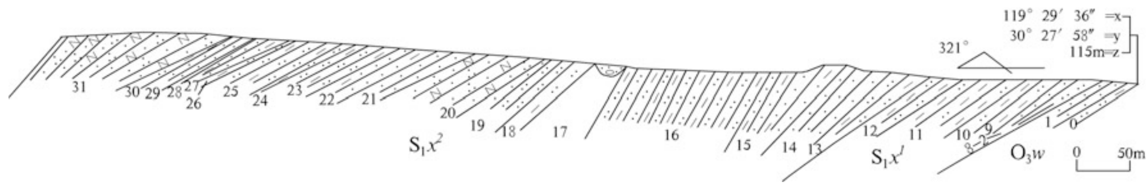


Fig. 2.86 Xiaxiang Formation (S_1x) profile in Fushi Reservoir, Anji County, Zhejiang Province

(2) Mainly distributed in the lower part of Xiaxiang Formation, composed of interbeds consisting of ① gray thin–medium laminated silty-fine sandstone and ② black carbonaceous silicon-bearing mudstone; the silty-fine sandstone: thin–medium laminated in the lower part, medium laminated mainly upward; the carbonaceous silicon-bearing mudstone: thin laminated mostly, micro-fine horizontal bedding developing; the ratio of silty-fine sandstone to the carbonaceous silicon-bearing mudstone: (3–5):1 approximately; the mudstone gradually increasing upward; belonging to the non-cyclic basic sequence with terrigenous clasts and thickness increasing upward.

The silty-fine sandstone in this member is mainly composed of feldspar and quartz. The clasts feature poor maturity and rounding and good sorting. They are the products of weathering, transportation, and deposition of far terrigenous granitic rocks and belong to the silt–mudstone facies of the outer margin of shallow shelf. The shale with high content of silicon and carbon and abundant graptolite is the sediments in bathyal reduction environment, belonging to the siliceous-argillaceous facies of shallow shelf–bathyal basin.

There is one type of basic sequences in the second member (S_1x^2) of Xiaxiang Formation.

(3) Consisting of ① thin–medium laminated silty mudstone, ② thin–medium laminated argillaceous siltstone, and ③ gray medium–thick laminated fine-silty sandstone; the fine-silty sandstone: mostly thick laminated, blocky–laminated occasionally, no obvious bedding developing; the argillaceous siltstone: medium laminated mostly, thick laminated for a small amount, parallel bedding developing; the mudstone: mostly thin laminated, thick laminated occasionally, pyrite visible locally, micro-fine horizontal bedding developing; the ratio of sandstone: siltstone: mudstone is (8–10):(3–4):1 approximately; mudstone often absent in the upper and lower parts of the second member; sandstone increasing and layer thickness increasing upward; belonging to the cyclic basic sequence with grain size decreasing and layer thickness increasing upward.

The strata in this member are mainly composed of feldspar–quartz silt and fine sand. The clasts feature poor maturity and rounding but finer grain size compared with Wenchang Formation. They are the products of weathering, transportation, and deposition of far terrigenous granitic rocks and belong to the far terrigenous clastic rock facies of the outer margin of shallow shelf.

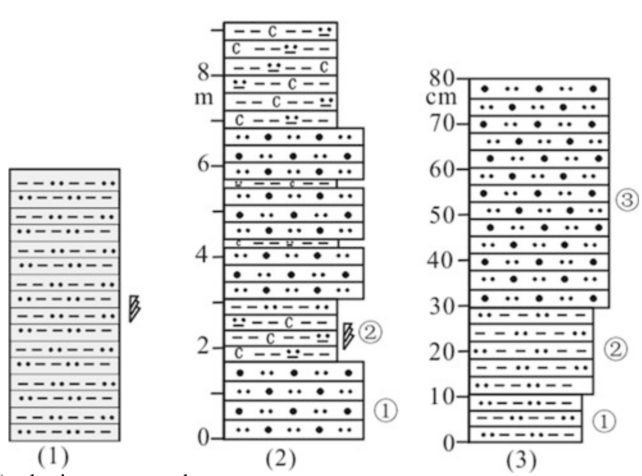


Fig. 2.87 Xiaxiang Formation (S_1x)—basic sequence chart

2.4.8.2 Sequence Stratigraphy

According to the characteristics of the lithology, paleontology, lithofacies association, and sequence boundary of the Fushi Reservoir profile of Hanggai map sheet, there is one third-order sequence Sq25 in Xiaxiang Formation (S_1x), which belongs to the second-order sequence SS8. It is briefly described as follows (Fig. 2.88).

Third-order sequence Sq25: consisting of the transgressive systems tract (TST) and highstand systems tract (HST). The bottom of Sq25 is the conformable interface between the black carbonaceous mudstone of the first member of Xiaxiang Formation and the thick laminated sandstone of Wenchang Formation, belonging to the type-II sequence boundary. The top of Sq25 is not discovered. TST is located in the first member and the bottom of the second member of Xiaxiang Formation. The sediments of TST mainly include carbonaceous argillaceous matter followed by silt and fine sand. The carbonaceous mudstone contains graptolite fossils. All these indicate that TST belongs to the sedimentation in oxidation–reduction environment below wave base of deep shelf. HST is located in the middle and upper parts of the second member of Xiaxiang Formation. The sediments of HST mainly contain fine sand, silt, and a small amount of argillaceous matter, indicating the clastic rock facies of shallow shelf during the gradual rise of sea level after the maximum flooding. The coarse clasts increase from bottom to top in this sequence, reflecting the gradual falling of the sea level. Therefore, this sequence is of aggradation–progradation type.

2.4.8.3 Biostratigraphy and Chronostratigraphy

Xiaxiang Formation (S_1x) in the Area inherited the lithofacies and paleogeographic conditions of Wenchang Formation. With the improvement of climatic conditions, planktonic graptolites feature new thriving but the monotonous genera and species. In this Project, a large number of graptolite fossils were obtained in the first member of Xiaxiang Formation (S_1x^1) around Fushi Reservoir, and two graptolite zones, i.e., *Akidograptus ascensus* zone and *Parakidograptus acuminatus* zone, were identified from bottom to top.

1. ***Akidograptus ascensus* zone**

The graptolites discovered in the carbonaceous silty mudstone in the lower part of the first member of Xiaxiang Formation in Saoshe profile include the zone fossil *Akidograptus ascensus* (Davies 1929) and the symbiotic molecules including *Normalograptus laciniosus* (Churkin and Carter 1970), *Normalograptus rhizinus* (Li and Yang, 1983), *Normalograptus ojsuensis*, and *Normalograptus angustus* (Perner 1895). Some graptolites suffered the metasomatism of pyrite (Fig. 2.89).

2. ***Parakidograptus acuminatus* zone**

Parakidograptus acuminatus zone is located in the silty mudstone in the upper part of the first member of Xiaxiang Formation. In the silty mudstone, which is khaki owing to weathering and about 10–12 m in the upper part of the first member of Xiaxiang Formation of Fushi Reservoir, a large number of graptolites were obtained, including the zone fossil *Parakidograptus acuminatus* Nicholson 1867 and other symbiotic molecules such as *Parakidograptus* sp. indet., diplograptid gen. & sp. indet., "*Climacograptus*" sp. indet., *Normalograptus* sp. indet., and *Normalograptus rhizinus* (Fig. 2.90).

According to the *Stratigraphic Chart of China* (*2014*), the *Akidograptus ascensus* and *Parakidograptus acuminatus* zones belong to Rhuddanian Stage of Early Silurian, and Xiaxiang Formation is a stratigraphic unit of the Lower Silurian.

2.4.8.4 Analysis of Sedimentary Environment

With the global glacier melting in the Late Hirnantian, a rapid sea level rise occurs, and the Area experienced a new round of abyssal sedimentation accordingly. In the first member of Xiaxiang Formation, the sediments mainly include terrigenous clasts consisting of fine sand silt followed by carbonaceous argillaceous matter. The terrigenous clasts feature relatively good sorting and mainly include quartz and feldspar. Therefore, they were brought by long-distance transportation. The carbonaceous argillaceous sediments are pelagic sediments, and the sulfide reflects the reduction condition. Therefore, the first member of Xiaxiang Formation should feature standing-water sedimentary environment of the deep shelf reduction zone. In the second member of Xiaxiang Formation, the sediments are mainly composed of gray and caesious medium–thick laminated silt and fine sand, interbedded with a small amount of silt and argillaceous matter. There is no biological fossil discovered. All these indicate the terrigenous clasts are abundant and the water body is anoxic and thus unfavorable for the survival of organisms. It can be inferred that there was a sea level rise, and the Area was in the weak reduction sedimentary environment in the transition zone between shallow shelf and deep shelf.

Regionally, the Xiaxiang formations in all areas all feature a set of argillaceous clastic rock formation of deep shelf–shallow shelf, but greatly a different stratum thickness. Northwestward to Ningguo City, Anhui Province, the thickness increases, the grain size of the clasts decreases, and silt becomes the main component. Southeastward to Lin'an,

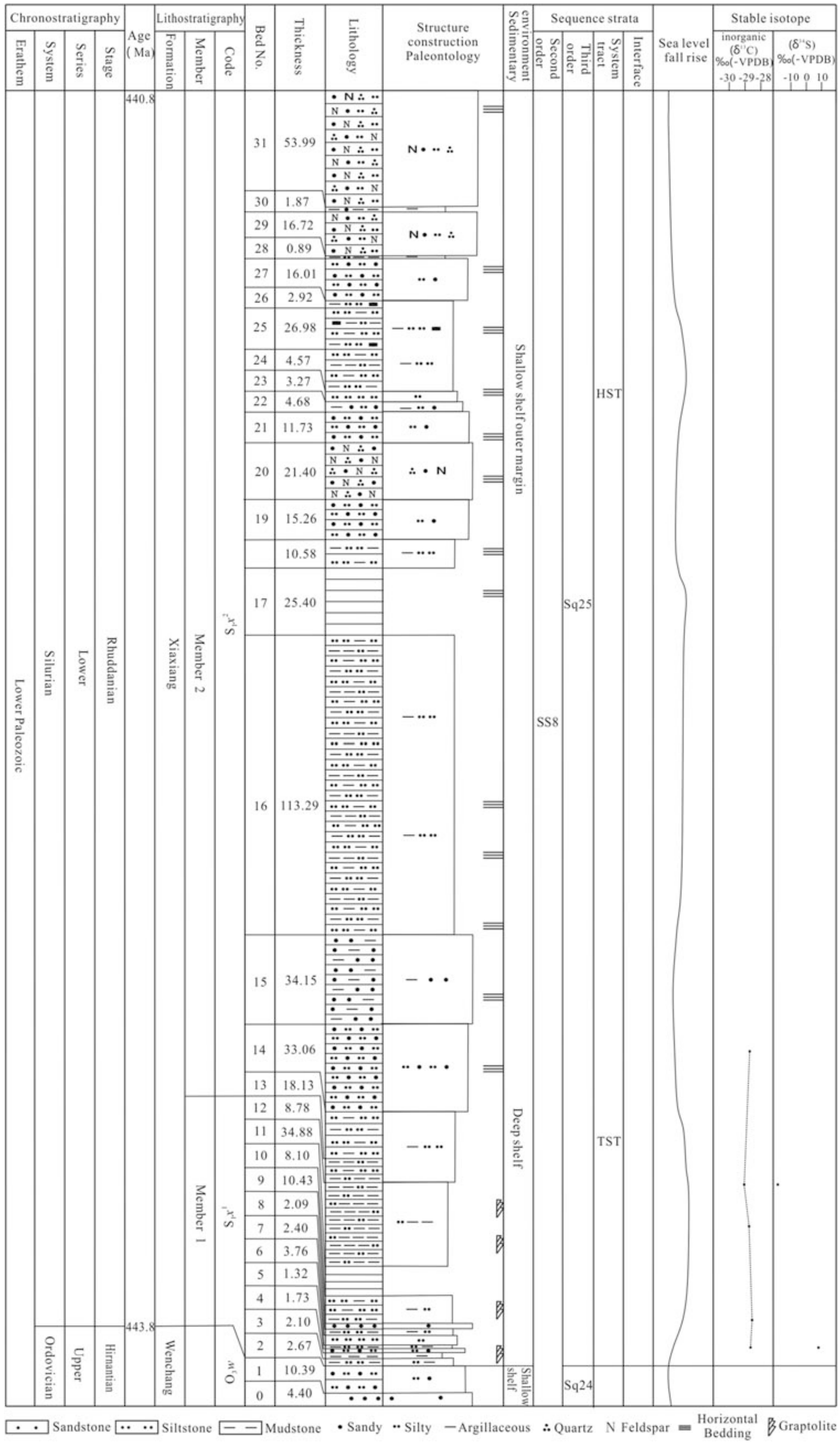


Fig. 2.88 Sequence of stratigraphic framework of Early Silurian Xiaxiang Formation in the area

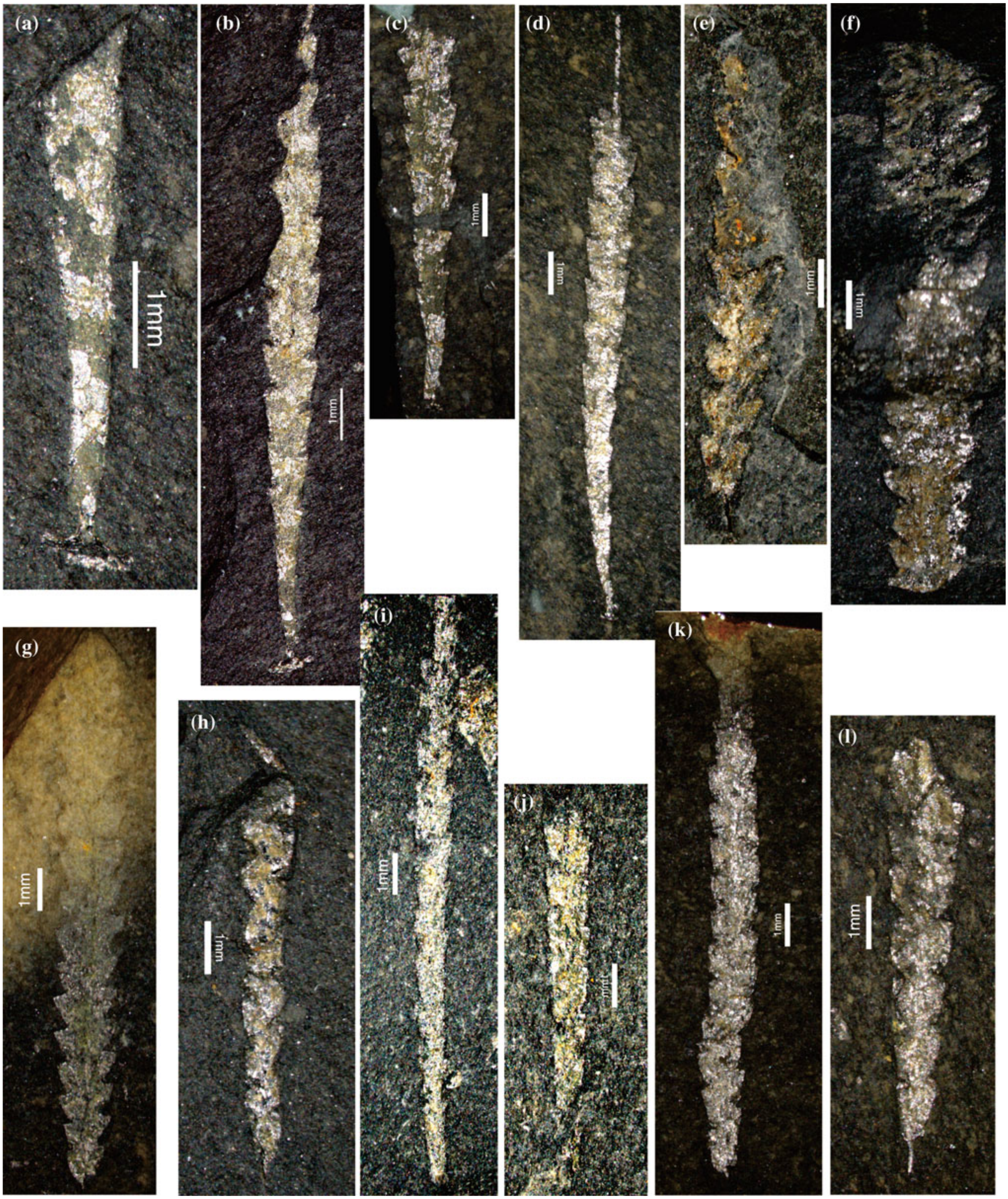


Fig. 2.89 Graptolite in *Akidograptus ascensus* zone in the first member of Xiaxiang Formation (S_1x^1): **a**, **b**, **c**, **d** *Akidograptus ascensus* Davies 1929 (Pm008-Hb15-3, -1e, -16a, -6e); **e**, **f** *Normalograptus laciniosus* (Churkin and Carter 1970) (Pm008-Hb15-13, -20); **g** *Normalograptus angustus* (Perner 1895) (Pm008-Hb15-21); **h** *Normalograptus laciniosus* (Pm008-Hb15-2); **i** *Normalograptus madernii* (Pm008-Hb15-5); **j**, **k**, **l** *Normalograptus rhizinus* (Li and Yang 1983) (Pm008-Hb15-12a, -18, -4). The length of the white scale is 1 mm

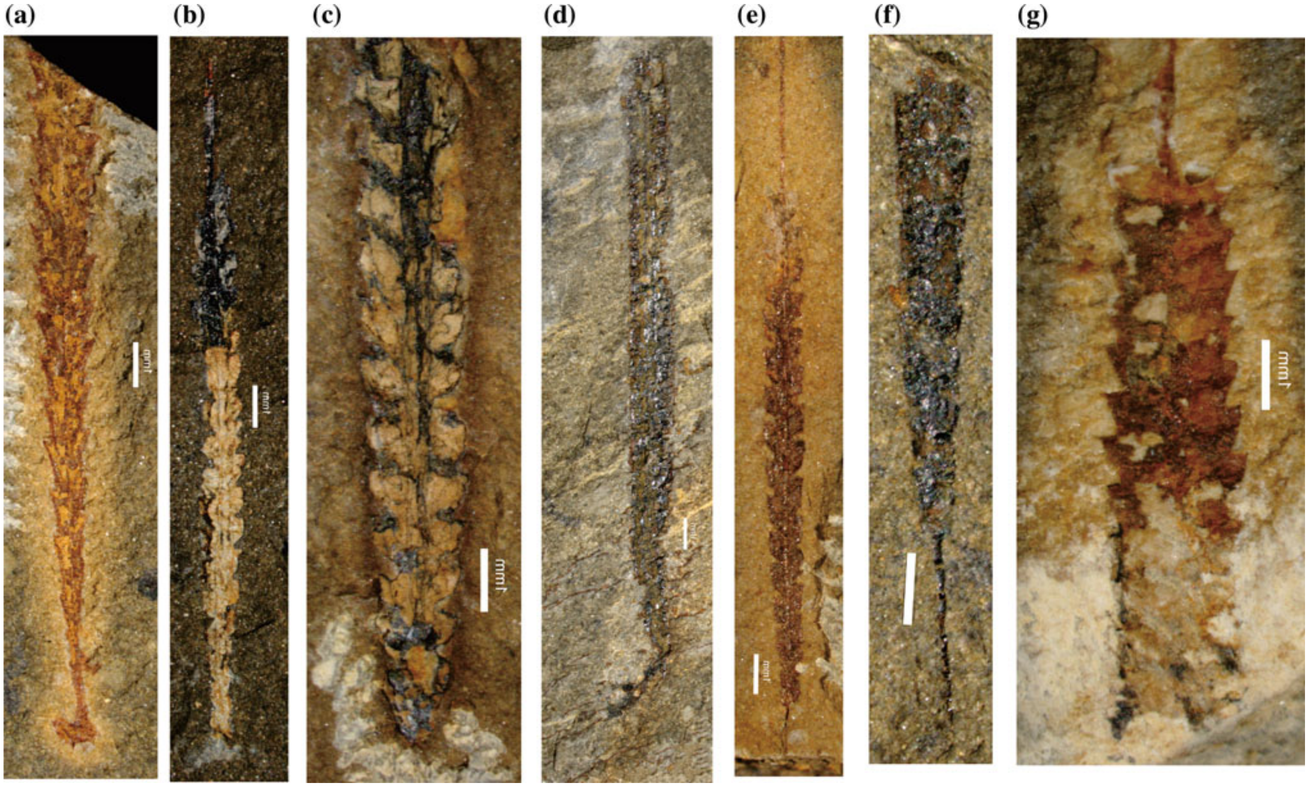


Fig. 2.90 Graptolites in *Parakidograptus acuminatus* zone in the first member of Xiaxiang Formation (S_1x^1): **a** *Parakidograptus acuminatus* Nicholson, 1867 (Pm009-Hb4-3); **b** *Parakidograptus* sp. (Pm009-Hb1-1); **c** *Normalograptus* sp. (Pm009-Hb3-1); **d** *Diplograptid gen.* & sp. (Pm009-Hb3-2); **e**, **f** *Normalograptus rhizinus* (Pm009-Hb3-1, Hb4-4); **g** *Climacograptus sp.* (Pm009-Hb10-1); the length of the white scale: 1 mm

the thickness evidently decreases, fine and medium sands become the main components, and tidal bedding developed locally. All these indicate that paleogeographic relief was high in the north and low in the south.

2.4.8.5 Characteristics of Stable Isotope

A total of seven carbonaceous mudstone samples were collected from Xiaxiang Formation of Saoshe profile (PM008) and Xiaofeng profile (PM009) to conduct whole-rock stable isotope analysis of $\delta^{13}C$ and $\delta^{34}S$. According to the analysis, the $\delta^{13}C$ value of Xiaxiang Formation is from −29.48 to −28.91‰ with a small variation range and an average of −29.24‰; the $\delta^{34}S$ value of Xiaxiang Formation is from −9.2 to 11.1‰ with the average 3.57‰. These values are basically consistent with the $\delta^{13}C$ value (−35 to −30‰) and $\delta^{34}S$ value (−10 to 10‰) of normal shale, indicating deep shelf sedimentation.

2.4.8.6 Trace Elements in Strata (Ore-Bearing)

Thirty rock spectra were systematically collected from Xiaxiang Formation (S_1x) of Fushi Reservoir profile (PM009). Among these spectra, 10 were collected from the first member (S_1x^1) and 20 from the second member (S_1x^2). Analysis was made on 14 trace elements, and then statistics were made on the arithmetic mean values and concentration coefficients of the analysis results. According to the statistics, the first member is enriched in Be, Sb, and F, and the second member is enriched in Be, Sb, W, Sn, F, and S. The possible reason is that after long-distance transportation, the clasts were worn and finer, and the heavy minerals containing W and Sn deposited and concentrated near the shore accordingly.

2.4.9 Comparison of Regional Stratigraphy

In northwest Zhejiang Province, the topographic pattern in the Ordovician was inherited from the Sinian–Cambrian. However, with the change in paleogeographic conditions and paleoclimate, the sediments and ancient organisms of the Ordovician are different from those of the Sinian and Cambrian. Except Yuhang–Fuyang area where the sediments were still composed of carbonate in the Early and Middle Ordovician, the sediments in other areas were dominated by argillaceous, sandy, and silty terrigenous clastics (Fig. 2.91) in the Ordovician. The regional stratigraphy was compared by taking the samples of the profile in the Area in Hanggai area, and Banqiao (Lin'an) profile and Sanxikou profile in Yuhang–Fuyang area from northwest to southeast.

The regional stratigraphy in the early and middle period of the Early Ordovician is as follows. In the northwest Hanggai area, obvious transgression took place twice, and the carbonate-bearing argillaceous matter–silicon-bearing argillaceous matter of deep shelf in the third member of Xiyangshan Formation and the first member of Yinzhubu Formation was deposited, with respective deposition depth of 255 m and 76 m. In Yuhang–Fuyang area, the sediments were composed of the mud and knotlike carbonate of platform facies in Lunshan Formation and the knotlike and reticulate carbonate of platform–shallow shelf facies in Honghuayuan Formation from bottom to top, with respective thickness of 329 m and 92 m, respectively, representing high-energy turbulent environment and open and de-saline neritic environment. The sedimentary rocks in the two sedimentary zones generally reflect the trend of crust subsidence and sea level rise.

The regional stratigraphy in the late period of the Early Ordovician is as follows. In Hanggai area, the sediments consisted of black graptolite-bearing siliceous mudstone of bathyal facies, with a thickness of less than 100 m. In Yuhang–Fuyang area, the sediments were composed of reticulate carbonate with the platform facies in the lower part of Guniutan Formation and a thickness of less than 20 m.

The regional stratigraphy in the early period of the Middle Ordovician is as follows. In Hanggai area, the sediments consisted of the graphite-bearing carbonaceous shale of sub-deepwater subcompensational basin facies in the Ningguo Formation, with a thickness of 70 m. To the late period of the Middle Ordovician, the maximum flooding surface appeared, and the silicalite of deepwater basin facies was deposited in Hanggai area. Southeastward to Yuhang area, the sediments changed from argillaceous carbonate–knotlike carbonate of the platform and shallow shelf facies in the first member of Guniutan Formation, to micro- to argillaceous–crystalline carbonate from bottom to top. In the late period of the Middle Ordovician, a small amount of siliceous of deep shelf was deposited in Yuhang area. Based on the absence of transitional environmental sedimentation, it is inferred that a strong crustal movement event occurred during that period.

The regional stratigraphy in the early period of the Late Ordovician is as follows. In the northwest Zhejiang Province, the argillaceous carbonate and knotlike carbonate of the Yanwashan Formation were deposited owing to the shallow shelf sedimentary environment, with a thickness of 10–20 m. Then, a new round of uneven crustal subsidence and transgression started. The siliceous mudstone of Huangnigang Formation was initially deposited. The bottom and middle of the Huangnigang Formation were intercalated with sparse knotlike limestone layers, and the thickness was reduced from 80 m to 35 m from north to south.

In the middle and late period of the Late Ordovician, the water body deepened from the southeast to the northwest, with the further enhancement of crust subsidence. In the inner margin of the slope in Yuhang–Fuyang area and the outer margin of the slope in Hanggai area far away from the sediment sources, the flysch clastic rocks of sedimentary slope facies were deposited at the same time, with the thickness of sedimentary rocks of 480–500 m, and the grain size of the clasts was relatively small. In Yuhang–Fuyang area close to the sediment sources, the thickness of the sedimentary strata was up to more than 1500–2000 m and the grains of the clasts were relatively coarse.

The Late Ordovician was a global glacial period, during which the sea level fell rapidly. In Hanggai area, thick blocky–laminated sandstone intercalated with thin laminated siltstone and graptolite-bearing mudstone of shallow shelf facies in Wenchang Formation was deposited. While in Yuhang–Fuyang–Wenchang area, Wenchang Formation was composed of clastic rocks of littoral neritic facies with tidal bedding developing, and a layer of conglomerate intercalated in the middle part of the formation.

At the beginning of the Silurian, the sea level rose in northwest Zhejiang Province with the melting of glaciers, and a new round of deep shelf terrigenous clast deposition began.

2.5 Cretaceous System

Cretaceous strata in the Area mainly include the volcanic rocks in Huangjian Formation. They are distributed in most areas of the southeast of Xianxia map sheet and the southeast of Chuancun map sheet. Besides, they are locally exposed in the northwest corner of Chuancun map sheet. The total outcrop area is up to about 519.72 km^2, accounting for 40.88% of the total bedrock area.

The name Huangjian Formation (K_1h) was created by Zou (1964) in Huangjian Mount, which lies in the south of Shouchang Town, Jiande City, Zhejiang Province. The original lithology of the Huangjian Formation was characterized into two parts, i.e., the upper part and the lower part. The upper part consisted of caesious rhyolitic tuff lava, vitric tuff, and tuff breccia interspersed with amaranthine rhyolite, with tuff interspersed with amaranthine siltstone constituting its top. The lower part was composed of purple and gray rhyolite and rhyolite porphyry. The name has been used up to now by Lin et al. (1989), Ding et al. (1999), Chen (2000), etc., as well as in *Lithostratigraphy of Zhejiang Province* (1996). In this Project, the name Huangjian Formation was still adopted based on the lithological

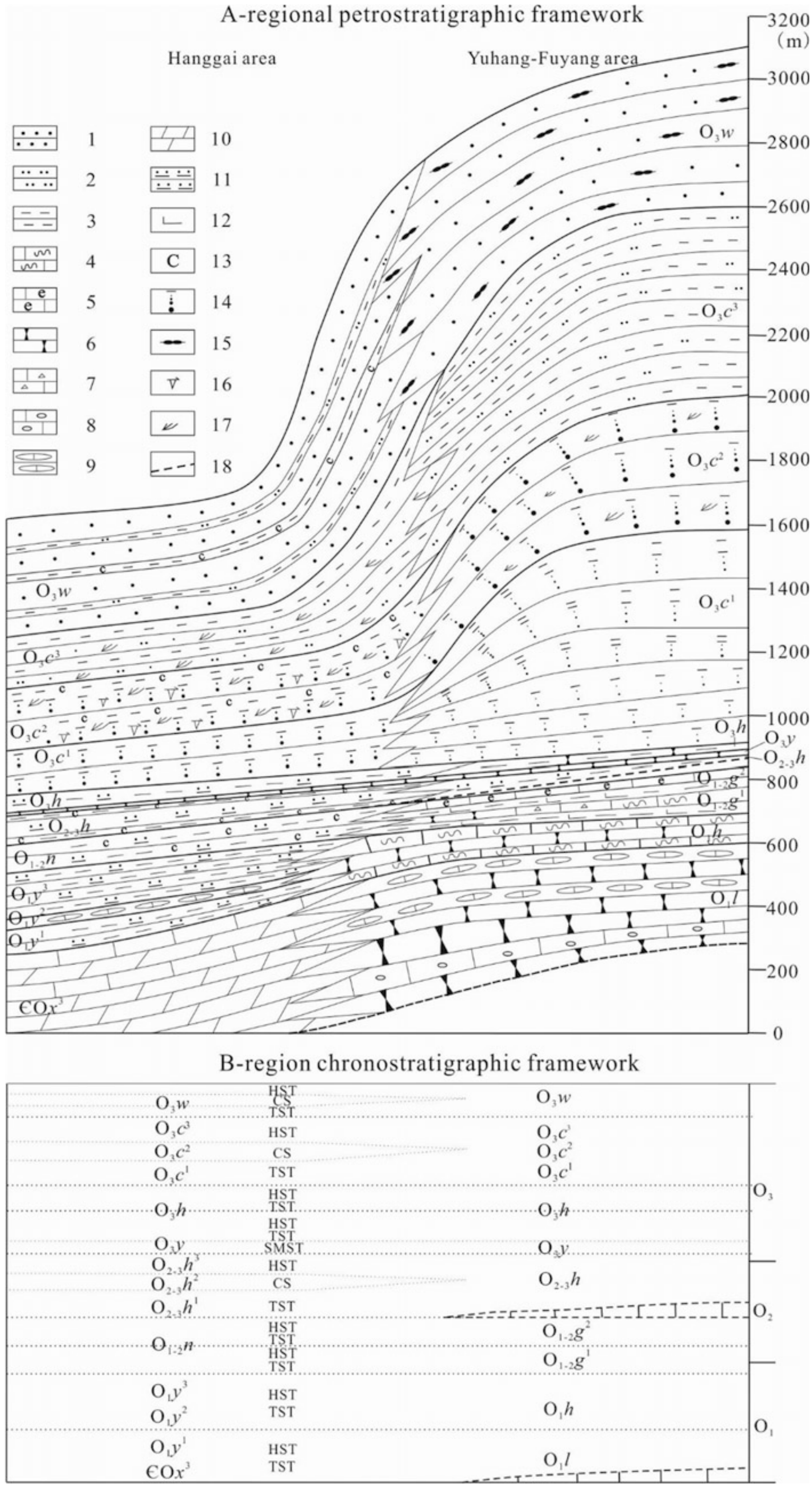


Fig. 2.91 Regional stratigraphic framework of Hanggai area and Yuhang–Fuyang Area in the Ordovician–Early Silurian: 1. sandstone; 2. siltstone; 3. mudstone; 4. reticulate limestone; 5. biogenic limestone; 6. knotlike limestone; 7. breccia limestone; 8. calcirudite; 9. pie-shaped limestone; 10. marl; 11. silicalite; 12. calcareous matter; 13. carbonaceous matter; 14. Bouma sequence; 15. veined structure; 16. groove casts; 17. cross-bedding; 18. disconformity; O_1y^1, O_1y^2, O_1y^3—the first, second, and third members of the Yinzhubu Formation; $O_{1\text{-}2}n$—Ningguo Formation; $O_{2\text{-}3}h$—Hule Formation; O_3y—Yanwashan Formation; ϵOx^3—the third member of Xiangshan Formation; O_3h—Huangnigang Formation; O_3c—Changwu Formation; O_3w—Wenchang Formation; O_1l—Lunshan Formation; O_1h—Honghuayuan Formation; $O_{1\text{-}2}g$—Guniutan Formation; SB1—type-I unconformity interface; SMST—shelf marginal systems tract; TST—transgressive systems tract; CS—starved section; HST—Highstand systems tract

characteristics of the volcanic rocks in the Shanxi great valley profile (PM023) in Xianxia map sheet, the profiles of Chuancun map sheet including Dongtianmu profile (PM020) in Lin'an City, Dongkencun profile (PM026) in Lin'an City, and Gaohong–Tianhuangping profile (PM060) as well as along the geological observation traverse.

2.5.1 Lithostratigraphy

On the basis of the characteristics of the lithological association, lithofacies, and spatial distribution of the volcanic rocks, Huangjian Formation in the Area is divided into four lithological members, i.e., the first member (K_1h^1), the second member (K_1h^2), the third member (K_1h^3), and the fourth member (K_1h^4), which are in angular unconformable, intrusive, or fault contact with the underlying Paleozoic strata. The first member (K_1h^1) is mainly distributed in Zhangcun and Yunti area in the west of the volcanic rock area as well as Shanxi great valley and Yangshuling forest farm area in the north of the volcanic rock area. The second member (K_1h^2) is mainly distributed in Yangtianping and Baishujian scenic area in the central and eastern part of the volcanic rock area. It is the main lithological member in the volcanic rock area. The third member (K_1h^3) is mainly distributed in Tianhuangping in the northern part of the volcanic area and locally on the top of Dongtianmu Mount in the south of the volcanic area. The fourth member (K_1h^4) is mainly distributed in Nantianmu area in the north of the volcanic rock area as well as Xitianmu and Longwang Mount in the southwest of the volcanic area.

1. **Stratigraphic section**

The lithology of the first member and the second member of Huangjian Formation is described by taking the example of the first member (K_1h^1)–the second member (K_1h^2) profile (Fig. 2.92) of Early Cretaceous Huangjian Formation of Xianxia map sheet in Shanxi great valley, Baofu Town, Anji County, Zhejiang Province. The details are as follows:

36. Light flesh red - gray quartz-monzonite porphyry; grain size of the matrix and the content and size of phenocryst decreasing at a certain degree in the contact zone with felsophyric rhyolite porphyry.

——— Intrusive contact ———

The second memberof Huangjian Formation Total thickness: 4466.0 m

35. Gray felsophyric rhyolite porphyry. 502.0 m

34. Celadon andesitic dike.

33.Gray felsophyric rhyolite porphyry. 1657 m

32. Ggreenish–grayish-yellow andesitic porphyrite dike.

31. Gray felsophyric rhyolite porphyry, the content of light flesh red K-feldspar phenocrysts: 5–10%, cementation of gray felsophyric lava. 157.9 m

30. Celadon basaltic porphyrite dike.

29. Grayish felsophyric rhyolite porphyry. 3.4 m

28. Celadon basaltic porphyrite dike.

27. Grayish felsophyric rhyolite porphyry. 1.7 m

26. Celadon basaltic porphyrite dike.

25. Grayish felsophyric rhyolite porphyry. 151.4 m

24. Dark flesh red orthophyre dike.

23. Grayish blocky nevadite, the content of K-feldspar phenocrysts: 10%−15%, matrix:cementation of grayish felsophyric lava, K-feldspar porphyroclast indistinctly visible in directional arrangement in NE60° trending on the weathered surface. 656.0 m

22. Dark gray felsophyric rhyolite porphyry; generally disintegrated; the content of K-feldspar phenocrysts: 3–5%, decreased at a certain degree comparatively; cementation of dark gray felsophyric lava. 137.5 m

21. Dark gray blocky nevadite; the content of phenocrysts: about 10%–15%,increased comparatively; the

matrix: dark gray felsophyric lava. 69.6 m

20. Off-white rhyolitic vitric tuff, bearing a small amount of quartz crystal pyroclast (3–5%) and of light off-white cryptocrystalline siliceous matter and crystalvitric tuff breccia (2%–3%). 17.2 m

19. Dark gray felsophyric rhyolite porphyry, the matrix: dark gray felsophyric lava. X-shaped joints developing locally. 369.6 m

18. Dark gray-celadon dacitic tuff breccia. 85.2 m

17. Dark gray breccia-bearing vitreous rhyolite porphyry; the breccia: early erupted Amaranthine rhyolitic crystalvitric ignimbrite, grain size: about 1–6 cm; platy joints developing with the thickness of 15–40 cm. 273.1 m

16. Gray dacitic breccia-bearing crystalvitric ignimbrite, interpenetrated with small apophysis of dark gray porphyric vitreous K-feldspar rhyolite porphyry; the apophysis: irregular composite twigs, general width: 5–25 cm, general strike: 330; recrystallization occurring locally and the grain size and content of the K-feldspar pyroclasts increasing with the apophysis intruding the border. 290.4 m

15. Dark gray breccia-bearing vitreous rhyolite porphyry, containing phenocryst (10%–15%), the matrix: dark gray vitreous lava. 15.6 m

14. Gray dacitic crystalvitric ignimbrite, apparently rhyolitic bands visible on weathered surface, attitude: 100°∠77°. Medium laminated bedding developing in the bottom and gradually becoming blocky upwards.

52.8 m

———————— Volcanic-eruption unconformable contact ————————

The first member of Huangjian Formation Total thickness: 855.1 m

13. Amaranthine medium–thin laminated tuffaceous sandstone; from bottom to top, the respective thickness of conglomerate-bearing gritstone, gritstone, fine sandstone, and dark-purple silty mudstone: 10–20 cm, 10–30 cm, 5–10 cm, and 5–8 cm; the lithology of the top: Grayish black carbonaceous argillaceous siltstone. 47.7 m

12. Amaranthine rhyolitic breccia-bearing crystalvitric tuff, locally interbedded with purple mudstone; the thickness of a layer: 10–50 cm, breccia, and crystal pyroclast reducing gradually but also increasing locally upwards. 125.2 m

11. Amaranthine tuffaceous breccia-bearing sandstone; the layers containing two rhythms consisting of fine sand–silt and gritstone; the respective thickness of fine sand–silt and the gritstone: about 20 cm, and 10–20 cm.

0.5 m

10. Darcitic breccia-bearing crystalvitric ignimbrite, overlying on dacitic conglomerate-breccia-bearing crystalvitric ignimbrite in zygomorphic way. 13.9 m

9. Darcitic conglomerate-breccia-bearing crystalvitric ignimbrite: the conglomerates are elongate and elliptical with a size of about (10–40) cm × (5–10) cm and a content in the ignimbrite of 5%; the breccia is subangular–sub-rounded with a grain size of 5–60 mm. 16.2 m

8. Dark gray dacitic crystalvitric ignimbrite. 27.6 m

7. Amaranthine dacitic breccia-bearing crystalvitric ignimbrite: the breccia with a small amount (5–10%) consist of components of light flesh red rhyolite, celadon crystalvitric ignimbrite, etc. 29.5 m

6. Amaranthine dacitic magma-fragment-bearing crystalvitric ignimbrite, obvious welded bands developing with length of 1–5 cm and magma fragments as the main component; locally interpenetrated with irregular fissure

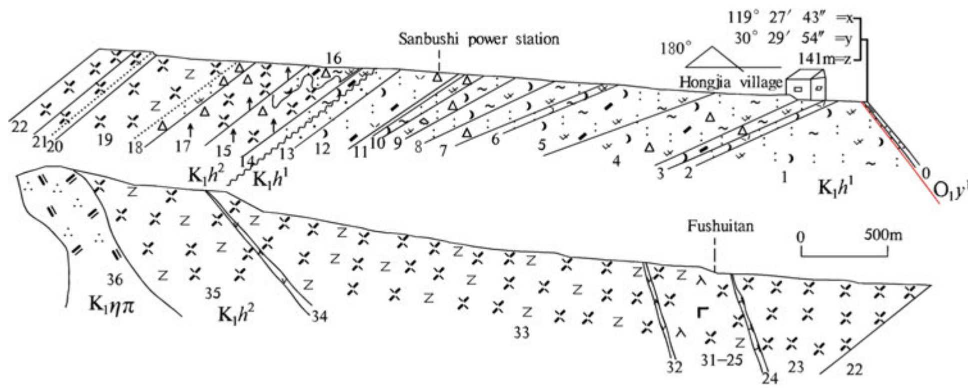


Fig. 2.92 First member (K_1h^1)–second member (K_1h^2) profile of the Early Cretaceous Huangjian Formation of Xianxia map sheet in Shanxi great valley, Baofu Town, Anji County, Zhejiang Province subvolcanic rock ($K_1\eta\pi$)

The lithology of the first member of Huangjian Formation is described by taking the example of the second member of Huangjian Formation(K_1h^2) profile (Fig. 2.93) of Chuancun map sheet in East Tianmu Mount scenic area, Lin'an City, Zhejiang Province. The details are as follows:

rhyolitic porphyry dike, which are 1–3 cm wide. 7.1 m

5. Grayish black dacitic crystalvitric ignimbrite, the crystal pyroclast of K-feldspar decreasing and the crystal pyroclast of plagioclase increasing in this bed, also containing a small amount of breccia. 280.6 m

4. Dark gray dacitic breccia-bearing crystalvitric ignimbrite. 211.3 m

3. Grayish purple dacitic breccia-bearing crystalvitric (strong) ignimbrite; welded bands developing very well; the bands: gray, distributed discontinuously, components: magma fragments and K-feldspar grains. 37.9 m

2. Amaranthine rhyolitic crystalvitric tuff, interbedded with unstable amaranthine thin laminated tuffaceous conglomerate-bearing sandstone in the lower part, a purple tuffaceous conglomerate-bearing sandstone agglomerate with the size of 2 m × 2 m visible in the upper. 18.9 m

1. Grayish purple dacitic vitric ignimbrite, welded bands (magma fragments) developing; the length and the width of the band: 1–3 cm and 0.2–1 cm. 38.7 m

——— Fault contact ———

The first member of Yinzhubu Formation of the Early Ordovician Total thickness: >30.8 m

0. Dark gray thin laminated broken hornfelsic argillaceous siltstone, interbedded with gray–off-white dolomitic limestone. 30.8 m

The middle part of the second member of Huangjian Formation Total thickness: > 303.1 m

25. Dark gray blocky rhyolite porphyry mainly composed of broken phenocrysts and matrix; the broken phenocrysts: cracks developing, fragments distributed in or close to its original place. 75.8 m

24. Light flesh red felsite vein.

23. Light flesh red rhyolite; the feldspar phenocryst: cracks developing generally; the broken fragments: distributed in or close to its original place; containing a small amount of quartz and dark minerals. 52.9 m

22. Purple-gray porphyritic rhyolite, rhyolitic structure obviously visible, rhyolitic bands developing and bypassing the phenocrysts. 111.7 m

21. Amaranthine blocky rhyolite porphyry, containing a small amount of breccia (10%) on the edge; intruded by a felsophyre vein with the width of about 8m inside this bed. 54.9 m

——— Volcanic-eruption unconformable contact ———

The lower part of the second member of Huangjian Formation Total thickness: 889.2 m

20. Caesious rhyolitic crystalvitric ignimbrite, apparently rhyolitic bands developing and bypassing crystal pyroclast; the magma fragments: celadon, arranging directionally in a depressed and elongated manner, length: 3 cm, width: 0.1–0.2 cm. 57.5 m

19. Amaranthine rhyolitic crystalvitric tuff. 25.0 m

18. Celadon altered olivine-bearing basaltic porphyrite dike.

17. Amaranthine rhyolitic crystalvitric tuff; the crystal pyroclast near the vein: content and grain size increasing, about 2–5 mm; a conglomerate layer with the thickness of about 2 m exposing locally in this bed, the breccia in the layer: content is 30% and size is 2–5 cm; quartz vein locally developing with the width of about 5–8 cm.

172.3 m

16. Celadon altered olivine-bearing basaltic porphyrite vein.

15. Amaranthine rhyolitic crystalvitric tuff. 38.1 m

14. Amaranthine rhyolitic crystal pyroclast tuff. 63.3 m

13. Celadon altered olivine-bearing basaltic porphyrite vein.

12. Amaranthine rhyolitic crystalvitric tuff; the crystal pyroclast: quantity increasing and gain size increasing to 2–4 mm upwards: the gain size of the feldspar contained: large locally, up to 1 cm × 4 cm. 155.3 m

11. Celadon rhyolitic crystalvitric tuff, celadon in the lower part and becoming amaranthine upwards. 13.8 m

10. Gray rhyolitic breccia-bearing crystalvitric tuff, with less breccia in the lower part. 6.5 m

3. Generally amaranthine rhyolitic conglomerate-breccia-bearing crystalvitric tuff, and locally rhyolitic crystal pyroclast tuff. The thickness of a single bed: 1–5 m; interbedded with amaranthine siltstone (10cm) and celadon sedimentary tuff (1m) locally. The conglomerate breccia: a small amount locally, crystal pyroclast increasing and gradually becoming rhyolitic crystal tuff. 94.2 m

2. Amaranthine rhyolitic crystalvitric tuff, apparently rhyolitic structure locally developin 40.5 m

1. Gray – celadon cataclasite, components: broken altered tufaceous conglomerate-bearing sandstone, vitric tuff, etc.; the broken zone: about 12m wide, discontinously arranged lens visible; the lens: 20–40 cm long and 6–10 cm wide. 8.1 m

——————— Fault contact ———————

The third member of Late Cambrian Xiyangshan Formation Total thickness >11.7 m

0. Gray medium–thick laminated calcareous mudstone. 11.7 m

Volcanic intrusion

24. Flesh red fine-grained granite porphyry.

25. Dark-celadon crushed fine-grained quartz diorite vein.

———————Intrusive contact———————

The third member of Huangjian Formation

26. Celadon dacitic breccia-bearing crystalvitric tuff. Owing to strong silicified alteration, local tuff becoming dense, blocky dacitic vitric ignimbrite; wide inserted and quartz felsite vein with a width of about 5m intruding and interpenetrating locally.

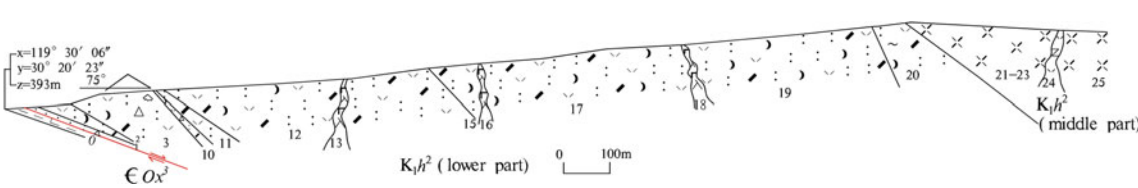


Fig. 2.93 Second member of Huangjian Formation (K_1h^2) profile in Tianmu Mount Scenic Area, Lin’an City, Zhejiang Province

The lithology of the third member of Huangjian Formation is described by taking the profile of the second member of Early Cretaceous Huangjian Formation (K_1h^2) (Fig. 2.94) of Chuancun map sheet in Dongken Village, Lin'an City, Zhejiang Province. The details are as follows:

The lithology of the third member of Huangjian Formation is described by taking the profile of the third member of Huangjian Formation (K_1h^3) (Fig. 2.95) of Chuancun map sheet in Dashancun–Tianhuangping area, Gaohong Town, Lin'an City, Zhejiang Province. The details are as follows:

27. Light flesh red felsite vein.

28. Gray rhyolitic crystalvitric tuff.

29. Light flesh red felsite vein.

30. Dark gray dacitic breccia-bearing crystalvitric ignimbrit e.

31. Light off-white thin–medium laminated tufaceous arkose, the thickness of a single layer: 5–30 cm, horizontal bedding extremely developing, diagonal bedding locally developing; components: fine sand generally, interbedded with 2–20 mm thick medium sand in the middle part.

32. Gray dacitic crystalvitric ignimbrite, apparently rhyolitic structure developing, containing an extremely small amount of breccia locally. The bioclastic pyroclast has been devitrified and becomes felsic aggregate, with the shape of plastic vitreous pyroclasts generally.

———— Volcanic-eruption unconformable contact ————

The second member of Huangjian Formation

33. Purple-gray–gray-black rhyolitic ignimbrite.

Volcanic intrusion

19. Grayish - light flesh red porphyritic mid-fine grained quartz monzonite.

———— Intrusive contact ————

The middle part of the second member of Huangjian Formation — Total thickness: 2317.9 m

18. Light flesh red–flesh red fine–micro grained rhyolitic tuff lava. 149.9 m

17. Light flesh red –flesh red fine-grained granite porphyry.

16. Light flesh red–flesh red fine–micro grained rhyolitic tuff lava. 555.8 m

15. Celadon andesite dikes.

14. Light flesh red–flesh red fine–micro grained rhyolitic tuff lava. 82.5 m

13. Light flesh red medium–micro grained rhyolitic tuff lava, off-white locally, the content of plagioclase increasing. 623.0 m

12. Light flesh red fine–micro grained rhyolitic tuff lava, the thickness of the matrix decreasing obviously compared with the beds above. 88.9 m

11. Light flesh red–light off-white medium–fine grained rhyolitic tuff lava, the grain size of the minerals slightly decreasing compared with the beds above. 101.9 m

10. Celadon andesitic dike.

9. Grayish–gray, medium-fine grained rhyolitic tuff lava, two sets of columnar joints developing; the respective intervals between horizontal joints and between vertical joints: about 150 cm and 10–90 cm; light flesh red fine-grained orthophyre vein with a width of about 8m visible locally. 261.3 m

8. Celadon andesite and light flesh red orthophyre dikes.

7. Grayish–gray medium-fine grained rhyolitic tuff lava, a set of joints with the attitude of 10°∠80° developing; the interval between the joints: about 20–100 cm. 77.4 m

——— Fault contact ———

6. Light flesh red crushed medium-fine grained rhyolitic tuff lava; pretty broken in general, secondary fracture surface developing internally; the width of the broken zone: about 10m as a whole; cataclasite and broken mud with a thickness of a about 10–40cm developing near the main fracture surface; the main fracture surface and the secondary fracture surface constituting a lentoid broken zone with a size of about 6 m × 2 m, belonging to tensile-torsional normal fault. 20.6 m

5. Gray-yellow andesitic dike.

4. Light flesh red fine-grained porphyritic syenite vein.

——— Intrusive contact ———

The lower of the second member of Huangjian Formation Total thickness: >174.0 m

3. Gray-purple rhyolitic crystalvitric tuff, silicified alteration developing. 41.4m

2. Celadon andesitic dike.

1. Gray rhyolitic crystalvitric tuff; strong silicified alteration developing; vitric pyroclast: recrystallized and micro-fine grained, with strongly coarse fracture surface. The rocks in this bed become dark gray-purple and denser gradually frontwards. The crystal pyroclasts of K-feldspar and quartz feature clear contour, and the crystal pyroclasts of K-feldspar increases locally. 132.6 m

Subvolcanic rock

22. Celadon—tawny rhyolite porphyry.

——— Intrusive contact ———

The third member of Huangjian Formation Total thickness: 2040.2 m

21. Gray–grayish rhyolitic conglomerate-breccia-bearing crystal ignimbrite; the agglomerate: (6–10cm) × (2–6 cm) in size; the breccia: 2–6 mm in size, mainly composed of amaranthine and celadon ignimbrite and tuff. A small amount of celadon magma fragment bands developing; the bands: arranging directionally and discountinously, size: (5–30) mm (length) × (1–5) mm (width). 257.0 m

20. Gray–dark gray dacitic crystal ignimbrite; light flesh red syenite and dark gray dacitic breccia visible individually; the size of the breccia: 10 cm × 5 cm–3 cm × 1.5 cm. 313.2 m

19. Gray ivernite.

18. Grayish–gray rhyolitic dacitic breccia-bearing crystalvitric ignimbrite, apparently rhyolitic structures visible locally. 571.2 m

17. Dark gray dacitic crystalvitric ignimbrite generally and vitric ignimbrite locally. Tufaceous cement feasures obviously higher density and high welding degree compared with the beds above. 7.0 m

16. Light flesh red fine-grained syenite vein.

15. Gray–dark gray dacitic crystal-bearing crystalvitric ignimbrite. 19.3 m

14. Gray ivernite.

13. Gray–dark gray dacitic breccia-bearing crystalvitric ignimbrite; the welding degree of the rocks in this bed is obviously higher compared with the beds above, and local rocks become gray-purple. 8.2 m

12. Celadon andesitic dike.

11. Grayish rhyolitic dacitic breccia-bearing crystalvitric tuff with weak welding. 96.8 m

10. Off-white felsite vein.

9. Gray-purple dacitic crystal vitric ignimbrite, nearly upright cleavages developing in the rocks on the edge of the contact zone. 60.6 m

8. Light flesh red fine-grained granite porphyry.

7. Gray dacitic crystalvitric ignimbrite, the content of crystal pyroclasts obviously decreases locally. 260.7 m

6. Gray dacitic crystalvitric ignimbrite, apparently rhyolitic structure developing. 47.9 m

5. Gray-purple rhyolitic dacitic breccia-bearing crystalvitric ignimbrite, apparently rhyolitic structure developing, agglomerate invisible, the content of breccia obviously decreases. 36.2 m

4. Off-white rhyolitic dacitic conglomerate-breccia-bearing crystalvitric ignimbrite; the respective size of the agglomerate and the breccia: 6–10 cm and 2–3 cm; both the agglomerate and the breccia mainly composed of (crystal) vitric ignimbrite and cryptocrystalline siliceous matter, etc.; apparently rhyolitic structure developing. 65.2 m

3. Grayish–dark gray rhyolitic dacitic crystalvitric ignimbrite, containing a small amount of dark gray–grayish breccia with a size of 2–8 mm. 113.8 m

2. Light flesh red rhyolitic tuff lava. 27.8 m

1. Gray rhyolitic dacitic breccia-bearing crystal ignimbrite; compared with the lava in the beds above, the outcrops feature obviously coarser weathering surface and no developed joint structure. Intrusion of andesitic dike with a width of about 10 cm is visible locally. 65.3 m

Volcanic-eruption unconformable contact

The second member of Huangjian Formation Total thickness > 12.4 m

0. Light flesh red - dark gray rhyolitic tuff lava. 12.4 m

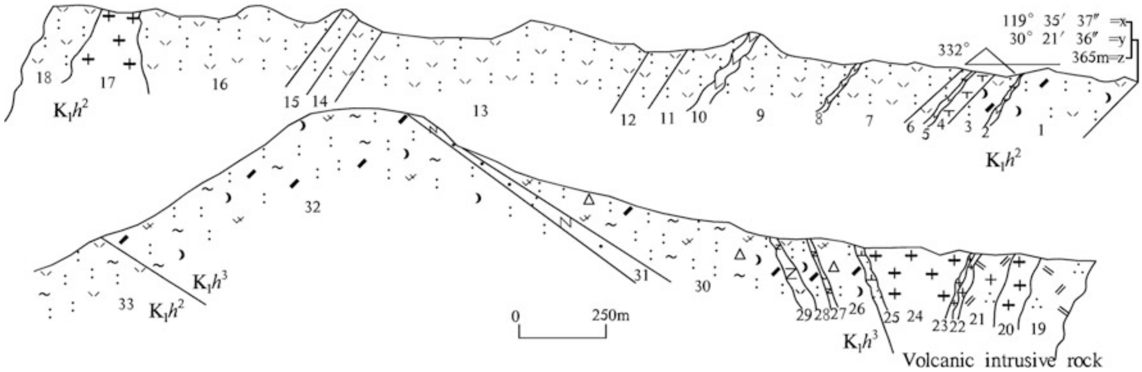


Fig. 2.94 Second member (K_1h^2)–third member (K_1h^3) tectonic–stratigraphic profile of the Early Cretaceous Huangjian Formation in Dongken Village, Lin'an City, Zhejiang Province

2. **Lithological characteristics**

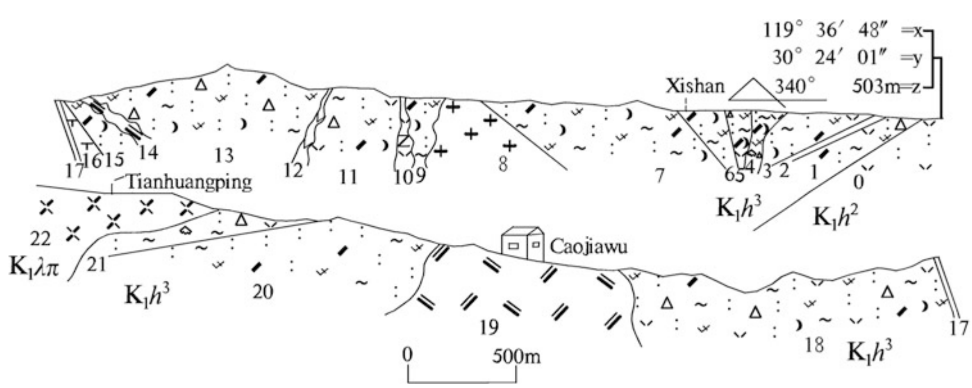
The lithology of the first member of Huangjian Formation (K_1h^1) is mainly characterized by dacitic conglomerate-bearing (magma-fragment-bearing) crystalvitric (strong) ignimbrite, rhyolitic dacitic crystalvitric tuff, and the interbeds consisting of tufaceous conglomerate-bearing sandstone, tufaceous sandstone, and siltstone.

(1) The dacitic conglomerate-bearing (magma-fragment-bearing) crystalvitric (strong) ignimbrite: light purple and gray, interbedded with amaranthine rhyolitic conglomerate-bearing crystalvitric tuff locally, interbedded with unstable thin laminated amaranthine tuffaceous conglomerate-bearing sandstone in its lower part. The thickness: greater than 682.2 m.
(2) The rhyolitic dacitic crystalvitric ignimbrite: light gray, thick–medium laminated generally, locally interbedded with 10–50-cm-thickness purple mudstone. The thickness: 125.2 m.
(3) The interbed consisting of tufaceous conglomerate-bearing sandstone, tufaceous sandstone, and siltstone: light purple-gray, medium–thin laminated generally, featuring internal dipping. The thickness: about 47.7 m.

The lithology of the second member of Huangjian Formation (K_1h^2) is mainly characterized by rhyolitic crystalvitric ignimbrite, vitric blocky rhyolite porphyry, felsitic blocky rhyolite porphyry, felsitic blocky nevadite, porphyritic rhyolite, micro-(fine)-grained rhyolitic tuff lava, etc.

(1) The rhyolitic crystalvitric ignimbrite: grayish–gray; thick laminated–blocky rhyolitic agglomerate breccia, rhyolitic crystalvitric tuff, and tufaceous conglomerate-bearing sandstone of volcanic sedimentation facies developing locally at the bottom. The thickness: 445.6–2373.6 m.
(2) The vitric blocky rhyolite porphyry, felsitic blocky rhyolite porphyry, and felsitic blocky nevadite: gray–dark gray, no rhyolitic structure developing. The phenocrysts feature broken cloudy shape that can be spliced together locally. The matrix features vitric structure on the edge and felsitic structure in the middle part. The thickness: about 4466 m.
(3) The porphyritic rhyolite: gray, grayish and gray purple, rhyolitic structure and a small amount of bubble structure developing, the attitude of rhyolitic structure

Fig. 2.95 Profile of the third member of Huangjian Formation (K_1h^3) (Fig. 2.95) in Dashancun–Tianhuangping, Gaohong Town, Lin'an City, Zhejiang Province



dipping northward or southward in general. The thickness: greater than 303.1 m.

(4) The micro-(fine)-grained rhyolitic tuff lava: grayish, no rhyolitic structure developing, composed of single component, the component of the phenocrysts: feldspar (20–40%). The thickness: greater than 2060 m.

The lithology of the third member of Huangjian Formation (K_1h^3) is mainly characterized by amaranthine and gray rhyolitic dacitic ignimbrite, and apparently rhyolitic structure band developed. The thickness of this member is about 341–2,701.8 m.

The lithology of the fourth member of Huangjian Formation (K_1h^4) is mainly characterized by light purple-gray–grayish bubble rhyolite or porphyritic rhyolite. The thickness of this member is about 560.1 m.

For specific lithological characteristics, refer to the sections about the features and types of volcanic rocks in Sect. 3.2.

2.5.2 Biostratigraphy and Chronostratigraphy

In this Project, no fossils were discovered in Huangjian Formation. According to previous information such as the regional geological survey on a scale of 1:200,000 of Lin'an map sheet in the Area, the biological fossils were mainly discovered locally in the first member (the former Laocun Formation) of Huangjian Formation all through in Huangjian Formation. The outcropped fossils mainly include the ones of *Ephemeropsis trisetalis* insects, *Zamites sp*. (new united), *Solenites sp*. (*approximate murrayana L. et H*), *Yong'an Sagenopteris, Podozamites lanceolatus, Coniopteris burejensis, Brachyphyllum obesum, midsized brachygrapta*, *Chinese Bairdestheria*, *Yumen bairdestheria,* and *Zhejiang bairdestheria*. Among these organisms, *Ephemeropsis trisetalis insects* are the most typical.

According to zircon U-Pb dating of the volcanic rocks and subvolcanic rocks in Huangjian Formation in the area, the age range of the volcanic rocks is 135.2–125.4 Ma (refer to the sections about the age and rhythm of volcanic eruption in Sect. 3.2 for specific chronological features). It is basically consistent with the age (134–115 Ma) obtained in the area where Jiande Zhou family is located by Li et al. (2011), geologically belonging to the Early Cretaceous.

2.6 Quaternary System

The Quaternary in the Area mainly consists of Yinjiangqiao Formation (Qh*y*). Yinjiangqiao Formation is about 61.25 km^2, accounting for about 4.6% of the total area. It is distributed in Hanggai Town and Baofu Town in southeast of Hanggai map sheet and Zhangcun Town and Xianxia Town in the northwest of Xianxia. Besides, it is exposed locally in Shanchuan Town and Baishuijian scenic area of Chuancun map sheet. The exposed strata are single, and only Holocene Yinjiangqiao Formation is visible. In terms of the origin types of formation, alluviation is the main type, and eluvial and proluvial rank the second.

Yingjiangqiao Formation (Qh*y*) is mainly distributed in the riverbeds of open and wide river valleys, first terrace, washland terrace as well as narrow and long gulley, such as the basin of Fushi Reservoir and Laoshikan Reservoir. A small amount of the formation is distributed in the footslope area in front of mountains. The formation is mainly formed by proluvial–alluviation and generally consists of banded landforms such as valley plains, river terrace, and proluvial fan. The lithology of this formation is mainly characterized by loose conglomerate stratum, sandy loam, and loam formed owing to alluviation and pluvial–alluvial, which constitute the dual structure of fluvial facies. In addition, there are small amounts of crushed rock layers and crushed-rock-bearing clay formed owing to eluvial and proluvial. The sand and conglomerate feature good sorting and roundness, and contain much cohesive soil locally. The formation is grayish yellow and gray generally, loosely structured, and 1–5 m thick. It overlies strata and migmatite of the pre-Cenozoic in the manner of angular unconformity.

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