



# Response to the Lomagundi-Jatuli Event in the southwestern margin of the Yangtze Plate: Evidence from the carbon and oxygen isotopes of the Paleoproterozoic Yongjingshao Formation

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## ARTICLE INFO

### Article history:

Received 9 May 2021

Received in revised form 20 April 2022

Accepted 12 May 2022

Available online 25 May 2022

### Keywords:

Lomagundi-Jatuli Event

Eucaryon

Paleoproterozoic

Bean-shaped fossil

Micro-filament fossil

Micro-columnar fossil

Carbon and oxygen isotopes

Yangtze Plate

Geological survey engineering

China

## ABSTRACT

The Lomagundi-Jatuli Event (LJE) refers to the significant positive carbon isotope excursion in seawater constituents that occurred immediately after the increase in atmospheric oxygen content during the Paleoproterozoic (2.22–2.06 Ga). The  $\delta^{13}\text{C}$  values of 46 dolostone samples collected from the Paleoproterozoic Yongjingshao Formation varied in the range of 0.05‰–4.95‰ (V-PDB; maximum: 4.95‰) in this study, which may be related to the multicellular eukaryotes in the Liangshan Formation in the Yimen Group. They are much higher than the  $\delta^{13}\text{C}$  values of marine carbonates (–1.16‰ on average). The  $\delta^{13}\text{C}$  values of other formations in the Paleoproterozoic Yimen Group are negative. The notable positive carbon isotope anomalies of the Yongjingshao Formation indicate the response to the LJE at the southwestern margin of the Yangtze Block, which is reported for the first time. Furthermore, they are comparable to the  $\delta^{13}\text{C}$  values of carbonates in the Dashiling Formation of the Hutuo Group in the Wutaishan area in the North China Craton, the Wuzhiling Formation of the Songshan Group in the Xiong'er area, Henan Province, and the Dashiqiao Formation of the Liaohe Group in the Guanmenshan area, Liaoning Province. Therefore, it can be further concluded that the LJE is a global event. This study reveals that LJE occurred in Central Yunnan at 2.15–2.10 Ga, lasting for about 50 Ma. The macro-columnar, bean-shaped, and microfilament fossils and reticular ultramicrofossils of multicellular eukaryotes in this period were discovered in the Liangshan Formation of the Yimen Group. They are the direct cause for the LJE and are also the oldest paleontological fossils ever found. The major events successively occurring in the early stage of the Earth include the Great Oxygenation Event (first occurrence), the global Superior-type banded iron formations (BIFs), the Huronian glaciation, the Great Oxygenation Event (second occurrence), the explosion of multicellular eukaryotes, the positive carbon isotope excursion, and the global anoxic and selenium-rich sedimentary event. The authors think that the North China Craton and the Yangtze Craton were possibly in different tectonic locations of the same continental block during the Proterozoic.

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## 1. Introduction

The study of tectonic events, ancient organisms, and

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Literary editor: Xi-jie Chen

doi:10.31035/cg2022033

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paleoclimate changes during the Early Proterozoic is currently a major cutting-edge topic in the geoscience field. The most dramatic change in the early stage of the Earth is probably the increase in the atmospheric oxygen content during the Paleoproterozoic (2.45–2.32 Ga), which is commonly known as the Great Oxygenation Event (GOE) (Chen YJ et al., 1998; Bekker A et al., 2006, 2008; Frauenstein F et al., 2009; Mاسترا S, 2010; Zhao ZH, 2010; Tang HS et al., 2011; Yang FY and Li LM, 2015; Peng P et al., 2017). This was immediately followed by a significant carbon isotope positive

excursion in seawater constituents, which is called the Lomagundi carbon isotope anomaly or LJE. The Lomagundi carbon isotope excursion (LJE) refers to the highly positive carbon isotope values of carbonates deposited at around 2.22–2.06 Ga during the Paleoproterozoic and it may reflect the composition of seawater. It is presently believed that the LJE was caused by the GOE and is possibly the response to the GOE. Accordingly, ancient organisms started to reproduce and gave rise to the longest and most serious disturbance to the biogeochemical carbon cycle in Earth history. Presently, many studies have been carried out on the LJE outside of China and they are mainly concentrated in the Lomagundi Group in Zimbabwe, the Tulomozerskaya Formation in Europe, and the Slaughterhouse Formation in North America (Kong FF et al., 2011; Tang HS et al., 2011; Lai Y et al., 2012; Kazumi O and Eiichi T, 2015). The LJE reported in China mainly occurred in the carbonates in the Hutuo Group in the Wutaishan area in the North China Craton in North China, the Paleoproterozoic Songshan Group in Henan Province, and the Liaohe Group in Guanmenshan area in Liaoning Province (Fig. 2b; Zhong H et al., 1993; Tang GJ et al., 2004; Tang HS et al., 2008; Yang FY and Li LM, 2015), while there is no report on the LJE in the Yangtze Block.

The Paleoproterozoic Yimen Group has been recently determined according to the latest geological field data and isotopic geochronological data of areas in Central Yunnan including Yinmin Town in Dongchuan District of Kunming City (Li J et al., 2018a; Liu JP et al., 2018b, 2020c, 2021a, b, c, e, f, 2022; Cui XZ et al., 2019, 2020), Tongchang Town in Yimen County, and Cuoke Village in Yuanjiang City during the preparation of the *Annals of Regional Geology of Yunnan Province* (Version 2, revision)<sup>①</sup> and the implementation of two 1:50000 regional geological survey projects of four map sheets in Yunnan Province represented by the Erjie<sup>②</sup> and Samaji<sup>③</sup> map sheets, respectively. The Paleoproterozoic Yimen Group is further divided into six formations, namely Abudu (Pt<sub>1a</sub>), Luowadie (Pt<sub>1l</sub>), Liangshan (Pt<sub>1s</sub>), Yongjingshao (Pt<sub>1y</sub>), Xishancun (Pt<sub>1x</sub>), and Shanmuqing (Pt<sub>1s</sub>) formations from bottom to top. It records a series of major geological events occurring in the early stage of the Earth (Li J et al., 2018a; Liu JP et al., 2020c, 2022), thus providing favorable conditions for the study of the LJE. Among its formations, the Paleoproterozoic Yongjingshao Formation (2.15–2.10 Ga), dominated by carbonates, is ideal for the study of the LJE and is also currently a research hotspot in the international geoscience field (Li J et al., 2018a; Liu JP et al., 2018b, 2019, 2020b; 2021c; Cui XZ et al., 2019, 2020).

This paper reports the characteristics of carbon and oxygen isotope data and new field findings of the carbonates

in the Paleoproterozoic Yongjingshao Formation in the Yimen-Dongchuan area at the southwestern margin of the Yangtze Block. By comparison with global relevant data, the carbon and oxygen isotope data and field data reported in this study allow for: (1) Conducting regional lithostratigraphic correlation based on carbon isotope data; (2) providing new constraints on the development of Paleoproterozoic basins in Central Yunnan; (3) ascertaining and redefining of the Precambrian stratigraphic eras, sequences, and tectonic framework of the southwestern margin of the Yangtze Craton and discussing the tectonic location relationship between the North China Craton and the Yangtze Craton during the Proterozoic; (4) discussing the age ranges of Proterozoic organisms and their relationships with the environment, and (5) discussing the age ranges and interrelations of major events during the Paleoproterozoic.

## 2. Geological setting

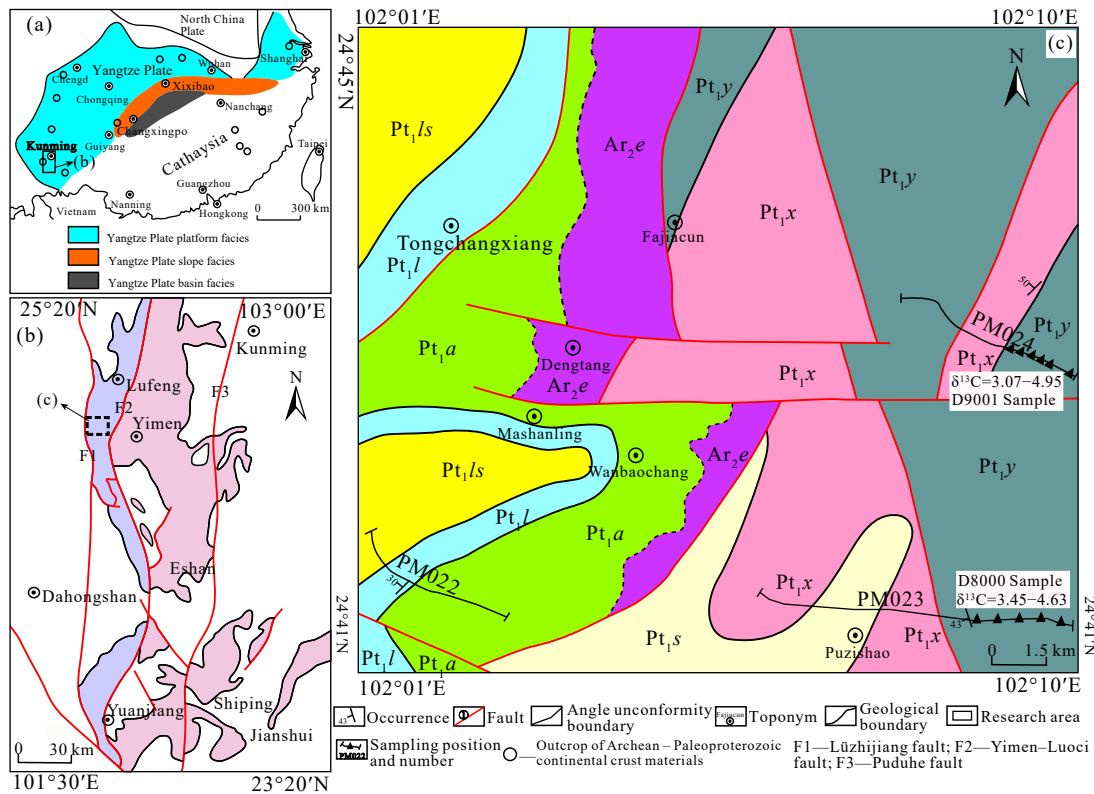
The study area is located in the Yimen area in Central Yunnan. Tectonically, it lies in the border area between two third-order tectonic units, namely the Chuxiong intracontinental basin (VI-2-12) and the Kangding-Yunnan basement fault-uplift zone (VI-2-11) in the ancient upper Yangtze Block (VI-2) on the Yangtze Plate (VI; Fig. 1a). Stratigraphically, it lies at the junction of the Chuxiong (VI<sub>4</sub><sup>2-1</sup>) and Kunming (VI<sub>4</sub><sup>2-2</sup>) stratigraphic minor regions in the Kangdian stratigraphic subregion (VI<sub>4</sub><sup>2</sup>), which is a part of the Yangtze stratigraphic region (VI<sub>4</sub>) in the South China stratigraphic super region. The outcrops in the study area include Archaean and Paleoproterozoic strata (Fig. 1c).

The Manlin Formation (Ar<sub>2m</sub>) of the Mesoarchean Yuanjiang Group is a set of flysch-like rhythms consisting of light-gray calcareous dolomitic granular quartzite (sandstones) and dark-gray phyllitic argillite, as well as a small amount of interbedded dolostone. As for the six formations in the Paleoproterozoic Yimen Group, the Abudu Formation (Pt<sub>1a</sub>) consists of clastic rocks interbedded with volcanic rocks and dolostones, and this formation was deposited at 2.50–2.30 Ga; the Luowadie Formation (Pt<sub>1l</sub>) is composed of volcanic rocks interbedded with dolostones, and this formation was deposited at 2.30–2.18 Ga; the Liangshan Formation (Pt<sub>1s</sub>) comprises clastic rocks interbedded with carbonates and was deposited at 2.18–2.15 Ga; the Yongjingshao Formation (Pt<sub>1y</sub>) mainly consists of carbonates interbedded with a small amount of slates and was deposited at 2.15–2.10 Ga; the Xishancun Formation (Pt<sub>1x</sub>) is generally composed of dark-gray carbonaceous silty slates and carbonaceous argillite interbedded with sandy slates and dolostones, and this formation was deposited at 2.10–1.90 Ga;

<sup>①</sup>Geological survey reports from the *Annals of Regional Geology in Yunnan Province* (Version 2, revision). 2021. Yunnan Institute of Geological Survey (in Chinese).

<sup>②</sup>1 : 50000-scale Regional Geological Survey Report of Erjie, Yimen County, Mingyihe, and Shangpubei Map Sheets in Yunnan Province. 2018. Yunnan Institute of Geological Survey (in Chinese).

<sup>③</sup>Result Report of 1 : 50000 Geological Survey of Maji, Yimen, Guicheng, and Shugu Map Sheets in Yunnan Province. 2021. Yunnan Institute of Geological Survey (in Chinese).



**Fig. 1.** Geotectonic location maps (a, b) and geological sketch map and sampling points (c) of the study area.  $Ar_2e$ —Etouchang Formation of Yuanjiang Group;  $Pt_1a$ —Abudu Formation of Yimen Group;  $Pt_1l$ —Luowadie Formation of Yimen Group;  $Pt_1s$ —Liangshan Formation of Yimen Group;  $Pt_1y$ —Yongjingshao Formation of Yimen Group;  $Pt_1x$ —Xishancun Formation of Yimen Group;  $Pt_1s$ —Shanmuqing Formation of Yimen Group; a—Geotectonic location map; b—geological sketch map of the study area; c—map showing the distribution of carbon and oxygen isotopes.

finally the Shanmuqing Formation ( $Pt_1s$ ) mainly includes volcanic rocks interbedded with clastic rocks and was deposited at 1.90–1.80 Ga (Li J et al., 2018b; Liu JP et al., 2018a, 2019, 2020b, 2020c, 2021d).

### 3. Sample collection and analysis

The section researched in this study is located along the secondary highways in Yunnan Province that respectively join Yimen County to Tongchang Town and Yimen County to Dapojiao Village (Fig. 1), where fresh outcrops can be found. A total of 94 carbon and oxygen isotope samples were collected from the section. Among them, 46 carbon and oxygen isotope samples were taken from the Paleoproterozoic Yongjingshao Formation ( $Pt_1y$ ) (Table 1), and the rest from the carbonate interbeds in the Paleoproterozoic Abudu ( $Pt_1a$ ), Luowandie ( $Pt_1l$ ), Liangshan ( $Pt_1s$ ), and Xishancun ( $Pt_1x$ ) formations.

Dolostones and limestones were researched in this paper. Fresh carbonate samples without shear deformation, foliation, or fracture were intermittently collected from the section during the 1 : 5000 geological section survey. Then thin section identification under a microscope was adopted to verify whether the samples were composed of carbonates. Carbon and oxygen isotopic analyses were carried out in the Hubei Geological Research Laboratory, Wuhan Sample Solution Analytical Technology Co. Ltd., and Beijing Createch Testing Technology Co., Ltd. Carbon and oxygen

isotope analyses were conducted according to the following steps. The carbonate samples were crushed into 200 mesh powders. Then the powders were elutriated to separate calcites or dolostones from them. Afterward, the calcites or dolostones were added to 100% phosphoric acid in a water bath at a constant temperature of  $(50 \pm 0.2)^\circ\text{C}$  in a vacuum system and left to react for 24 hours. The released  $\text{CO}_2$  was then collected for mass spectrometric analysis (samples were prepared with phosphoric acid) using a 253 Plus Isotope Ratio Mass Spectrometer equipped with GasBench. The standards used to report the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of carbonates are the Vienna Pee Dee Belemnite (V-PDB) and Vienna standard meteoric ocean water (V-SMOW), respectively. The test accuracy was 0.2‰ ( $1\sigma$ ), and the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of the certified reference materials for V-PDB and V-SMOW standards were 0.57 and  $-8.49$ , respectively (Rosenbaum J and Sheppard SMF, 1986; Chen YQ et al., 2005).

### 4. Testing results

The LJE is the most important global event after the GOE (Chen YJ et al., 1998; Bekker A et al., 2006, 2008; Frauenstein F et al., 2009; Mاسترا S, 2010; Zhao ZH, 2010; Yang FY and Li LM, 2015). The  $\delta^{13}\text{C}$  values of 46 dolostone samples taken from the Yongjingshao Formation varied in the range of 0.05‰–4.95‰ (V-PDB, maximum: 4.95‰). They are notably higher than the  $\delta^{13}\text{C}$  values of marine carbonates ( $-1.16$ ‰ on average). As a comparison, the  $\delta^{13}\text{C}$  values of

other formations in the Paleoproterozoic Yimen Group were negative, the second highest  $\delta^{13}\text{C}$  value occurred in the Liangshan Formation, and the  $\delta^{13}\text{C}$  values of three samples from the Xishancun Formation were the lowest ( $-7.90$ – $-5.69$ , average:  $-6.80$ ; Table 1; Fig. 2a). The notable positive carbon

**Table 1. Analytical results of carbon and oxygen isotopes of the Yongjingshao Formation in Yimen area, Yunnan Province.**

Sample No.	Sample name	$\delta^{13}\text{C}_{\text{V-PDB}}/\text{‰}$	$\delta^{18}\text{O}_{\text{V-SMOW}}/\text{‰}$
D8000-7	Limestone	2.13	-9.15
D8000-8	Limestone	1.61	-10.02
D8000-9	Limestone	0.86	-8.73
D8000-11	Limestone	2.78	-7.49
D8000-14	Limestone	1.84	-9.23
D8000-15	Dolostone	3.45	-10.96
D8000-16	Limestone	2.61	-15.74
D8000-17	Limestone	2.67	-7.93
D8000-19	Limestone	0.40	-13.02
D8000-20	Dolostone	3.00	-6.45
D8000-22	Limestone	0.07	-10.52
D8000-23	Dolostone	3.48	-14.01
D8000-24	Dolostone	2.64	-11.68
D8000-25	Dolostone	4.63	-11.70
D8000-26	Limestone	1.78	-13.38
D8000-27	Limestone	0.05	-12.13
D8000-28	Limestone	1.92	-13.37
D8000-29	Limestone	1.73	-8.88
D8000-35	Dolostone	4.20	-11.31
D8000-36	Dolostone	4.62	-9.85
D8000-40	Dolostone	0.05	-10.25
D8000-48	Dolostone	0.18	-9.48
D8000-49	Dolostone	1.48	-7.01
D8000-50	Limestone	1.37	-7.20
D8000-51	Dolostone	1.23	-7.68
D8000-53	Limestone	1.14	-9.06
D8000-54	Dolostone	1.03	-8.97
D8000-55	Limestone	1.24	-7.67
D8000-56	Dolostone	1.13	-7.80
D8000-58	Dolostone	1.11	-7.94
D8000-59	Dolostone	0.29	-8.37
D8000-61	Dolostone	0.54	-11.53
D8000-62	Dolostone	0.64	-11.21
D8000-63	Limestone	0.84	-11.34
D8000-64	Dolostone	0.05	-10.64
D9001-2	Dolostone	0.37	-11.37
D9001-11	Limestone	0.78	-15.33
D9001-12	Dolostone	4.57	-12.41
D9001-14	Dolostone	2.47	-13.12
D9001-15	Limestone	3.95	-5.38
D9001-16	Dolostone	4.03	-5.67
D9001-20	Limestone	2.46	-13.28
D9001-21	Dolostone	4.95	-9.54
D9001-25	Dolostone	3.07	-12.59
D9001-26	Dolostone	2.76	-13.56
D9001-27	Dolostone	3.76	-10.56

Notes: V-PDB denotes the Vienna Pee Dee Belemnite; V-SMOW represents the Vienna standard mean ocean water; and  $\delta$  refers to relative abundance of stable isotopes. Other data are not listed here.

isotope anomalies of the Yongjingshao Formation indicate the response to the LJE at the southwestern margin of the Yangtze Block. Moreover, they are comparable to the  $\delta^{13}\text{C}$  values of the carbonates in the Dashiling Formation of the Hutuo Group in the Wutaishan area of the North China Craton, the Wuzhiling Formation of the Paleoproterozoic Songshan Group in Henan Province, and the Dashiqiao Formation of the Liaohu Group in the Guanmenshan area, Liaoning Province. This further indicates that the LJE is a global event, which provides an important concept and a reference for further intensifying the research in this field.

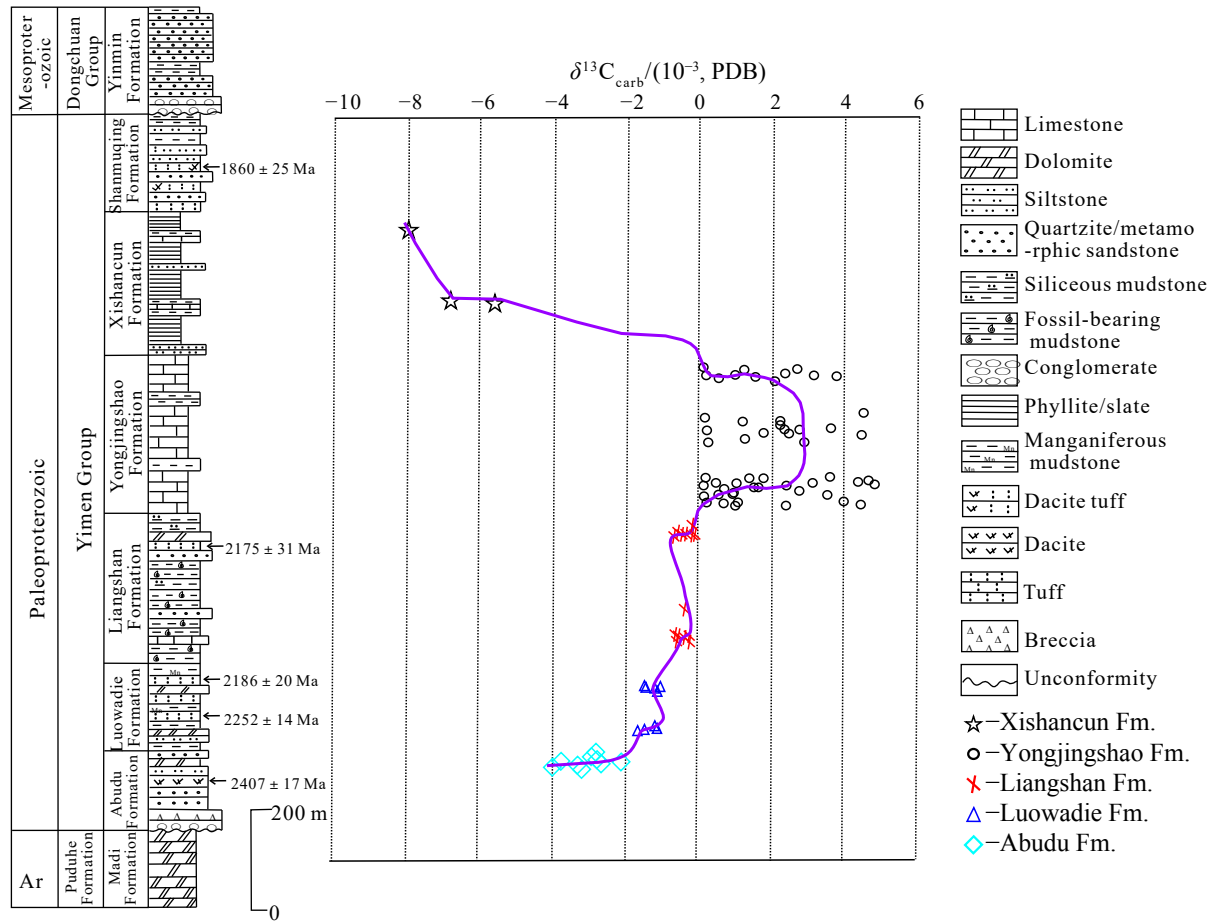
## 5. Discussion

### 5.1. Carbon isotope anomalies of Proterozoic strata and their global spread

It has been determined that the LJE occurred at around 2.22–2.06 Ga from the end of the Upper Paleoproterozoic glaciation in the Fennoscandian Craton to the mantle plume event at 2.22 Ga and, lasting for about 150 Ma (Bekker A et al., 2003; Martin AP et al., 2013). Positive carbon isotope anomalies were first found in the Paleoproterozoic carbonates in the Jatuli area ( $9.4\text{‰}\pm 0.20\text{‰}$ , V-PDB; Galimov EM et al., 1968; Schidlowski M et al., 1976). Then the positive carbon isotope anomalies in the Kuusamo Group, the Slaughterhouse Formation, the Uve Formation, and the Murmac Bay Group were subsequently reported, and the maximum  $\delta^{13}\text{C}$  value of the Nash Fork Group is up to  $+28\text{‰}$  (Fig. 3; Bekker A et al., 2006, 2008; She ZB et al., 2016). Large amounts of data at present confirm that positive carbon isotope anomalies also occurred in the North China Craton. For example, they were reported to have occurred in the Dashiling, Dashiqiao, and Guanmenshan formations (Fig. 3; Zhong H et al., 1993; Kong FF et al., 2011; Tang HS et al., 2011; Lai Y et al., 2012; Yang FY and Li LM, 2015). The abovementioned strata are similar to the Yongjingshao Formation of the Yimen Group determined in this study in terms of formation era and rock associations, appearing alternatively between clastic and carbonate rocks. From this and the positive isotope anomalies of carbon ( $0.05\text{‰}$ – $4.95\text{‰}$ , V-PDB) in the Paleoproterozoic Yongjingshao Formation in Central Yunnan at the southwestern margin of the Yangtze Block discovered by the authors, it can be inferred that the LJE also occurred in the Yangtze Block. Therefore, the LJE is confirmed as a global event, which provides strong geochemical evidence for the global regional correlation of Paleoproterozoic strata.

### 5.2. Indicative significance of carbon isotope anomalies

The LJE represents a significant disturbance to the carbon cycle of the Earth in the deep time. Life on Earth consisted of carbon-based organisms, and thus a large-scale change and fluctuation of the carbon cycle played a key role in the origin and early evolution of the Earth's biosphere. Marine carbonates serve as the most important carriers of carbon elements. Therefore, the study on the carbon isotopes in



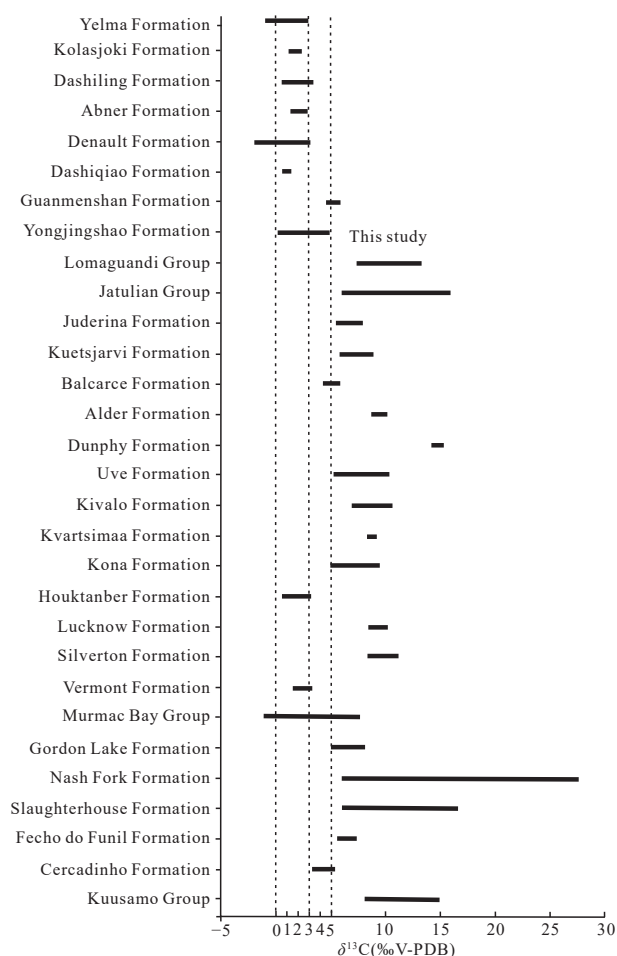
**Fig. 2.** Characteristics of carbon and oxygen isotopes of Paleoproterozoic strata (Yimen Group) in the Central Yunnan.

Paleoproterozoic marine carbonates can provide an important basis for reconstructing the evolutionary history of the Earth's paleoclimate, paleogeography, and ancient marine environment and, at the same time, it is an important method and means for the global regional stratigraphic correlation and the research on major geological events in the early stage of the Earth (Chen YJ et al., 1996; Guan P, Guan P and Wang YJ, 2009; Yang FY and Li LM, 2015; Li J et al., 2018a).

The Paleoproterozoic strata exposed in many areas in the North China Craton keep records of positive carbon isotope excursions. The  $\delta^{13}\text{C}$  values of the Hutuo Group in the Wutaishan area vary in the range of  $-3.7\text{‰}$ – $-3.5\text{‰}$  (V-PDB; Zhong H et al., 1993; She ZB et al., 2016; Chen WY et al., 2018b), those of the Paleoproterozoic Songshan Group in Xionger area, Henan Province vary between  $0.4\text{‰}$  and  $4.2\text{‰}$  (V-PDB; Lai Y et al., 2012), and those of the Liaohe Group in Benxi area, Liaoning Province vary from  $3.5\text{‰}$  to  $5.9\text{‰}$  (V-PDB; Tang HS et al., 2011; Yang FY and Li LM, 2015). Similarly, the Yongjingshao Formation in the Paleoproterozoic Yimen Group in Central Yunnan at the southwestern margin of the Yangtze Block reported in this study also shows positive carbon isotope anomalies, with  $\delta^{13}\text{C}$  values of  $0.05\text{‰}$ – $4.95\text{‰}$  (V-PDB; Fig. 3). These indicate that the Yongjingshao Formation is comparable to the Dashiling Formation of the Hutuo Group, the Wuzhiling Formation of the Songshan Group, and the Dashiqiao Formation of the

Liaohe Group mentioned above (Fig. 4). The LJE provoked a strong response in the Yongjingshao Formation of the Yimen Group in Central Yunnan, which was deposited at 2.15–2.10 Ga. Subsequently, the overlying black shale of the Xishancun Formation represents the start of a reducing environment, which may denote the end of the local LJE (Li J et al., 2018a; Liu JP et al., 2018a, 2019, 2020a, 2020c). Therefore, the LJE is a global event, and it occurred at 2.15–2.10 Ga in Central Yunnan, with a duration of about 50 Ma.

A great deal of available data show that the North China Craton and Yangtze Craton witnessed the same magmatic activities, tectonic-thermal events, paleogeographic environment, stratigraphic framework, and major tectonic events during the Proterozoic (Fig. 4; Li J et al., 2018a; Liu JP et al., 2018b, 2019, 2020b; 2022; Cui XZ et al., 2019, 2020). Furthermore, both were involved in the aggregation and break-up of the Kenorland and Columbia supercontinents as important parts (Liu JP et al., 2020c). Most notably, according to the Hf isotopic analysis of the 3890 Ma zircons discovered by Liu JP et al. (2021b) in the Proterozoic strata in the Dongchuan area, Central Yunnan, it is believed that the Dongchuan area may have a genetic relationship or affinity with the sediment provenance of the North China Craton during the Proterozoic and they may originate from the same source (Liu JP et al., 2021b). Based on this and the findings of this study, it can be further confirmed that the North China



**Fig. 3.** Carbon isotope composition of global Paleoproterozoic carbonate strata (strata are increasingly young upward; modified from Chen WY and Chen YJ, 2018a).

Craton and the Yangtze Craton may have originated from the same continental block during the Proterozoic. Their differences in deformation and metamorphism are possibly a consequence of their different tectonic locations and different tectonic events they underwent during the Proterozoic.

### 5.3. Major tectonic events and the coevolution of life recorded in the Paleoproterozoic strata in Central Yunnan

The Paleoproterozoic Yimen Group in Central Yunnan keeps records of a series of major geological events occurring in the early stage of the Earth. In detail, the Abudu Formation (Pt<sub>1a</sub>) records the early Huronian glaciation (Li J et al., 2018a); the Liangshan Formation (Pt<sub>1s</sub>) records the appearance of multicellular organisms (Figs. 5i–k; Li J et al., 2018b; Liu JP et al., 2018a, 2019); the Yongjingshao Formation (Pt<sub>1y</sub>), mainly consisting of carbonates, records the LJE event; and the Xishancun Formation (Pt<sub>1x</sub>) records the anoxic, selenium-rich, and rare earth element-rich event after the collapse of an oxygen-rich atmosphere (Kazumi O and Eiichi T, 2015; Liu JP et al., 2020c).

The Huronian glaciation, also known as the Snowball Earth event, is a global event following the BIF event during the Siderian. As the representative of the Huronian glaciation,

moraines were found in the Abudu Formation in Yimen and Dongchuan areas, Central Yunnan in this study. They show poor sorting and contain sheepback rocks and flatiron boulders, with scratches and torsion cracks visible (Figs. 5i–k). Furthermore, the carbonates in the Abudu Formation exhibit a negative carbon isotope excursion, which may be related to the massive oxidation of organic matter following the emergence of the oxygen-rich atmosphere (the Snowball Earth event). After that, the Great Oxygenation Event occurred at about 2.4 Ga, during which the oxygen content in the atmosphere greatly increased, leading to the aerobic differentiation of the continental crust. Meanwhile, large amounts of nutrients were brought into the sea due to rapid weathering, resulting in the boom of  $2.1 \times 10^9$  macroscopic multicellular fossils in the Liangshan Formation in Central Yunnan (Li J et al., 2018a; Liu JP et al., 2018a, 2019, 2021a). The death of large numbers of organisms led to the availability and burial of organic matter, which is the direct cause for the positive carbon isotope anomalies of the carbonates in the Yongjingshao Formation (Li J et al., 2018b; Liu JP et al., 2019, 2021a). The era of the macroscopic multicellular fossils is close to that of grypania in North America and multicellular fossils in large groups in Gabon (Albani AE et al., 2010; Liu JP et al., 2018a, 2019, 2022). The black rock series in the Xishancun Formation of the Paleoproterozoic Yimen Group that were formed after the collapse of the oxygen-rich atmosphere are composed of anoxic and selenium-rich sediments, which correspond to the global anoxic and selenium-rich event. The large amounts of organic matter buried in the sediments was widely oxidized. As a result, the carbon rich in  $^{12}\text{C}$  returned back into the sea, representing the end of the LJE and leading to the negative carbon isotope anomalies of the Xishancun Formation, which are comparable to the negative carbon isotope excursion of the Zaonega Formation in the Francevillian Basin in Gabon during the same time (2.08–2.05 Ga) (Albani AE et al., 2010). The above events recorded in the Paleoproterozoic Yimen Group in Central Yunnan in the Yangtze Block are all global events, which is a favorable basis for global stratigraphic correlation and is an important support for the study of early life evolution on the Earth.

Multicellular eukaryotic organisms were found in the Liangshan Formation of the Paleoproterozoic Yimen Group in the Yimen area, Central Yunnan. Their fossils mainly include macro-columnar, bean-shaped, and microfilament fossils and reticular ultramicrofossils (Figs. 5a–h; Liu JP et al., 2019, 2021e). They are the direct cause for the LJE in the early stage of the Earth and are presently the only record across South China of the fact that ancient organisms existed in Paleoproterozoic strata. According to available data, the carbon isotope excursions recorded in North China and South China were weak, while those recorded in typical regions in the world in the same period mostly range from +5.3‰ to +15.4‰, or even up to a maximum of +28‰. Such distinct difference may be attributable to the then sedimentary environment, paleogeographic location, and paleontological

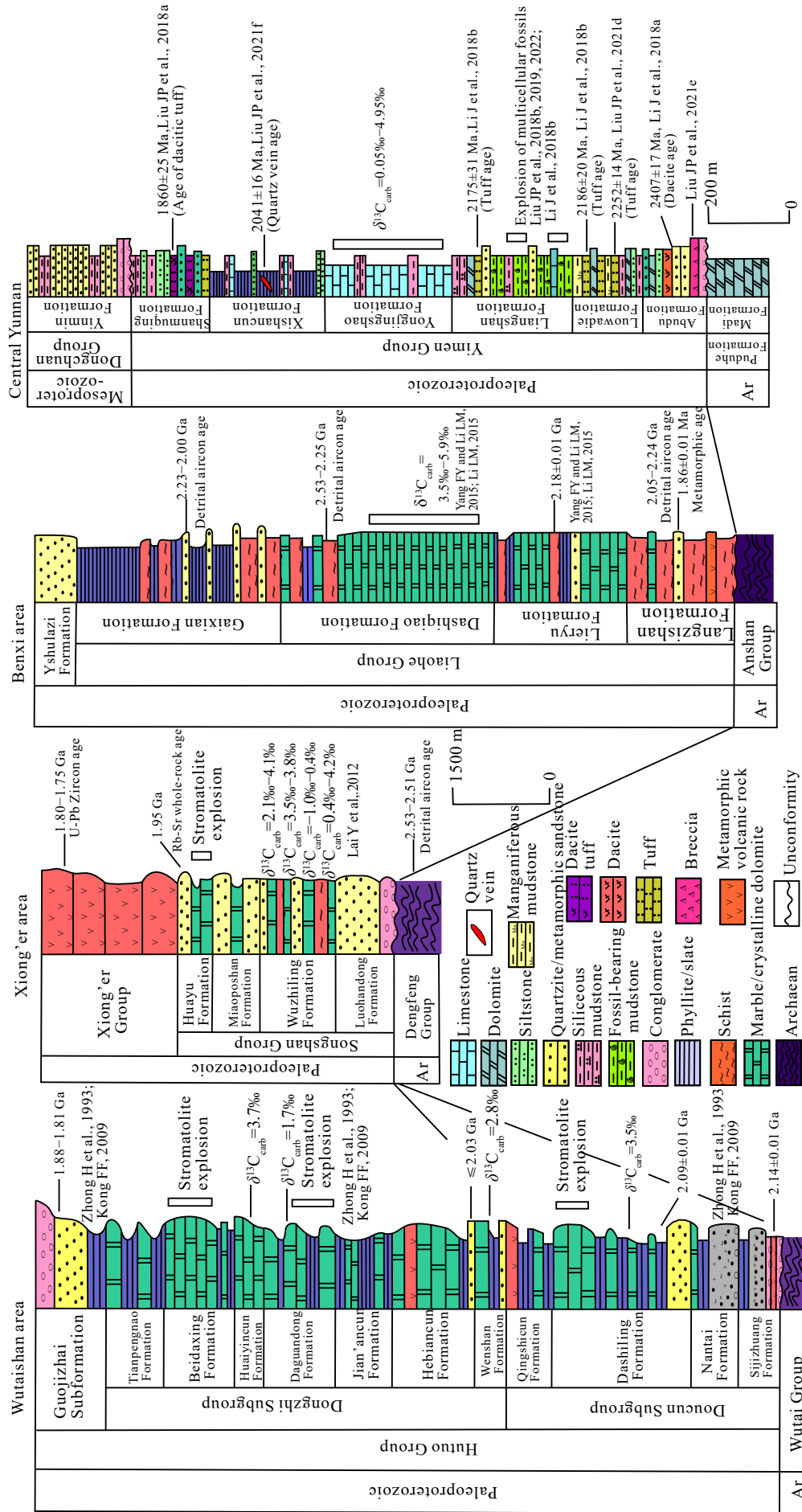
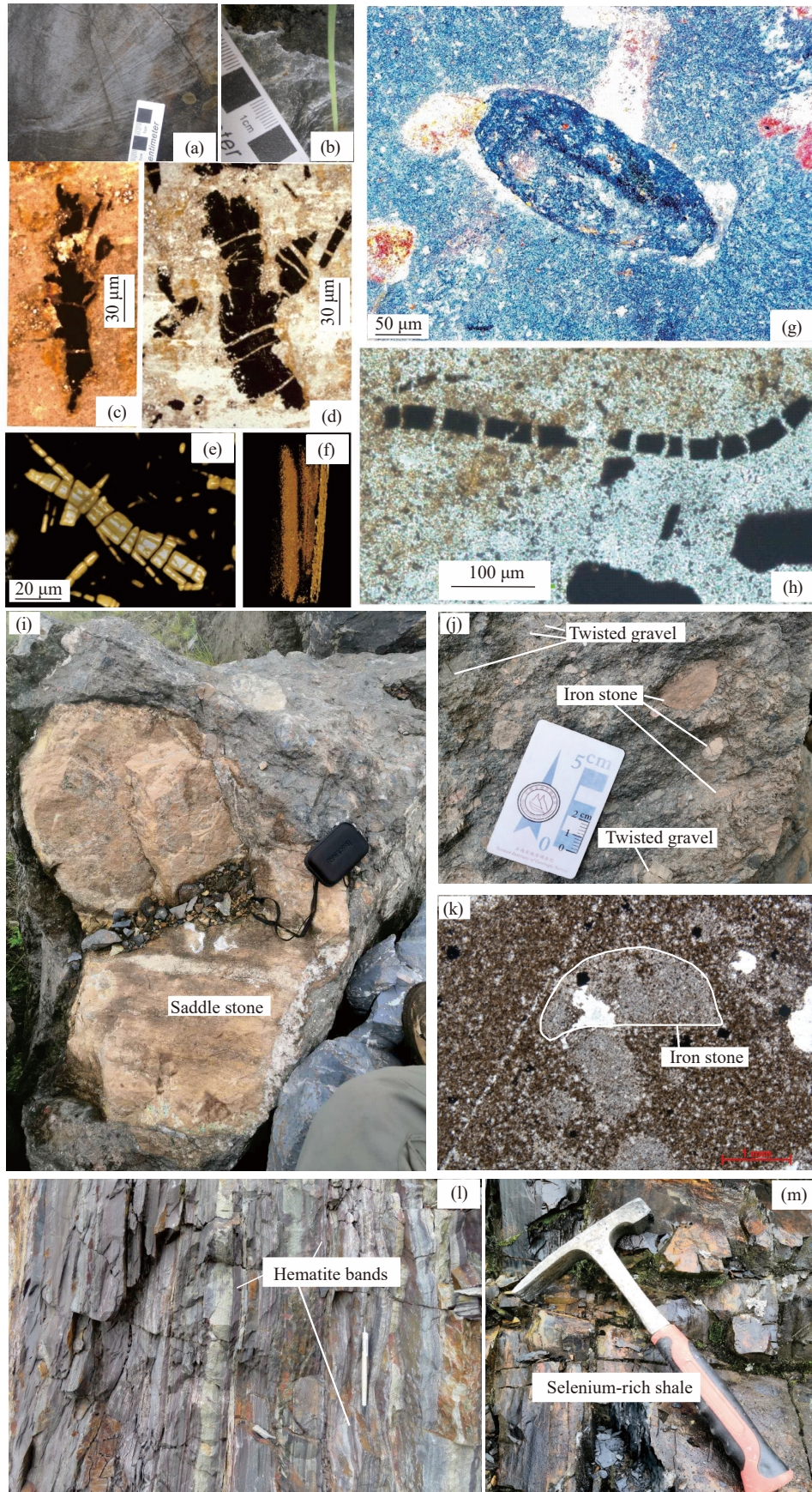


Fig. 4. Comparison of carbon isotope anomalies in Paleoproterozoic strata between the Yangtze Plate (Central Yunnan) and the North China Plate (Wutaishan, Xiong'er, and Benxi areas) (modified from Yang FY and Li LM, 2015).



**Fig. 5.** Field characteristics of major events in the early stage of the Earth in the Central Yunnan (modified from Liu JP et al., 2018a, 2019, 2021e). (a–d)–Field characteristics of carbon isotope samples; (c–f)–CT photos of macro-columnar fossils; g–characteristics of bean-shaped fossils; h–characteristics of microfilament fossils; (i–k)–complex moraines; l–characteristics of hematite quartzites in the Longtoushan Formation; m–characteristics of selenium-rich shales in the Xishancun Formation.

reproduction rate, which needs further confirmation and is also a major subject of subsequent studies.

#### 5.4. Time ranges and interrelation of major events on the early stage of the Earth

It is generally acknowledged that the major events in the early stage of the Earth include the great oxidation event, the global Superior-type BIFs, the Huronian glaciation, the explosion of multicellular eukaryotes, the positive carbon isotope excursion and the global anoxic and selenium-rich event. (Chen YJ et al., 1996; Kong FF et al., 2011; Tang HS et al., 2011; Lai Y et al., 2012; Kazumi O and Eiichi T, 2015; Chen WY et al., 2018b; Chen WY and Chen YJ, 2018a). However, the chronological order and duration of these events have not been extensively studied, which directly restricts the understanding of the nature and genesis of these events.

As revealed by this study, the great oxidation event is the main cause for the overall change in the Earth's surface system and it is manifested through multiple sub-events or secondary events occurring according to natural laws. The newly determined Neoproterozoic Puduhe Group and Paleoproterozoic Yimen Group in Central Yunnan are the direct petrological records of the major events occurring in the early stage of the Earth. Among them, the first great oxidation event (about 2.6–2.5 Ga) led to an increase in the photosynthesis in the hydrosphere (Holland HD, 1994; Chen WY and Chen YJ, 2018a; Chen YJ et al., 1996, 2000), the gradual oxidation of the hydrosphere at about 2.5 Ga (the Siderian), and the development of global superior-type BIFs. They are reflected in the development of large amounts of hematite quartzites in the Neoproterozoic Longtoushan Formation at 2.6–2.5 Ga (Fig. 5l). After the BIF event (the oxidation of the hydrosphere), the atmosphere was rapidly oxygenated, CH<sub>4</sub> and CO<sub>2</sub> decreased as they were transformed into organic matter and were buried, and the global climate became cold, leading to the occurrence of the global Huronian glaciation. This is reflected in the moraines in the Paleoproterozoic Abudu Formation (around 2.45 Ga) in Central Yunnan (Figs. 5i–k; Liu JP et al., 2021e). During the second great oxidation event at around 2.3 Ga, the atmosphere was rapidly oxygenated, leading to the boom of 2.1×10<sup>9</sup> macroscopic multicellular fossils in the Paleoproterozoic Liangshan Formation in Central Yunnan (Figs. 5a–h; Liu JP et al., 2018a, 2019). Then the demise of great numbers of organisms led to the availability and burial of large amounts of organic matter, thus inducing the positive carbon isotope excursion in the Yongjingshao Formation. The black shales in the Xishancun Formation of the Paleoproterozoic Yimen Group formed after the collapse of the oxygen-rich atmosphere; they are composed of anoxic and selenium-rich sediments (Fig. 4m), which correspond to the global anoxic and selenium-rich event. Therefore, it is held that the major events in the early stage of the Earth occurred in the following chronological order: the great oxidation event (first occurrence), the global Superior-type BIFs (Liu JP et al., 2021e), the Huronian

glaciation, the great oxidation event (second occurrence), the explosion of multicellular eukaryotes, the positive carbon isotope excursion, and the global anoxic and selenium-rich event.

## 6. Conclusions

(i) The δ<sup>13</sup>C values of dolostones in the Yongjingshao Formation vary in the range of 0.05‰–4.95‰ (V-PDB, maximum: 4.95‰), which is notably higher than that of marine carbonates (–1.16‰ on average). The positive carbon isotope anomalies of the Yongjingshao Formation indicate the occurrence of the LJE at the southwestern margin of the Yangtze Block. The North China Craton and the Yangtze Craton were possibly in different tectonic locations of the same continental block during the Proterozoic.

(ii) The LJE occurred in Central Yunnan at 2.15–2.10 Ga, lasting for about 50 Ma. The macro-columnar, bean-shaped, and microfilament fossils and reticular ultramicrofossils of multicellular eukaryotes in this period were discovered in the Liangshan Formation of the Yimen Group. They are the direct cause for the LJE and are also the oldest paleontological fossils ever found.

(iii) The major events in the early stage of the Earth include the great oxidation event (first occurrence), the global Superior-type BIFs, the Huronian glaciation, the great oxidation event (second occurrence), the explosion of multicellular eukaryotes, the positive carbon isotope excursion, and global anoxic and selenium-rich event (in chronological order).

### CRedit authorship contribution statement

Jun-ping Liu and Wei Yin conceived of the presented idea. Jun-ping Liu and Wei Yin wrote the manuscript in consultation. Jun-ping Liu and Shi-pan Yang supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

### Declaration of competing interest

The authors declare no conflict of interest.

### Acknowledgement

Qiu-yun Yuan from the Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd. and Dan Zhu and Shi-yang Pan from the Hubei Geological Research Laboratory assisted in the carbon and oxygen isotope analyses. Three professorate senior engineers Jing Li, Hu Zhang, and Sai-ying Yu from the Yunnan Geological Survey Institute guided the preparation of this manuscript. Thanks also go to Yu Liu from the Yunnan University for providing CT photos of fossils and to researcher Shi-xing Zhu from the Tianjin Institute of Geology and Mineral Resources, China, for providing multicellular fossil photos taken using microscopes. The reviewers put forward valuable suggestions for revision. The

authors hereby would like to extend their sincere gratitude to all of them. The work was financially supported by the project entitled "1 : 50000 Regional Geological Survey of Samaki, Yinmin, Guicheng, and Shugu Sheets in Yunnan Province (D201905) organized by the Land and Resources Department of Yunnan Province, Training Object Project of *technological innovation talents in Yunnan Province*(202205AD160073), the project entitled "1 : 50000 Regional Geological Survey of Dazhuang, Fabiao, Ditu, and Dianzhong Sheets in Yunnan Province " (S53A00722001048-007), "Joint Foundation Project between Yunnan Science and Technology Department and Yunnan University " (CY21624103) and the project entitled "Area Summary and Service Product Development of Regional Geological Surveys in Yunnan Province" initiated by the China Geological Survey (121201102000150012-02).

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