Glacier Relics of the Last Glacial and Holocene Periods Discovered in the Middle-low Mountains of Eastern China: Sedimentary Sequences and Environmental Evolution of Mengshan Mountain in Shandong Province since 80 ka

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Abstract: The goal of this research study is to describe academic issues which have been debated in the field of Chinese geosciences for a century. In 1922, Jonquei S. Lee（Li Siguang） discovered Quaternary glacial relics at Taihang Mountainin eastern China. In 1947, he published his research findings in the magazine *Mount Lushan in Glacial Age*. The research results had established three Ice Ages: Poyang (Gonzi), Dagu (Minde), and Lushan (Lisi). However, at that time, no Wurm glacial relics of the last Ice Age had been found in Lushan Mountain. Since then, the research team represented by Shi Yafeng, who is considered to be “the father of glaciers in China”, questioned Jonquei S. Lee's research results and concluded that “Professor Jonquei S. Lee's Quaternary glacier research in Lushan Mountain having misread the debris flow”. In 2005, the “middle-low mountains” in eastern China were finally defined as follows: “We clearly and unambiguously believe that there were no glacial activities in the middle-low mountainous areas of eastern China (east of 102° to 104°E; below 3,000 and 2,500 m) during the Quaternary Period”. Currently, the long-standing academic debate appears to have come to a conclusion.

As of 2015, the author and others began to investigate and study the Quaternary glacial relics in Mengshan Mountain (1,156m above sea level), Shandong Province, one of the “middle-low mountains” of eastern China. The relics have been observed to posses the systematic features of glacial erosion, trough and valley striations, and moraine deposits. The applied dating method shave confirmed that there were not only glacial relics of the last Ice Age (Wurm), but also Holocene glacial relics in the Mengshan Mountain area. Therefore, in order to further establish the corresponding relationship between the glacier, loess, stream sediment series, and MIS in the Mengshan Mountain area, a large number of chronological studies have been carried out regarding the various types of sediments in the area, and 24 dating datahave been obtained using OSL, CRN, and ^{14}Cmethods.On this basis, the corresponding relationship between the sedimentary sequences and the MIS was established for the first time in eastern China, which in dicates the environmental changes which had occurred in eastern China since 80ka. These discoveries s and chronological study results confirm the existence of the Last Ice Age, as well as Holocene glacial relics at Mengshan Mountain, there by confirming that Quaternary glaciation had occurred in the middle-low mountain areas of eastern China.

Key words: OSL, CRN, MIS, glacial relics, last Ice Age, Holocene, Eastern China

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1 Introduction

It has been debated for a century whether Quaternary glaciers had in fact existed in the middle–low mountainous areas of eastern China. James et al. (1874), a Scottish geologist, was the first researcher to record the existence of Quaternary glacial remains in eastern China. Also, a British traveler named Williamson recorded in his book that he had found very large boulders which were possibly formed by glacial transportation in the northeastern part of Shandong Province, along with nearby Tongguan in Shaanxi Province. Lee (1922) published information regarding the Quaternary glacier relics he had found near Shahe River in the eastern foothills of Taihang Mountains in Hebei Province and Datong in Shanxi Province. A Swedish geologist named Johann Gunnar Andersson, who was a consultant to the Ministry of Agriculture and Commerce of the Government

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of Republic of China (1912 to 1949) at that time, had disapproved of the existence of Quaternary glaciers in northern China (see in Lee, 1975]. Since then, Lee (1933) had successfully discovered and studied the local glacial landforms and moraines in the Lushan region of Jiangxi Province. For the first time, three Ice Ages [Poyang (Gonzi), Dagu (Minde), and Lushan (Lisi)] had been established in China. In 1934, Li Siguang, together with the Scottish geologist George B. Barbour (1890 to 1977); French clergyman and geologist Pierre Teilhard de Chardin (1881 to 1955); and Swedish scholar Norin E (1895 to 1982), conducted on-site investigations and discussions of the glacial relics in the Lushan region. However, their research findings did not receive the recognition of the above-mentioned scholars (Li, 1964, 1975). Later, Li (1947) discussed in detail the glacial landforms, moraine deposits, and divisions of the Quaternary Ice Age in the Lushan region. These discussions became landmark events in the study of the Quaternary glaciers in eastern China (Sun, 1950). During that process, Sun (1944), Wang et al. (1952, 1963), Jing (1979), and Yang et al. (1980) had also believed that there were Quaternary glaciers in the middle-low mountainous areas of eastern China. Meanwhile, Ding (1945) had continued to deny their existence.

Shi (1981, 2010) wrote an article questioning the glacier relics in the Mount Lushan area. He believed that they were the products of debris flow. Huang (1982), Ai Derbyshire et al. (1982), and Xie et al. (1983) wrote articles in support of Shi Yafeng's view. For example, Shi (2010) pointed out that Jonquei S. Lee's study of the Quaternary glaciers in Mount Lushan had clearly misread the debris flow in the area. Shiet al. (1989, 2005, 2011) concluded that there had never been glacial activities in the middle-low mountain areas below 3,000 to 2,500m in eastern China(east of 102°–104°E) during the Quaternary period. As a result, the “middle-low mountains” were effectively defined for eastern China.

This academic debate on the existence of Quaternary glaciers in the middle-low mountainous areas of eastern China has been a unique phenomenon in the history of the field of Natural Science in China due to its long duration and large number of participants (Jing et al., 2010). Therefore, the question of whether or not Quaternary glaciation had existed in the middle-low mountainous areas of eastern China remains unresolved. Also, it is still debated whether or not the “Glacier-free Zone” as defined by Shi Yafeng in 2005 is in fact accurate.

2 Features of Glacier Relics in Mengshan Mountain

Mengshan Mountain is located in the hilly and lowland areas of eastern Shandong Province (Fig. 1a), which is part of the “middle-low mountains” defined by Shi et al. (2005). There is an obvious northwest to southeast trending in the area (Fig. 1b). The elevation of the main peak is 1,156m above sea level (35The 36.25″N;117°50′ 44.65″E). The body of the mountain is mainly composed of granodiorite and monzogranite. The Quaternary glacial relics in the Mengshan area are distributed around the mountain. However, they are more evident on the southern slope than on the northern slope. In addition to the glacial erosion landforms, the glacial relics also have trough and valley striations and moraine deposits which display obvious systematic features. Among the numerous relics, the clear traces of troughs and valley striations, along with the lateral moraines which have melted from glaciers, constitute important evidence of glaciation in the middle-low mountainous areas of eastern China (Wang et al., 2017a, b, c; Wang et al., 2018; Wang et al., 2019a, b, c). Therefore, without a doubt, the discovery of the aforementioned systematic evidence has also aroused academic controversy (Wang et al., 2017a, b; Li et al., 2017). The following provides a brief introduction of the cirque landforms, trough and valley striations, moraine features, etc. of the study area.

2.1 Cirques and ice sills

The glacial erosion landform of Mengshan Mountain is known to be mainly composed of cirques, Arêtes, and glacial horns, and so on. It was observed that many well-developed cirques had been produced in the study area. Fig. 1d details the Huangliankou Cirques (35°30′43.87″ N;117°52′38.96″E). A U-shaped valley was found to be connected under the cirques. At the outlet of the cirques, the moraine had accumulated into terminal moraines. The terminal moraines were determined to be composed of angular and sub-angular shaped moraines of different sizes, in which the surfaces were observed to have developed with a variety of striation types (Fig. 1e; 35°30′ 36.80″N;117°52′37.41″E). The striations indicated the unique multiple directionality of the glacial striations. Some of the striations displayed “nail head and rat tail” features, which were found to be consistent with the third type of striation defined by Rea (2007). These types of scratches were also found on the valley walls of Lanxi Canyon.

In addition, several short and coarse striations which ran in a parallel direction were observed on the sides of the huge moraine formation at the outlet of the Nantianmen Cirques (35°35′57.68″N;117°49′49.36″E), as illustrated in Fig. 1c.

2.2 Trough and valley striations and crescentic cracks

The striations on the rock walls of Lanxi Canyon (Fig. 2a) in the Mengshan Mountain area the most complete, clear, and well-preserved areas within the Mengshan Glacier Valley. Figure 1f (35engs35.28″N;117°49′45.52″ E) details the typical glacier striations, which are in a fine, straight, and parallel arrangement on the glacial polished surfaces at approximately 10m above the bottom of Lanxi Canyon (position shown in Fig. 2a). Figure 1g (35igfi35.28″ N;117° 49′ 45.52″ E) shows the striation combination of the crescentic cracks which are perpendicular to the parallel striations on the same polished surfaces(position shown in Fig. 2a). In addition, there are many glacier polished surfaces observed on the valley walls on both sides of Lanxi Canyon. Among those, various types of striations were evident, such as thrust striations, cross striations, and so on. Furthermore, it was found that extrusion collapses had formed on several ends of the wall striations due to the great lateral pressure

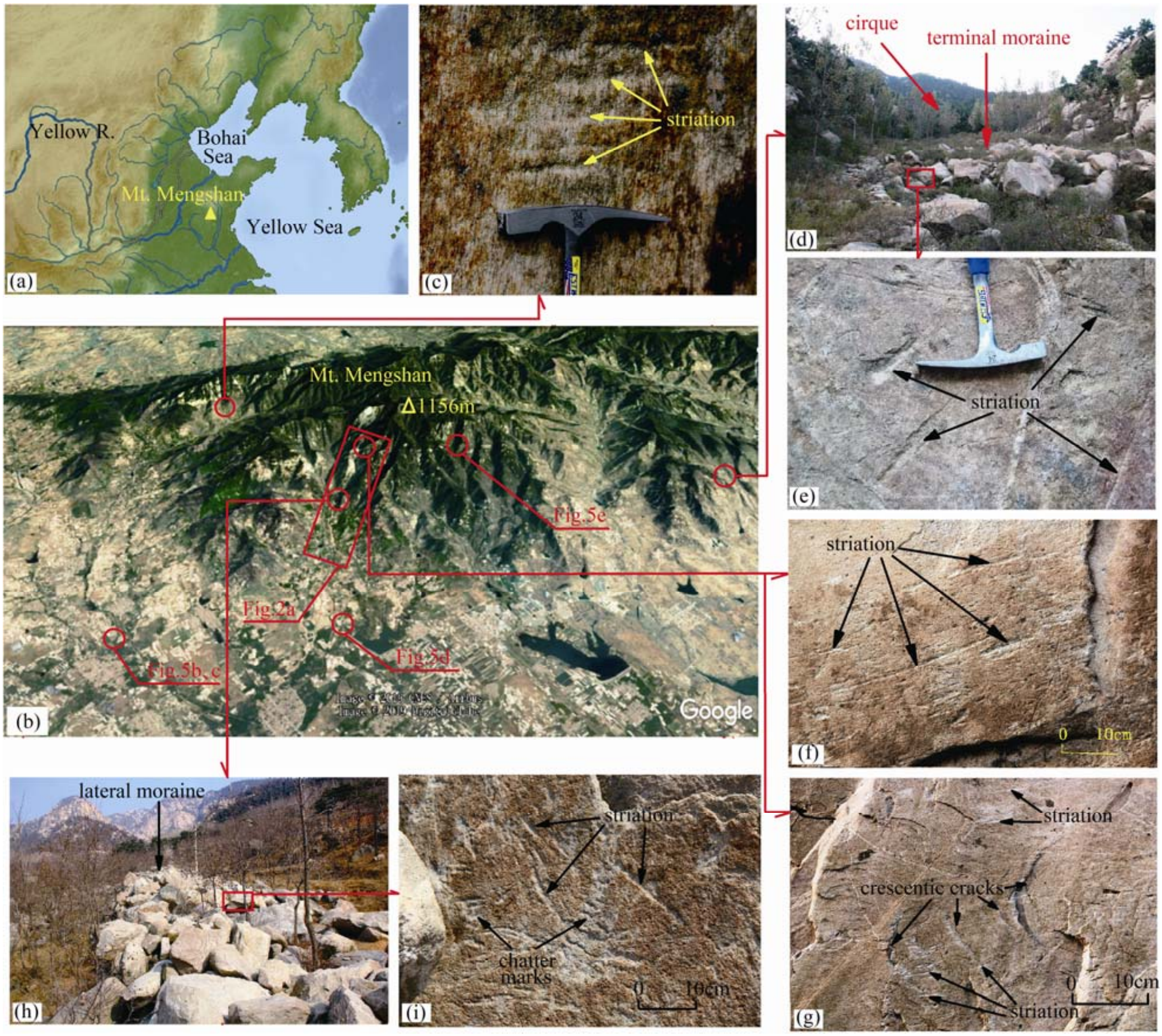

Fig. 1. Map showing the geographical location of the Mengshan Mountains and typical glacier relics.
(a) Location of Mengshan Mountain; (b) locations of the typical glacier relics in Mengshan Mountains; (c) striations of the terminal moraines in the Nantianmen Cirques; (d) cirques and terminal moraine of Huangliankou; (e) striations of the terminal moraine of Huangliankou; (f) striations on the rock walls of Lanxi Glacier Canyon; (g) striations and crescentic cracks on the rock walls of Lanxi Glacier Canyon;(h) lateral moraine of the Lanma Wall (by glacial melting moraine); (i) striations and chatter marks on the surfaces of the moraine ridges in the Lanma Wall.

conditions (Wang et al., 2019c).

2.3 Lateral moraine and striation stone

At the outlet of Lanxi Canyon, lateral moraines which had melted from glacier drifts were observed to be situated on both sides of the valley (Fig. 2a). The moraines could be divided into an upper moraine ridge and a lower moraine ridge. The upper ridge is located on the north side of the valley, and the lower ridge is on the south side (Fig. 1h). The gigantic ridges of the riverside areas were characterized by steeper inclination angles (between 70° and 90°) due to the trimming effects of the glacial bodies. Meanwhile, the very large shore-side ridges were observed to have gentler inclination angles of approximately 20° to 30°. These formations have displayed obvious angular features of steep on the inside and gentle of the outside (Fig. 1h). The boulder formations show obvious imbrication characteristics in some parts of the study area. The lateral moraines are superimposed by a large amount of boulders of various sizes, and some with masses up to

hundreds of tons. Also, there are irregular voids between the boulders without any fine materials filling observed. This had resulted in large voids which could not be easily entered by the research team. The boulders were found to be mainly subangular and subcircular, and the lithology was determined to be dominated by granodiorite and monzogranite. Various types of relics, such as striations (shown in Fig. 1i and at the inner circle of Fig. 1h); chatter marks (Gary et al., 1972; Bussert, 2010); and crescent chisel mouths are common on the surfaces of the study area. The scratches on the striation stones indicate multidirectional characteristics. Furthermore, some of the

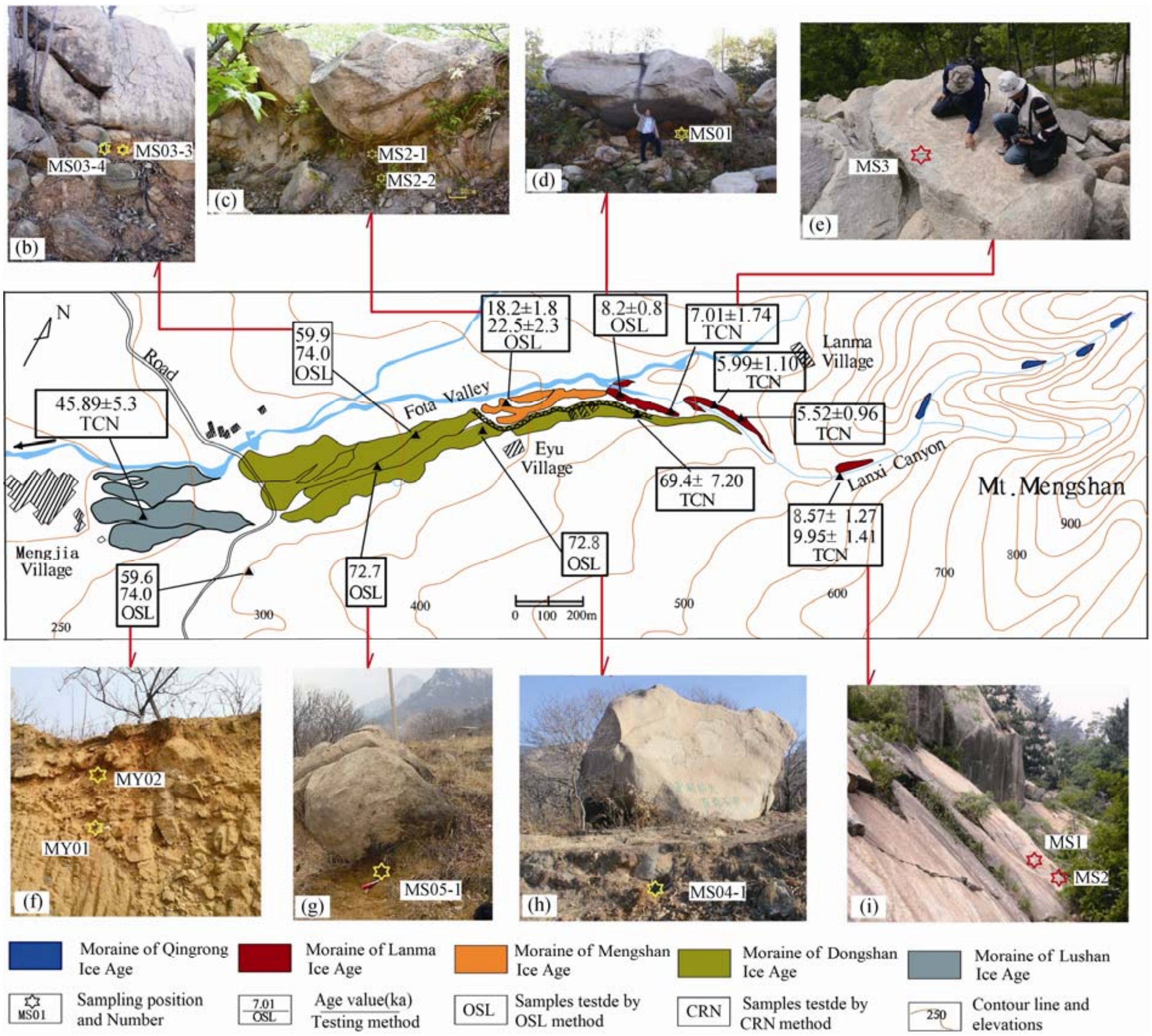

Fig. 2. Distribution, sampling locations, and ages of the moraine since the last glacial period in the Fota Valley of Lanxi Canyon.

striations display arc characteristics which had been caused by slow rotations during the transportation of the moraines (Wang et al., 2019c).

The glacial striations produced by Mengshan Mountain area characterized by abundant types and clear features. Moreover, there are systematic features observed between the cirques, trough and valley striations, and moraines. Therefore, it could clearly be seen that Quaternary glaciation processes had occurred in the Mengshan area. Due to the slight weathering and clear and distinct features of the observed glacial relics, it was confirmed that the glacial actions took place not that long ago. In November 2017, the author investigated the modern glacier scratches in Hailuogou of Sichuan province, and found that they are completely consistent with the characteristics of glacier scratches in Mengshan Mountain (Wang et al., 2019b).

3 Sample Collection and Results

In the study area, it was found that loess, glacier, and stream sediment deposits are concentrated in the foothills of the southern slope of Mengshan Mountain. Therefore, that location provided a basis for the study of the environmental evolution processes in the study area. In order to examine the sedimentary processes and environmental evolution of the area, 20 samples of different ages were collected in this study. Then, according to the characteristics and conditions of the samples, dating methods include ^{14}C, OSL, and CRN. In total, there were 15OLS samples, 5cosmogenic radio nuclide (CRN) samples, and 1 ^{14}C sample. The sampling points and surrounding environmental conditions are shown in Figs. 1b and 2a. The samples mainly included the loess and stream sediment of the Wangjiapo stratigraphic profile (Fig. 3b, c); moraine of the Qingrong Canyon (Fig. 3e); friction surface of the rock wall in Lanxi Canyon (Fig. 2i); moraine (Fig. 2e) and sediments (Fig. 2d) of the Lanma moraine ridge; and the moraine ridge of the Fota Valley (Fig. 2b-d, 2f-h).

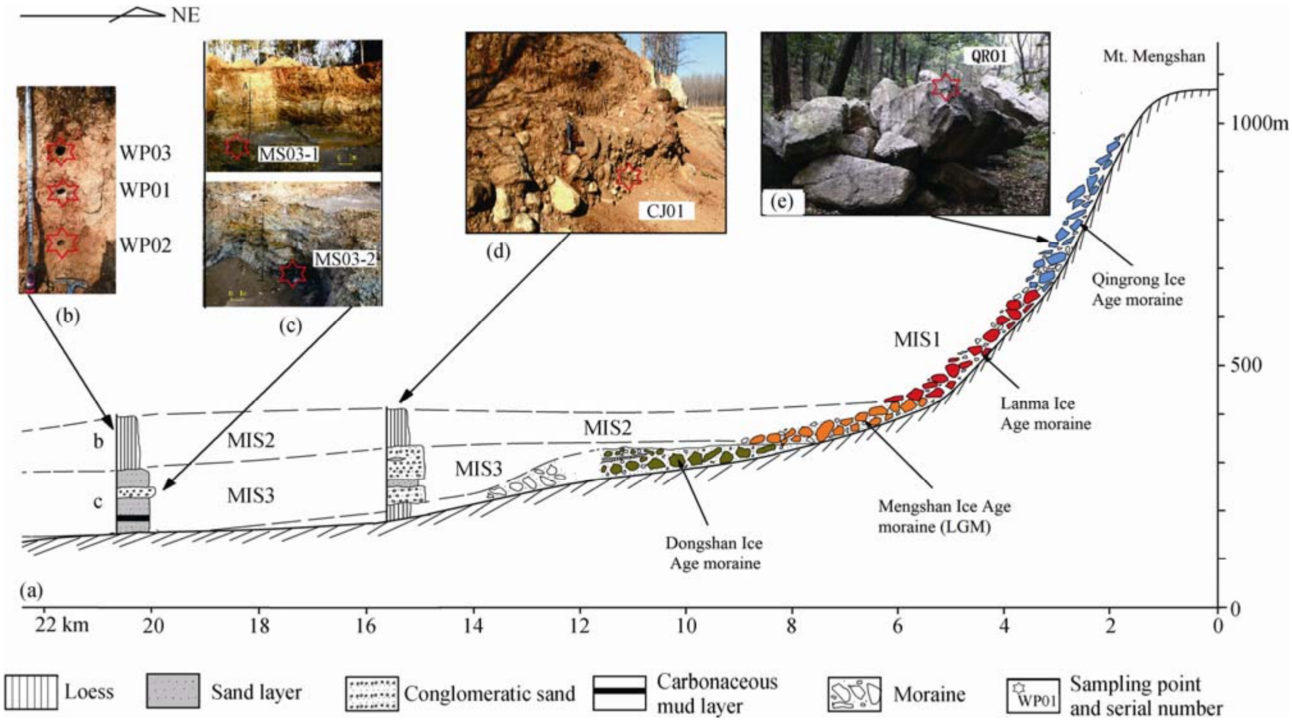

Fig. 3. Section diagram showing the sedimentary framework of the southern slope of Mengshan Mountain.
(a) Section diagram of sedimentary framework; (b) Wangjiapo section loess; (c) Wangjiapo section sand layer; (d) Chenjiazhuang section; (e) Qingrong Canyon moraine ridge.

3.1 Test data of the OSL

A total of 15OSL samples were collected in this study. Among those, the MS03-1 and MS03-2 samples were obtained from the black silty mud blocks at the bottom of the Wangjiapo hot spring profile. The other 13samples were obtained using a 3 cm diameter steel tube. During the sampling and submission processes, a light-shielding treatment had been adopted.

All of the samples obtained in this study were tested at the Marine Geological Experimental Testing Center of the Ministry of Land and Resources, and the results are shown in Table 1.

The test results of the samples were checked, and it was determined that the majority of the samples had met the error range requirements. Therefore, the data were found to have the reliability necessary to meet the test requirements. The equivalent dose values of six of the samples (MS03-3, MS0304, MS04-1, MS05-1, MY01 and MY02), were found to be too large to obtain the error values. Therefore, those values were utilized for reference purposes only. However, since the six samples were taken from the same moraine ridge, the age approximations were obtained. The age value of the cosmogenic radio nuclides obtained by Zhang (Communication, 2018) on the surfaces of boulders of the same moraine ridge is 69.4+7.2 ka, which confirms the reliability of the data.

3.2 Test data of the CRN

Six cosmogenic radio nuclides samples were collected in this study, as detailed in Table 2 (it should be noted that sampleFT01 had no dating data). The samples were collected from the large boulders and valley walls of the glacial troughs and valleys in the open-field areas (Figs. 2a, e, i and 3e). In accordance with the testing requirements of the cosmogenic radio nuclide samples, the quartz-rich granodiorites or quartz veins were directly collected from the rock masses. The samples contained surface rock with thicknesses of 2cm, and each sample weighed approximately 3 kg. In addition, three cosmogenic radio nuclide ages were collected in the study area, as detailed in Table 2 (samples 6 to 8).

The pretreatments of the samples were completed in the Super-Clean Laboratory of the Geography College of Nanjing Normal University. The element content levels were tested in the Xi'an Accelerator Mass Spectrometry Center of the Institute of Earth Environment at the Chinese Academy of Sciences.

3.3 ^{14}C test data

In the current study, the samples were collected from the plant residues (OSL age sample:MS03-2, Fig. 3c) in the black mud layers at the bottom of the Wangjiapo profile (35°33′40.94″N;117°45′50.97″E). The samples were black-brown in appearance, with columnar sizes measuring 22×2×0.5 mm. The collected samples were tested by the Beta Laboratory (United States). The experimental results were determined to meet the requirements of the ISO/IEC 17025:2005 Testing Accreditation PJLA, #59423.

Since the deposition time of the samples was approximated to the decay limit of ^{14}C, an open age value of >43,500 BP was given by Beta Laboratory (Table 3). Therefore, due to the fact that the detection limit of ^{14}C is generally approximately 50 ka, the obtained results had

Table 1 Test data of the optically stimulated luminescence (OSL) dating

Serial No.	Sample No.	Latitude (N)	Longitude (E)	Altitude (m)	Sample description	U (ppm)	Th (ppm)	K (%)	Mass water Content(%)	DE (Gy)	Age (Ka)	Figure No.	Source
1	MS01	35°33'24.84"	117°48'52.60"	352	Medium grain sand with moraine	2.27	11.10	1.94	19.57	39.6	8.2±0.8	Fig. 2d	Wanget al., 2017b
2	MS2-1	35°33'19.58"	117°48'41.36"	339	Medium grain sand with moraine	2.76	20.1	3.05	3.50	141.9	18.2±1.8	Fig. 2c	Wanget al., 2017b
3	MS2-2	35°33'19.58"	117°48'41.36"	339	Medium grain sand with moraine	2.59	8.90	2.81	6.60	128.7	22.5±2.3	Fig. 2c	Wanget al., 2017b
4	MS03-1	35°33'40.94"	117°45'50.97"	156	Black silty sand in the river	5.66	8.33	2.07	13.94	258.4	50.6±5.1	Fig. 3c	Wanget al., 2019a
5	MS03-2	35°33'40.94"	117°45'50.97"	158	Black silty sand in the river	6.34	9.29	2.03	15.22	248.9	46.0±4.6	Fig. 3c	Wanget al., 2019a
6	MS03-3	35°33'14.07"	117°48'35.42"	308	Medium grain sand with moraine	3.21	16.27	3.13	18.40	453.2	74.0	Fig. 2b	this paper
7	MS03-4	35°33'14.07"	117°48'35.42"	308	Medium grain sand with moraine	4.65	34.32	2.70	12.86	490.2	59.9	Fig. 2b	this paper
8	MS04-1	35°33'16.90"	117°48'42.43"	331	Medium grain sand with moraine	2.56	14.83	2.67	13.14	387.2	72.8	Fig. 2h	this paper
9	MS05-1	35°33'05.27"	117°48'29.03"	283	Medium grain sand with moraine	2.07	15.21	2.89	8.21	397.0	72.7	Fig. 2g	this paper
10	MY01	35°32'50.41"	117°48'20.75"	263	Medium and fine sand with moraine	2.28	15.53	2.36	2.52	375.0	>74.0	Fig. 2f	this paper
11	MY02	35°32'50.41"	117°48'20.75"	263	Loess	2.61	17.33	3.22	3.26	375.0	>59.6	Fig. 2f	this paper
12	WP01	35°33'43.50"	117°45'50.87"	164	Loess with gravel and sand	1.64	12.34	2.38	1.44	78.8	17.5±1.8	Fig. 3b	this paper
13	WP02	35°33'43.50"	117°45'50.87"	164	Silty loess	1.15	13.65	2.68	2.60	89.6	18.7±1.9	Fig. 3b	this paper
14	WP03	35°33'43.50"	117°45'50.87"	164	Silty loess	1.94	11.99	2.31	6.76	70.2	15.7±1.6	Fig. 3b	this paper
15	CJ01	35°32'15.09"	117°47'31.08"	169	Medium and fine sand with gravel	1.60	16.12	2.21	3.96	158.9	33.8±3.4	Fig. 3d	this paper

Testing Organization: Marine Geological Laboratory Testing Center of Ministry of Land and Resources.

indicated that the deposition time had ranged between 43.5 and 50 ka. Then, by combining those results with the OSL ages obtained for the same horizon (46.0±4.6 ka and 50.6±5.1 ka, respectively), it was determined that the ^{14}C age had reference value in the current research.

All the above-mentioned chronological examinations and data dating results which were obtained in this study had covered the sediment of the moraine, loess, and streams in the study area, and provided a data premise for the establishment of the sedimentary sequences and comparative study using MIS.

4 Discussion

The related research of the Marine Oxygen Isotope Stage (MIS) began in the 1970s (Shackleton, 1967; Hayset al., 1976). The variations of the benthic foraminifera's $\delta^{18}O$ content in deep-sea sediment were used to deduce the changes in the temperatures and global ice volumes during different time-periods and were found to accurately reflect the environmental alternations between the glacial and inter Ice Ages. That is to say, the odd-number phases of the MIS curves indicated warm periods and corresponded to the inter Ice Ages (stadial). Meanwhile, the even-number phases indicated cold periods. The MIS curves are considered to be relatively complete records of the evolution rules of the global climate conditions (Shackleton, 1967; Zhao et al., 2011; Zhang et al., 2013). Therefore, since sediment is the product of natural environments, the sediment will record the environmental information during a deposition. Subsequently, as long as the formation times of the sediment can be determined, the sedimentary environmental conditions can be comparatively analyzed using MIS.

The Holocene climate evolution curve was based on the Rub/Sr curve of Dajiuhu Lake in Shennongjia, Hubei province (Zhang et al., 2017), which is located in the eastern section of China and more detailed. Currently, the age values which have been obtained in the Mengshan area still range within 80 ka, which belongs to the MIS4 to MIS1 stages(from the last Ice Age to the Holocene Period).

4.1 MIS 1 stage

The MIS1 stage of the marine oxygen isotopes corresponds to the Holocene period. In accordance with the results obtained in the study conducted by Shi et al. (1992), the climate changes during that period are reflected well in the Dunde'er ice core of the Qilian Mountains (Fig. 4c). In addition, Zhang W et al. (2017) examined the elemental geochemistry, isotope geochemistry, and sporo-pollen records of peat sediment samples from Shennongjia Dajiuhu Lake in Hubei province, and determined that obvious cooling events had occurred in eastern China in 8.2 ka and 9.2 ka, respectively (Fig. 4b).

Those cooling events had corresponded to the dating values obtained on the polished surfaces of the troughs and valleys in Lanxi Canyon, as well as the moraine ridges of Lanma in the Mengshan Mountains area. The result of the OSL aging which were obtained from the south ridge

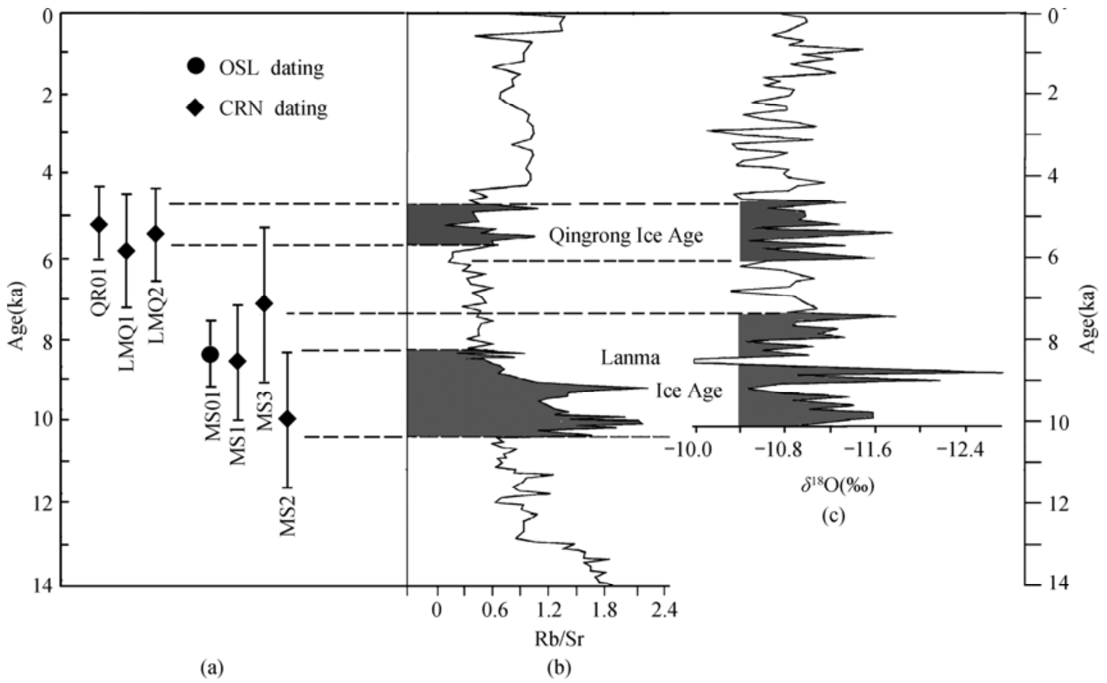

Fig. 4. Dating data of the Holocene moraine in Mengshan Mountains and comparisons with the climate records of Dajiuhu Lake in Shennongjia, Hubei Province and the Dunde'er ice core of the Qilian Mountains
(a) Sample age value, tolerance, and number; (b) climate record curve of Dajiuhu Lake in Shennongjia, Hubei Province; (c) Dunde'er ice core of the Qilian Mountains.

Table 2 Test data results of the cosmogenic radio nuclide (CRN) dating

Serial No.	sample no.	latitude (N)	longitude (E)	Altitude (m)	sampling depth (cm)	quartz sampleweight (g)	^{9}Beload weight(g)	$^{10}Be/^9Be$	tolerance (%)	^{10}Be density (10^4atoms/g)	Dating results (ka)	figure no.	source
1	QR01	35°32′49.89″	117°50′45.32″	752	2	13.34798	0.0002499	2.87E^{-14}	14	3.28±0.46	5.27±0.90	Fig. 3e	
2	MS1	35°33′28.82″	117°49′22.46″	458	2	17.1633	0.25327	4.60E^{-14}	11	4.54±0.52	8.56±1.27	Fig. 2i	
3	MS2	35°33′28.82″	117°49′22.46″	483	2	16.0660	0.25000	5.05E^{-14}	11	5.26±0.56	9.95±1.41	Fig. 2i	this paper
4	MS3	35°33′25.28″	117°49′58.80″	384	2	9.5668	0.25578	1.91E^{-14}	23	3.42±0.79	7.01±1.74	Fig. 2e	
5	FT02	35°32′52.00″	117°48′11.30″	232	2	12.80306	0.0002436	1.59 E^{-13}	5.8	19.91±1.157	45.89±5.3	Fig. 2a	
6	LMQ1	35.5°	117.8°	412	2	15.97466		2.54E^{-13}	14	2.41±0.33	5.99±1.10	Fig. 2a	Zhang et al.,
7	LMQ2	35.5°	117.8°	409	2	18.03057		2.65E^{-13}	12	2.24±0.28	5.52±0.96	Fig. 2a	2018
8	MS7	35.5°	117.8°								69.4±7.2	Fig. 2a	Zhang (communication)

Testing organization: The Xi'an Accelerator Mass Spectrometry Center, Instituteof Earth Environment, Chinese Academy of Sciences.

Table 3 Test data results for the ^{14}C samples

Serial no.	sample no.	latitude (N)	longitude (E)	altitude (m)	sampling location	submission substances	isotope content (0/00)	regular age	Fig. no.	source
1	MSC01	35°33′40.94″	117°45′50.97″	158	bottom of black mud layer	plant residue	$\delta^{13}C$=-25.8	>43,500 BP	Fig. 3c	this paper

Testing Organization: Beta Analytic Inc.

of the Lanma moraine was 8.2±0.8 ka in the current study, as shown in Fig. 2d. Furthermore, the cosmogenic radio nuclide aging result obtained from the surfaces at the northern end of the moraine (Fig. 2e) was 7.01±1.743 ka. Also, for the samples obtained from the upper reaches of the valley walls in Lanxi Canyon (Fig. 2i) had cosmogenic radio nuclide age values of 8.56±1.26 ka and 9.95±1.41 ka, respectively. Therefore, with the exception of one relatively small value of 7.01 ka, all of the other data results correspond well to the previously confirmed cooling events during the early Holocene Period.

During that cooling event, large-scale moraine ridges had formed in the Mengshan area, which were distributed into many valleys. Therefore, that particular cooling event has been referred to as the Lanma Ice Age (Fig. 4) (Wang et al., 2017b). It can also be said that that Ice Age had corresponded to the 8.6 ka BP glacial advance events which had occurred in the European Alps and Andes mountain range of South America (ShiYafeng et al., 2005).

Fig. 3b details the temperature evolution map of Tb/Rr element geochemical series in the Dajiuhu peat of Shennongjia in Hubei province. Also, the cooling event which occurred between 4.66 ka and 5.66 ka BP during the middle of the Holocene Period are shown. The age values of the cosmogenic radio nuclides (5.27±0.90 ka) obtained on the surfaces of the moraines in Qingrong Gorge, which is located approximately 750 m above sea level in the Mengshan area, had also corresponded to the aforementioned cooling event.

In the study area, in view of the formation of the large-scale moraine in the valleys (Fig. 1d), the cooling event was referred to as the Qingrong Ice Age (Wang et al., 2018). Previously, Zhang et al. (2018) had obtained two age values of the cosmogenic radio nuclides on the boulder surfaces of the Lanma north ridge, which were determined to be 5.99±1.10ka and 5.52±0.96 ka, respectively (Fig. 3a). These obtained CRN dates were also within the range of the aforementioned cooling event. Following further analysis, it was found that the ice-snow conditions of the Qingrong Ice Age had covered the pre-glacial Lanma Period. The glacial advances during the middle Holocene Period were also found to be reflected in the Dunde'er ice core of Tibet (Shiet al., 2005). In the study conducted by Denton and Karlen (1993), evidence of the glacial advance shad also been found in their research results, which they had referred to as the "Second New Ice Age". Therefore, based on these findings, two distinct Ice Ages could be distinguished during the Holocene Periods in eastern China: The Lanma Ice Age and the Qingrong Ice Age, respectively. This was the first time that these distinct periods had been successfully identified in the middle-low mountainous areas of eastern China.

4.2 MIS 2 stage (LGM)

The current study examined the hot spring stratum profile of North Wangjiapo Village, which is located at the southern foot of Mengshan Mountains (Fig. 3b, c). The lithological stratification of the profile was found to be clear, with the upper part composed of gray-yellow loess. Three OSL ages were obtained in the area. The lower part contained fluvial facied-conglomeratic sand, which contained two layers of black humus silt. Two OSL ages and one ^{14}C age value were obtained in the black silt. The bottom of the sand bed was observed to be composed of Archaean gneissic granodiorite.

The three ages were obtained from samples obtained from the upper loess (Fig. 3b) as follows: 15.7±1.6 ka; 17.5±1.8 ka; and 18.7±1.9 ka from the top to the bottom, respectively. These age values were found to correspond to the middle and late stages of the MIS2 (Fig. 5). In addition, the two OSL ages which had been obtained from the moraine of the lower reaches of the Lanma boulders were 18.2±1.8 ka and 22.5±2.3 ka (Fig. 2c, Table 1), which had corresponded to the early and middle stages of the MIS2. The aforementioned five ages, as well as the formed sediment, were found to be closely related to the climatic characteristics of the MIS2 stage. It was observed that they had the characteristics of products normally found under the cold climate conditions of Ice Ages (Fig. 5). The Mengshan area was named the Mengshan Ice Age, which corresponded to the late stadial of the Wurm Ice Age.

4.3 MIS3 stage

Two OSL ages 46.0±4.6ka (MS03-2) and 50.6±5.1ka (MS03-1)were obtained from the fluvial facie-sand layer in the lower part of the Wangjiapo profile (Fig. 3c and Table 1). The ^{14}C age was obtained from the black mud in the same layer of the MS03-2 and was over 43.5 ka BP (Fig. 3b and c, Table 3). The two ages were mutually verified. In the conglomeratic sand layer of the Chenjiazhuang profile (Fig. 3d), an age value of

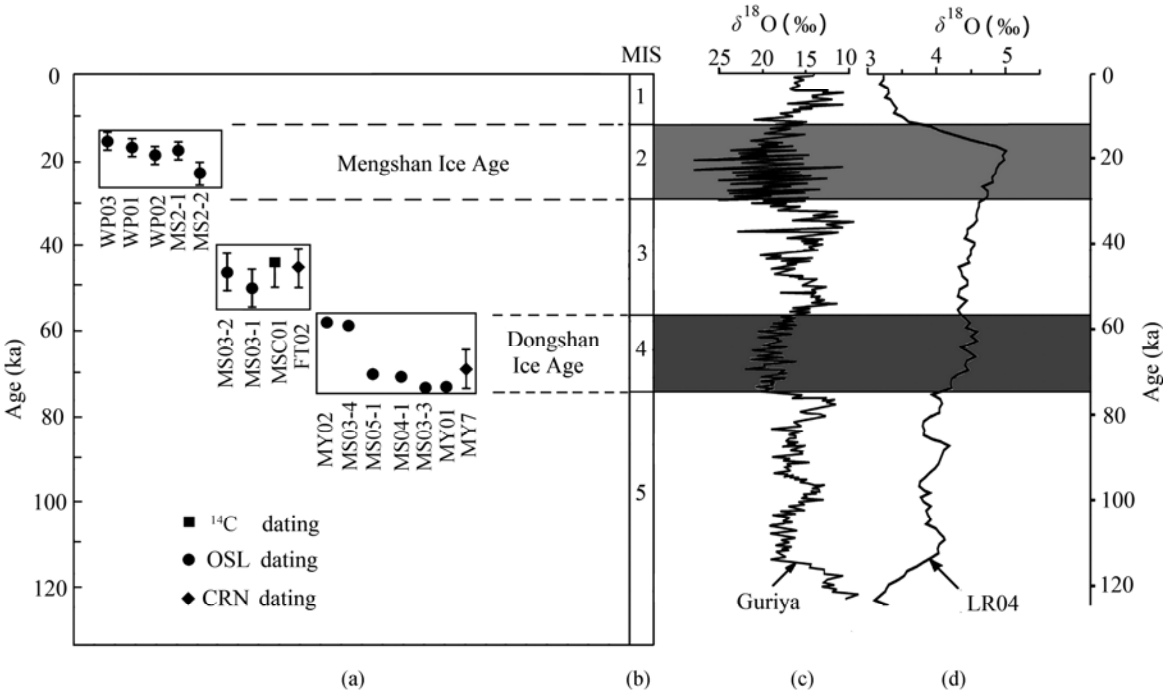

Fig. 5. Dating data of the glacial relics in the Mengshan Last Ice Age and comparisons with different climate records.
(a) Dating data, tolerance, and number; (b) marine oxygen isotope stage; (c) Guliya ice core; (d) LR04 marine oxygen isotope curve.

33.8±3.4ka was obtained. Also, there was obvious horizontal bedding observed in the conglomeratic sand. It was determined that this fluvial facie deposit had belonged to the product of the MIS3 (Fig. 5).

The fluvial facie deposits in the study area indicate that the MIS3 stage in the Mengshan area was character zied by warm climate, resulting in the formations of fluvial facie deposits in the low-lying areas. Despite the fact that there are no depositional remnants in the higher sections of the Mengshan area, such as the Fota Valley, obvious erosion arcs was found to have formed on the moraine during the early MIS4 stage.

4.4 MIS 4 stage

In this study, six OSL ages were obtained on the outer and downstream moraine ridges of Lanma Ice Age (MIS1) and Mengshan Ice Age (MIS2), i.e.74.0 ka, 59.9 ka, 72.8 ka and 72.7 ka, (Fig. 2, Table 2), respectively, as detailed in Fig. 4. In addition, Zhang Zhigang (Communication, 2018) had previously obtained an age of 69.4±7.2 ka (CRN) for the same moraine ridge. These age values were found to correspond to the MIS4 stage of the last Ice Age of the Late Pleistocene. In the Mengshan area, this Ice Age has been referred to as the Dongshan Ice Age (Fig. 5). This time period also corresponds to the early glacial stage of the Wurm Ice Age.

In the study, based on the distribution and occurrence of the moraines from different generations on the southern slope of Mengshan Mountain, and combined with the Wangjiapo profile, loess and stream sedimentary sequences, and the formation ages in the Chenjiazhuang profile, a sketch map of the stratigraphic sedimentary framework of the study area since the last Ice Age was successfully achieved (Fig. 3). The loess deposits were determined to have corresponded to the depositional stages (MIS2, MIS4) of valley moraine, and were identical in time. The steam depositional layers (MIS3) in the low-lying areas were determined to have not formed deposits in the valley moraine distribution area. However, evidence of the strong erosion effect of floods on moraine ridges had been left behind and were evident in the obvious arc erosion formations.

At the present time, although ancient moraine (prior to MIS4) have not yet been found in the Mengshan area, the age data of the moraine continue to be explored. It is believed that with further development of the related explorations in the study area, the moraine ages will be gradually clarified and detailed in future studies. Take these two samples(OSL) for example: (MY01>74.0ka, MY02>59.6 ka).

5 Conclusions

This study focused on eastern China’s Mengshan area (which is only 1,156m above sea level).It was found that not only could moraine deposits of the last Ice Age be observed, but also clear glacial remains from the Holocene Period. These findings, along with their corresponding chronological studies, have fully proven the existence of Quaternary glacial remains in the middle-low mountain areas of eastern China. Therefore, the previous conclusion that there has never been Quaternary glaciation in the middle-low mountainous areas of eastern China below 3,000 to 2,500 m was found to be debatable. Previously, such a conclusion had been put forward by Shi (1989, 2005).

Based on the dating results of the sequence sediment in the Mengshan area, as well as the comparative study results using MIS, it was found in this study that there was a high correspondence between Mengshan Mountain in eastern China and the Guliya ice core and MIS in the Qinghai-Tibet Plateau. These findings indicate that there

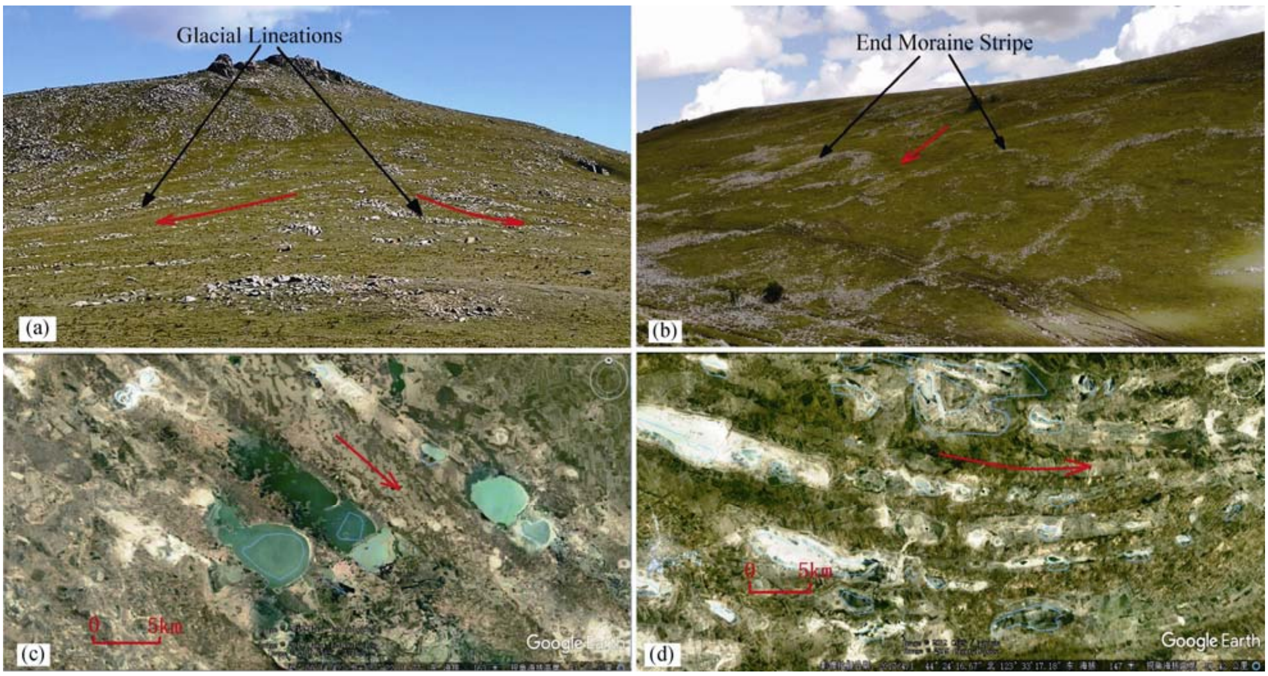

Fig. 6. Lineations structures of the “Xing 'an Ice Cap” and “Songliao Ice Sheet”.
(a) Glacial Lineations; (b) End Moraine Stripe; (c and d) Mega-Scale-Glacial Lineations; (Red arrows indicate the direction of ice sheet migration).

had been a synchronization between the Quaternary climate evolution in eastern China and in the western Qinghai-Tibet Plateau, possibly even a global climate evolution. Furthermore, the discovery of Holocene glacial remains in the Mengshan Mountains area had indicated that the eastern region had still morebeen sensitive to climate changes.

The confirmation of the Quaternary systematic glacial remains and the establishment of a sequence framework of the sedimentary sequences in the Mengshan area of Shandong province will greatly promote the new understanding of Quaternary geology and paleoclimate evolution processes in both eastern China and East Asia. The "East Asian cold trough" (Wang et al., 2017c)was the dominant climate factor controlling the glaciation in the middle and low mountains of eastern China, The leading factor of glaciation in the Qinghai-Tibet Plateau is high altitude. There are essential differences between the two.

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Note: The “Xing'an Ice Cap” indicated by “Glacial lineations” (Fig. 6a, coordinates: 43°17′18″N, 117°40′40″ E) and “End Moraine Stripe” (Fig. 6b, coordinates: 43°18′ 18″N, 117°44′50″E) recently discovered by the author; and the “Songliao Ice Sheet”, which is indicated by the “ which is Glacial Lineations” (Fig.6c and 6d, coordinates: 45°00′04″N, 122°22′01″E and44andinate，123ndinates), all confirm the quaternary glaciation in the middle-low mountains of eastern China.

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