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The glacial extent and glacial advance/retreat asynchroncity in East Asia during Last Glaciation

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Abstract: New dates for last glacial cycle in Tibetan bordering mountains and in East Asia show the glacial extent during the early/middle (MIS3-4) stage is larger than that of the late stage (MIS2) in last glacial cycle. It is asynchronous with the Northern Hemisphere ice sheets maximum and changes in oceanic circulation that predominately control global climate. In research areas, three seasonal precipitation patterns control the accumulation and ablation of glaciers. The modes of the westerlies and the East Asian mountains/islands in and along the Pacific Ocean are favorable to glacier advance with mainly winter precipitation accumulation. There was a global temperature-decreasing phase in the middle stage (MIS3b, 54-44 ka BP), when the glacier extent was larger than that in Last Glaciation Maximum due to the low temperature combined with high moisture. It is revealed that the Quaternary glaciers not only evolved with localization, but also maybe with globalization. The latest studies show a fact that the developmental characteristics of glaciers in high mountains or islands along the western Pacific Ocean are not in accord with those inland areas. Therefore, it can be concluded that glacier development exhibits regional differences. The study validates the reasonableness of the asynchronous advance theory, and ascertains that both the synchronous and asynchronous advance/retreat of glaciers existed from 30 ka BP to 10 ka BP. It is not suitable to emphasize the synchronicity between global ice-volume and glacier change.

Key words: Last Glaciation; asynchronous advance; monsoon; glacial extent; East Asia
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1 Introduction

It has been accepted that the glacial extent in the early stage was larger than that in the late stage in Eastern Asia during the Last Glaciation and was different from Europe and North America (Li, 1992; Cui *et al*., 2000). Many scholars have noticed that MIS3b (54-44 ka BP), corresponding to interglacial glacial stage of the three phases in MIS3 of the deep-sea oxygen isotope curve, was the descent temperature period (Shi and Yao, 2002; Owen *et al*., 2002). Moreover, the glacial advance resulting from lower temperature with more precipitation was larger than that during Last Glaciation Maximum (LGM), which possibly indicates the glacier evolvement of Last Glaciation in East Asian monsoon is not only a regional characteristic but also the global. In addition, Benn and Owen (1998) highlighted the importance of the mid-latitude westerlies and the South Asian monsoon on glacier formation both at regional and local scales on the Tibetan Plateau and the Himalayas, and suggested that the relative importance of the two climatic systems varied throughout the Quaternary, in turn influencing the style and timing throughout the region. They checked the glacial extent and timing of many selective areas in the Himalaya ranges and the Tibetan Plateau, and hypothesized that glaciations may have been asynchronous between different regions of the Tibetan Plateau and the Himalayas. Some further studies in these regions of central Asia using the new dating methods, such as the optically

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stimulated luminescence (OSL), cosmogenic nuclide surface exposure dating, supported Benn and Owen's idea (Richard *et al*., 2000; Phillips *et al*, 2000; Owen *et al*., 2002; Yi *et al*., 2002; Finkel *et al*., 2003). These research works all concentrate on the Tibetan Plateau and the Himalayas, especially in the monsoon-affected regions. Shi and Yao (2002) checked global evidence from 23 selected places of a dozen regions in low and middle latitudes and found that the glacial extent in MIS3b (54-44 ka BP) stage was larger than that during the LGM, which further confirmed Gillespie and Molnar's (1995) and Benn and Owen's hypotheses.

However, the timing framework was not well reconstructed because of the low abundance of organic matter in the sediments of high mountain environments for radiocarbon dating. Therefore, in this paper, we selected some glaciated mountains with new dates on southeastern and northeastern bordering mountains of the Tibetan Plateau, and the mountains in and along the western Pacific Ocean to test Gillespie and Molnar's (1995) and Benn and Owen's hypotheses, and our work was also based on Shi and Yao's (2002) paper. The main purpose of this paper is to answer the following questions: Are the developments of mountainous glaciers synchronous? How long is the time span if they are synchronous? Can the synchronous view that the largest ice cap in high latitudes and mountainous glaciers in low latitudes occurred simultaneously also be applied to Asia or to larger areas? The location of each selected area is shown in Figure 1 and the glacial extent and chronologies in Figure 2 and Table 1 are discussed below.

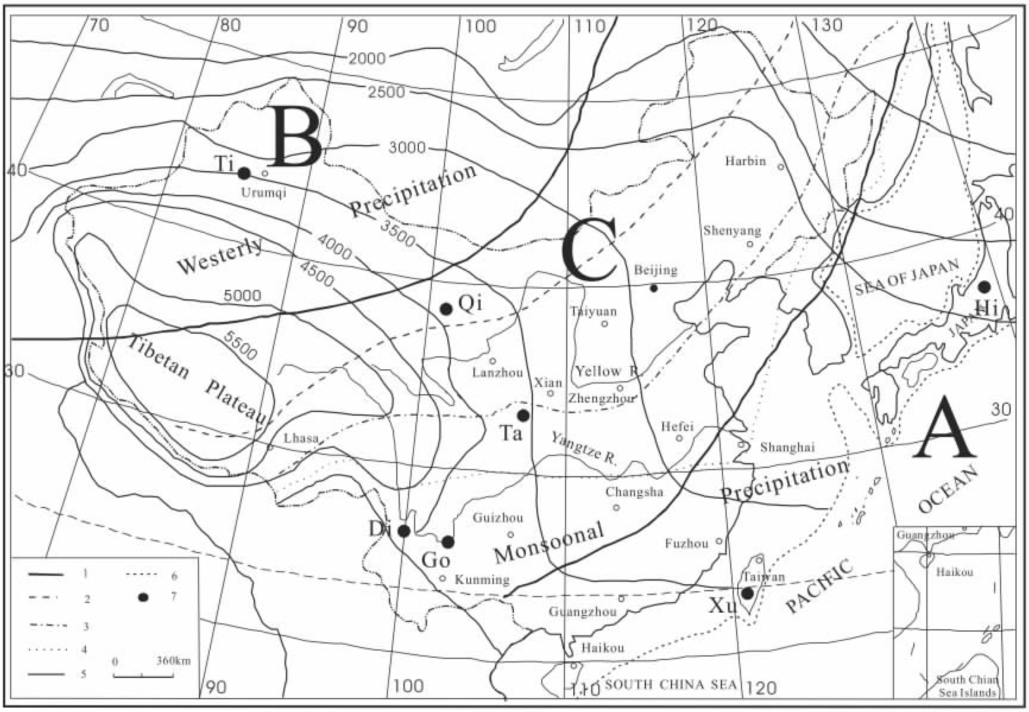

Figure 1 Map of modern precipitation distributed sub-areas (after Shi, 2002; Ono and Naruse, 1997)

1–Boundary of present monsoonal precipitation and sub-area of monsoon region; 2–Boundary of monsoonal precipitation in the Last Glaciation; 3–Present isoline of precipitation 1000 mm/yr; 4–Isoline of precipitation 1000 mm/yr in LGM; 5–Snowline in the Last Glaciation; 6–Coastal line in the Last Glaciation; 7–Location of selected glaciated mountains Ti-Tianshan Mt.; Qi-Qilian Mt.; Ta-Taibai Mt.; Di-Diancang Mt.; Go-Gongwang Mt.; Xu-Xueshan Mt. and Hi-Hidaka Range

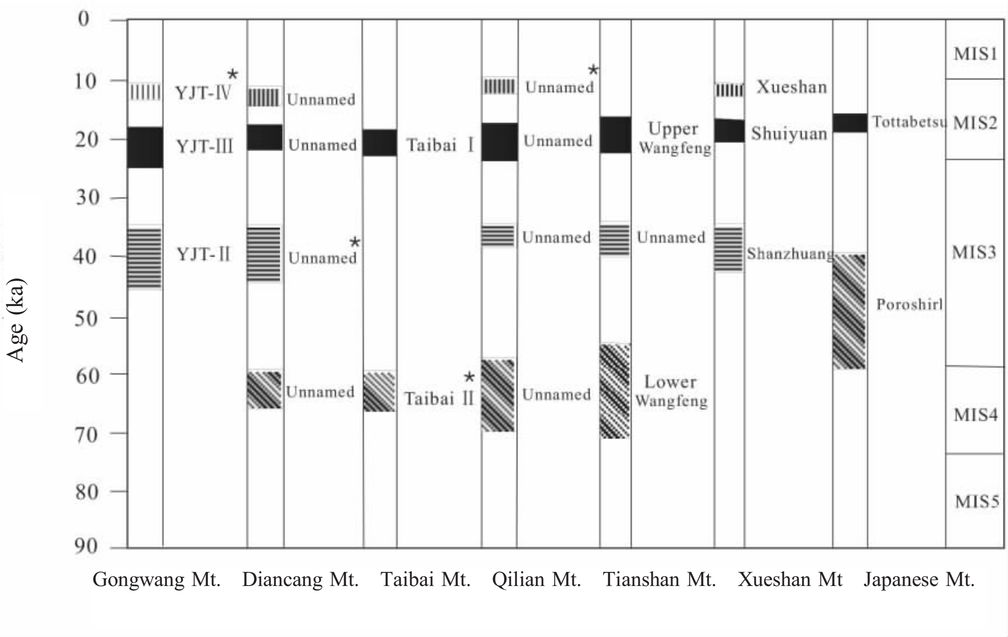

Figure 2 The locations and glacial chronologies that have been numerically dated in the selected regions

(The bar represents the likely duration of each glacial advance and
the name of each stage has been put in the right column near the bar.
An asterisk after each name indicates that no absolute dating can control the glaciation directly.)
(Data from Yi *et al.*, 2001; Zhao *et al.*, 2002; Guo *et al.*, 1995; Shi *et al.*, 2000; Zhou *et al.*, 2001; Rost, 1994; Zhang and Cui, 2003; Kuang and Zhao, 1997; Yang and Cui, 2003; Cui *et al.*, 2000a, 2002; Ono and Naruse, 1997)

2 The glacial timing and extent during Last Glaciation

There are two characteristics of the glacier advances in many mountain ranges in the monsoonal Asia during the Last Glaciation (Li, 1992).

2.1 The glacier extent in the early stage of the Dali Glaciation (Last Glaciation) was larger than that in the late stage, which is different from Europe and North America

It is considered that the glacier maximum advance of the Last Glaciation occurred within 25-15 ka BP according to the documents from Vostokin ice core in South Pole, the GRIP ice core in Greenland and the oceanic isotope SPECMAP curve. During this period, the ice cap advanced farthest, the global sea surface declined to its lowest level, the climate was the coldest and the ice amount reached to its maximum. However, the recent research indicates that glacier extent in the early stage (Ziliangka Glaciation) was larger than that in the late stage (late Ziliangka Glaciation) in Japan during Last Glaciation (Kind, 1972; Ono *et al.*, 1984, 1991). Other studies on Japanese islands also indicate that the height of snowline and the change in eolian dust flux reflected the palaeoenvironment differences in Japanese islands in these two stages (Ono *et al.*, 1997). In the stage of MIS4, the lower snowline elevation and the smaller dust flux represented a kind of cold and humid climate dominated by winter monsoonal precipitation between 70 and 55 ka BP. In the stage of MIS2, especially about 18 ka BP, the higher snowline elevation and the larger dust flux represented a kind of cold and very dry summer with a reduced winter monsoon precipitation. Tsukada *et al.* (1967) have also concluded that glacier extent in the early stage was larger than that in the late stage during Last Glaciation because precipitation in southwestern

Table 1 Absolute age correlation between the selected mountains

Mountain	Name	Last glacial stage	Ages (ka)	Dating method	References
Tianshan Mt.	Unnamed	Late glaciation	no ages		
	Upper Wangfeng	LGM	14.29±0.75	^{14}C	Wang (1981)
			19.08±0.51	AMS^{14}C	Yi *et al*. (1998)
			23.02±0.45		
			27.6±	ESR	Yi *et al*. (2001)
			37.4±		
			35±3.5		Zhao *et al*. (2002)
	Unnamed	Middle stage (MIS3)	41.8±5.4	OSL	Ju (2004)
	Lower Wangfeng	Early stage (MIS4)	72.6±	ESR	Yi *et al*. (2001)
			58.6±		
			54.6±		
			56.6±		
Qilian Mt.	Unnamed	Late glaciation	13.4±	ESR	Zhao *et al*. (2002)
	Unnamed	LGM	25.615±0.37	^{14}C	Guo *et al*. (1995)
	Unnamed	Middle stage (MIS3)	31.15±0.76	^{14}C	Guo *et al*. (1995)
			39.9±4.0	ESR	Shi *et al*. (2000)
			35.7±3.6		
			36.7±3.4	ESR	Zhao *et al*. (2001)
	Unnamed	Early stage (MIS4)	73±7.3	ESR	Zhou *et al*. (2001)
			55.8±5.0		
Taibai Mt.	Taibai Ⅰ	LGM	19±2.1	TL	Rost (1994)
	Taibai Ⅱ	Early stage (MIS4)	no ages		
Gongwang Mt.	YJT-Ⅳ	Late glaciation	no ages		Zhang and Cui (2003)
	YJT-Ⅲ	LGM	18.23±1.42	TL	
			25.42±2.11		
	YJT-Ⅱ	Middle stage (MIS3)	40.92±3.40		
	YJT-Ⅰ	Early stage (MIS5d)	104±8.3		
			101.1±7.78		
Diancang Mt.	Unnamed	Late glaciation	10.78±0.80	TL	Yang (submitted)
	Unnamed	LGM	19.32±1.47		
			21.08±1.62		
			17.39±1.29		
			17.92±1.36		
			16±	ESR	Kuang and Zhao (1997)
	Unnamed	Middle stage (MIS3)	no ages		
	Unnamed	Early stage (MIS4)	57.6±	ESR	Kuang and Zhao (1997)
Xueshan Mt.	Xueshan	Late glaciation	10.68±0.84	TL	Cui *et al*. (2002)
	Shuiyuan	LGM	18.62±1.52		
			14.28±1.13		
	Shanzhuang	Middle stage (MIS3)	44.25±3.72		

Japan during the LGM was only 30%-50% of the modern one according to the changes in ancient vegetation type. Recent researches also show the same fact that the glacial extent in the early stage (MIS3-4) is larger than that in the late (MIS2) in China, even including the Qinghai-Xizang (Tibet) Plateau and its surrounding mountainous regions (Figure 2), where the neo-tectonic movements are very intensive.

In Tianshan Mountains, the perfect multiple Quaternary glacial landforms and remains were preserved from Glacial Station (3200 m) to Hongwuyue Bridge inside the main trough valley, outside the modern glaciers. Using the AMS14C and ESR dating methods, Yi *et al*. (1998, 2001), Zhao *et al*. (2001, 2002) and Zhou *et al*. (2001) dated the glacial remains in this region and indicated the Upper Wangfeng Stage happened during the late stage (LGM) of the last glacial circle, which coincides with the idea of Wang (1981). However, two ESR dates, i.e., ~37.

4 ka and ~27.6 ka are older than the AMS^{14}C for several thousand years (Yi *et al*., 2001). The Lower Wangfeng Stage glacier advance is more complex than that of the Upper Wangfeng Stage. Yi *et al*. (2001) considered the Lower Wangfeng Stage glacier advance during 50-70 ka BP was based on four ESR dates (Table 20), corresponding to the early stage of the last glacial circle, and not the Penultimale glaciation concluded by Wang (1981). Shi and Yao (2002) concluded the moraines/tills of the Lower Wangfeng Stage are the compounds during the glacial advance periods of MIS4 and MIS3b according to the dating results (Yi *et al*., 1998, 2001). Furthermore, this conclusion was approved by new OSL dating result. Ju (2004) dated the soils of the glacial deposits (2518 m) near the Hongwuyue Bridge and obtained one OSL age of 41.8±5.4 ka. These researches show the glacial extent during LGM was less extensive than the early (MIS4)/the middle (MIS3b) cold stage during the last glacial circle. The Lower Wangfeng Stage's glacial length, with a terminus at about 2300 m a.s.l. near the Hongwuyue Bridge, is 6 km longer than that of the Upper Wangfeng Stage.

A series of terminal moraines ranges for three kilometers in the Baishuihe river exit on the piedmont of the Lenglongling Mountain, ^{14}C dating proved that the front moraines formed at 37,380 yr BP are deformed by the crunch of back moraines which were formed only at 11 ka BP. Guo *et al*. (1995) dated the glacial remains of the two parts with ^{14}C (Figure 2) and considered that both the front and the back parts were formed during the early and late stages of the last glacial circle respectively. In addition, using the ESR method, Shi *et al* (2000), Zhou *et al*. (2001) and Zhao *et al*. (2001, 2002) mainly examined the glacial succession in Laolongwan and Gangshenka valleys in this region and roughly agreed with the idea of Guo *et al*. (1995). They considered that the most extensive glacial advance represented by the ~3 km lateral moraine with a terminus at 3240 m asl in Laolongwan valley took place during the early stage of the last glacial circle. However, the ESR dates of ~35-40 ka BP show this glacial advance may also happen during the middle stage (MIS3) of the last glacial circle. Moreover, one ESR data of 36.7±3.4 ka from the back part of the above-mentioned glacial section in Gangshenka valley also supports here one phase glacial advance once took place during MIS3 stage.

Near the main peak of Diancang Mountain, there preserved ancient cirques of two steps, Kuang and Zhao (1997) dated the glacial deposits at the bottom of Shuangtanzi cirque (3850 m asl) and Yunnongfeng cirque (3600 m asl) using ESR, and concluded they possibly correspond to the late (~16 ka) and early stages (~57.6 ka) of Last Glaciation respectively. Our recent work shows that younger glacial advance extensively took place near Yuju Peak and Longquan Peak (Yang *et al*., submitted). For example, near Yuju Peak (4097 m asl), a TL of date ~10.78±0.80 ka BP from the upper tongue-shaped moraine at 3960 m asl shows this glacial advance took place during the late glaciation, while the dates ~19.32±1.47 ka, ~21.08±1.62 ka from the moraine deposits on the southern slope of Yuju Peak and 17.39±1.29 ka, 17.92±1.36 ka on the northern slope indicate the glacial advance events taking place during the LGM. The ESR and TL datings suggest the most extensive glaciations culminated prior to ~57 ka BP, while the less extensive glacial events occurred approximately 17-21 ka BP, indicating that the local maximum glacial advance in Diancang Mountain is asynchronous with the global glaciation maximum at 15-25 ka BP. On Xueshan Mountain in Taiwan, the glacier extent of Shanzhuang stage (TL: ~40 ka BP) was larger than that in the Shuiyuan stage during Last Glaciation (TL: ~18 ka BP) (Cui *et al*., 1999, 2002). And on Gongwang Mountain in Yunnan province, the recent TL dating evidences reveal that the outer lateral moraine levee was formed at 40.89±3.4 ka BP and the end of the glacier was once down to 3050 m asl, its extent was larger than that in the LGM (TL: 18 ka BP, 25 ka BP) when the end of the glacier was once down to the lowest latitude of 3500 m asl (Zhang *et al*., 2003). Moreover, similar events occurred in the Taibai Mountain in Shaanxi province (Rost, 1994).

The above examples show that it might have been common for the glacier extent in the early stage to be larger than that in the late stage during the Last Glaciation in the Asian monsoon region, not the local one caused by evaporation change in Sea of Japan. The Guliya ice core record on the west of Kunlun Mountains indicates that the temperature during this period of time was 5℃ lower than that at present and it was an obvious cold stage with relatively sufficient precipitation, which caused glaciers to advance and exceed the extents during drier and colder LGM. Shi and Yao (2002) consider that the MIS3b cold stage was induced by precessional cycle, which caused a cold phase to appear in the summer low-angle sun incidence in the middle and low latitudes. Compared to the largest global ice volume in the MIS2 stage, the temperature decline was smaller and the precipitation was larger in this stage. Glaciers in mountainous areas advanced and expanded because accumulation exceeded ablation. Therefore, this phenomenon that the glacier extent in the MIS3b cold stage was larger than in the LGM might have occurred in many other middle and low latitude regions in Asia, Europe, North America, South America and Australia.

2.2 For the first time mountain regions close to the sea experienced glacier expansion and the inland areas retreated

Comparing the distribution and scale of the glaciers during the Last Glaciation with those in the mid-Pleistocene glacial stage, it can be concluded that it is the first time that glacier actions occurred in some western Pacific Ocean mountain regions, such as Taiwan, Japan, Changbai Mountain, during the Quaternary period. It implies that glaciated areas in the Last Glaciation were expanding but evidences from areas with several glacial stages show that glacial scales in the Last Glaciation were shrinking. The evidences appear to be contradictory but they were caused by the same phenomenon. Glacier movement occurring in Japan, Taiwan and New Guinea etc. until Last Glaciation might indicate that these mountains nearly reached to the present height just before Last Glaciation. However, the uplift of the Himalayas made the Qinghai-Xizang Plateau a climatic barrier. It is reported that the Qinghai-Xizang Plateau rose further 1500 m during late Pleistocene, the average is 1 cm every year (Li *et al*., 1979). So the climate in many inland areas shows a drought tendency, which leads to favorable effects on glaciers being balanced by the drought. Even today, the glacier extent is still quite small. Meanwhile, the glacier extent in Siberia also shrank during Last Glaciation. A possible reason for that might be related to the uplift of the coastal mountainous region in East Pacific Ocean. Precipitation required by glacial formation was reduced because it was difficult for the marine air mass to penetrate inland. Therefore, the glaciation in East Asian monsoon regions during Last Glaciation was enhanced in the context of intensive neo-tectonic movement.

3 Influence of Chinese mainland monsoon regions and the westerlies on glacier extent

The East Asian monsoon regions can be roughly divided into three sub-regions from ocean to inland according to the precipitation based on the new data (Figure 1):

A: East Asia coastal islands and the mountains near the Pacific Ocean, such as the Taiwan mountains, the Japanese archipelagoes, and Changbai Mountains, are regions rich in winter precipitation.

B: The northwestern part of the Qinghai-Xizang Plateau, Xinjiang, Hexi Corridor of Gansu and West Mongolia are affected by the westerlies where the precipitation is fairly uniform throughout the year and both the spring and autumn precipitation can replenish glaciers.

C: The region between regions A and B is dominated by summer precipitation.

These three distribution modes of seasonal precipitation result in three modes of glacier supply. To be brief, the modes of the westerlies and the East Asia coastal islands are favorable to glacier advance. Under these conditions, glacier would expand during ice ages. In contrast, the mode of summer precipitation is not favorable to glacier development. In order to provide a clearer picture, it is necessary to discuss the relation between temperature and precipitation, which determines the snowline and thereby controls glacier advance and retreat.

Shi (2002) also put forward a similar idea. When discussing the characteristics of glacier development on the Qinghai-Xizang Plateau and in the East Asian monsoon regions, he suggested that the monsoon regions might have roughly been divided into two belts according to the strong monsoon and the weak monsoon precipitation. The former is the oceanic cool glacier region, such as the Hengduanshan mountain ranges in the southeastern part of Tibet; the latter is the continental glacier region including all other regions except the former. Important boundaries are shown in Figure 1, including the western boundaries of the modern (to the west) and the LGM (to the east) monsoon precipitation as well as the modern and the LGM precipitation isolines of 1000 mm/a.

Without any other influence, the annual accumulation is mainly determined by annual solid precipitation, and the annual ablation is mainly determined by summer ablation temperature, which can be roughly replaced by the mean temperature from June to August according to the rule of annual ablation equal to accumulation at the ELA.

Shi *et al*. (1997) pointed out, from the relationship between the annual precipitation and the mean temperature from June to August based on the modern glaciers in the west of China and the east of Alps (Su *et al*., 1984; Kerschner, 1985), that the temperature near the snowline increases as the precipitation does. In order to adapt to the temperature increase, the snowline elevation will somewhat decline. On the contrary, the temperature near the snowline decreases when precipitation does, which makes the height of snowline rise. The ratio of snowfall to precipitation, however, decreases as the temperature near snowline increases. According to the observation on the snowfall probability in different temperature conditions on the Qilian Mountains, the ratio of snowfall to precipitation is about 70%, 40%, and 20% when the ground temperature is 2°C, 4°C, and 6°C correspondingly (Ding *et al*., 1985). Moreover, Wu *et al*. (1985) concluded that solid precipitation rate changes between 88.5% and 10.9% if the monthly mean temperature is within the range of 0-10°C based on the relationship between monthly solid precipitation rate and the temperature. The regression exponential curve indicates that the range of snowfall ratio is 70%-80%, 50%-60%, 30%-40%, and 10%-20% if monthly mean temperature is 2°C, 4°C, 6°C, and 8°C correspondingly. So an increase in summer precipitation and temperature would expedite the ablation and erosion on the ice surface rather than increase the accumulation. When the summer temperature increase exceeds a threshold, precipitation would not favor glacier development and the snowline would rise to keep a balance through obtaining a lower temperature, reducing ablation and increasing accumulation, which would lead to glacier retreat. On the contrary, if glacier development depends on the precipitation supply in autumn, winter and spring, glaciers will advance.

The above principle is helpful to the explanation of some phenomena in the Last Glaciation. There were great glaciation advances in Last Glaciation in the eastern part (95°E) of the Qinghai-Xizang Plateau. Some larger valley glaciers advanced over 100 km. The area of the glacier cap expanded to a maximum of over 3000 km^2. The proportion of modern glaciers to the Last Glaciation, however, is only 5%. The change in snowline elevation is the sharpest. By contrast, this proportion increases from 20% to 45% in the western part of the Qinghai-Xizang Plateau. This contrast shows that glacier developmental conditions varied to different degrees in different regions. All glaciers and glacial caps disappeared in the east (such as Daocheng and Xinlong glacial caps), while 45% of the glaciated area remains in the western regions. In brief, the glacier developmental conditions in the west were more stable than those in the east. The reason might be that the scale of the eastern borderline of westerlies and the western border of the monsoon shifts according to the above-mentioned three zones. The western border of the Asian monsoon retreated 500-600 km because of changes in air circulation and the distribution pattern of land and ocean, together with large area of eastern continental shelf exposed as land during the Last Glaciation (Xie *et al*., 1996). At the same time, the westerlies possibly strengthened and affected wider regions where the monsoon climate once dominated. For example, the supply mode of glacier development has changed from favorable conditions under the westerlies to unfavorable summer precipitation conditions in the eastern part of the

Qinghai-Xizang Plateau from Last Glaciation to the present. Shi and Yao (2002) considered that the Karakorum Mountains, the Hindu Kush Mountains and Himalayas are likely to witness the influence of westerlies retreat from these regions; at least this is true in the western regions of Asia. Besides some mountains in the eastern part of China uplifted by the intensive tectonic movement during late Pleistocene, including the coastal mountains and the eastern part of Qinghai-Xizang Plateau (such as Taibai Mountain, Maxian Mountain, Gongwang Mountain and Diancang Mountain), developed the glacier only in Last Glaciation, other mountains with several times of glacial actions during Pleistocene such as Luoji Mountain, Dalijia Mountain, Xiaoxiangling Mountain, and mountains with modern glaciers such as Yulong Mountain, Siguniang Mountain, Xuebaoling and Gongga Mountain, have witnessed changes in the glacier extent from large to small since Last Glaciation. In addition to the reasons that the high mountains are the barriers restraining vapor penetration and glacier development, the more important is that the influence of monsoon climate follows as the east boundary of the westerlies moves westwardly.

It should be pointed out that the so-called east boundaries of westerlies and the west boundary of the Asian monsoon are unstable. Li (1992) argued that Asian monsoon region was unstable during the Last Glaciation because of the unstable atmosphere movements. The scales of boundary will change even including the annual and the perennial especially between glacial stage and interglacial stage. In fact, these changes just mean the area changes between westerlies and Asian monsoon. The authors here only emphasize the shifts of westerlies and point out the characteristics of different supply modes to glaciers by the westerlies and Asian monsoon belts. Moreover, Schäfer *et al*. (2002) also concluded that there is a correlation between North Atlantic and East Tibet climate, which is most likely established by the effects of westerlies during the last glacial circle.

Similar to ancient glacial series in Japanese mountains and eastern Siberia but quite different with inner mainland, Taiwan mountains during Last Glaciation experienced two glacial phases (Arkhipov *et al*., 1973). The glacial series in Gongwang Mountain in the northeast of Yunnan during Last Glaciation are characterized by the perfect series of early, middle, glacial maximum, and late phase (Zhang *et al*., 2003), while the ages of glaciation in Diancang Mountain are new and mainly fall into the late period of Last Glaciation (Cui *et al*., 2002). The common characteristics in these two regions are that, however, the glacier series are multiple and successive. The differences might show that even under the influence of the same monsoon system, the glacier development gives birth to the regional differentiation because of different water and atmosphere conditions in different geographic positions, or in other words, there exist two different precipitation types including the Ample Precipitation in Winter (APW) along the Pacific Ocean and the Ample Precipitation in Summer (APS) in the mainland. Although there are some differences in quantities, the climate pattern during Last Glaciation should be similar to that in the modern times. Because the APW is favorable for glacier accumulation, the glacial advances in the early and late stages during Last Glaciation are very obvious and the glacier extent in the early stage is larger than that in the late stage (10-11ka BP) in mountains of Taiwan and Japan.

This is one of the characteristics of the mountain glacier development in the East Asian coastal area. The trend weakens gradually to the west region when the monsoon front moves to the inland. There are few reactions in Yulong Mountain in the south and Qilian Mountains in the northwestern China, which are mainly the APS of the continental monsoon region with dry and cold climate in winter. The Asian glacier development, particularly during Last Glaciation, is heavily controlled by the sub-monsoon region of APW and APS. However, before Last Glaciation (for example, mid-Pleistocene), the glacier would expand when the vast mainland regions were not dominated by the Asian monsoon like today and the APW-affected regions were much larger than those in the modern times. Therefore, the glacial area in Qinghai-Xizang Plateau is ten times or scores of times larger than that now. Then the westward shift of the east boundary of westerlies made the precipitation change from relatively even to uneven. Especially after winter monsoon strengthened, the conditions for glacier accumulation worsened and in turn, larger regions were affected under this worsened conditions. This surely made the glaciers formed during late Pleistocene sharply disappear in the eastern part of the Qinghai-Xizang Plateau. But the large areas of glacier still remain in the west of the Qinghai-Xizang Plateau because of the less effects. This phenomenon represents the brand in glacier development caused by the monsoon evolvement with spatio-temporal changes. As it were, the glacier extent within its influenced regions is becoming smaller as the modern Asian monsoon is shaped (dry and cold in winter but hot and humid in summer).

4 Discussion and conclusions

The above discussion should be connected with the perspective of the asynchrony/synchrony of the glacier advance. In the 1960s, Russian geomorphologist Markov proposed the theory of asynchronous advance of mountain and continental glaciers, that is, the glacial maximum did not appear simultaniously because of great differences of regional climate systems. Recently, Velichko *et al*. (1997), Benn and Owen (1998) and Gillespie and Molnar (1995) reiterate this conception based on the detailed data. Discussing asynchronous/synchronous advance of mountain and continental glaciers would greatly improve our understanding because there are more dating evidences than those in the 1960s. When Markov put forward the question about asynchronous advance of glaciers, he was unable to point out the specific time scale. Nowadays, while Velichko *et al*. discussed this question with specific time scale (Velichko *et al*., 1997), Shi *et al*. (2002) considered that glacier advances in many places during the stage of MIS3b (5.8-4.4 ka BP) seem to mean synchronous advance of the glaciers in low and middle latitudes. It is time to discuss the asynchronous/synchronous glacier advance because some significant conclusions might be drawn as enough evidences have been accumulated, but the key question is how long the time scale should be involved in the asynchrony and synchrony.

When discussing the glacier advance during MIS3b stage, Shi *et al*. (2002) considered that the scope of descending temperature was little but the precipitation amount might increase. This combination led to the glacier advance and exceeded the glacial scale during the LGM. But why did the precipitation during MIS3b stage increase? They think it is caused by huge volume and thermal capacity of seawater which made precipitation change lag behind temperature change. The precipitation might be abundant even it was reduced inconspicuously during the MIS3b cold stage after the MIS3c (65-55 ka BP) warm stage. This cold and humid climate, together with the snowline decline and snow cover expansion, is advantageous to glacial advance. The further decline in temperature during MIS2 stage caused further precipitation reduction so that cold and dry environment formed, which made glacier accumulation reduce and restrained glacier expansion. The direct consequence is the glacier extent in MIS2 stage was not larger than that in MIS3b stage.

Most events of glacier advance were collected from 23 sites in 12 areas concentrated within the period of 57-35 ka BP. According to the brief analysis, the regions where the ages of advance events accord with 54-44 ka BP (MIS3b) include Urumqi headwater region of the Tianshan Mountains (Yi *et al*., 2001), Karakorum Mountains (Wu *et al*., 1985), Hindu Kush Mountains (Owen *et al*., 2002) and Himalayas (Barnard, *et al*., 2004) etc. in Asian alps, while advance events within the same time range have hardly seen evidences in the occident regions such as Alps, Pyrenean, the mountains in the western United States, Central and South America. Given the advance events of dating evidences in the period < 40 ka BP and > 58 ka BP not counted, only evidences in the period between > 40 ka BP and < 58 ka BP are counted, the former in 58-40 ka BP have 23 data, while the latter fitting to this request only have 12 data. This implies that the places experienced the largest glacier expansion during MIS3b stage might also be restrained in some regions.

The illumination is gained that to discuss this problem it is necessary to connect it with the theory of asynchronous advance of glaciers. Recently, Velichko *et al*. (1997) have found the glacier's extent in the world during Last Glaciation is different in different regions according to the new dating evidences. Moreover, Gillespie *et al*. (1995) and Benn and Owen (1998) also discussed the asynchronous advances of glaciers all over the world and in the Tibetan Plateau and the Himalayas respectively. Based on the glacial geomorphology, stratum, and dating evidences, Velichko *et al*. (1997) have found that only very small area, even no area, was covered with ice and snow in the arctic circle of high latitude regions in Canada when the most regions of North America were covered with Laurentide ice cap. The similar instances can be found in Eurasia. The outmost moraine levee of Scandinavian ice cap was formed in the period of 24-18 ka BP. Similarly, the outmost moraine levee of Novayazemlya ice cap in the north of Siberia was formed at 33 ka BP. The occurrence of largest scale of this ice cap is about 9-15 ka prior to the Scandinavian ice cap. When the latter expanded to its largest extent, the former had already been in shrinking stage. Similar examples can also be found in South and North America and Oceania (Gillespie *et al*., 1995). The reason might be that the eastern part of Eurasia (including West Siberia (Novayazemlya)) was more favorable to glacier advance than the western part (including Europe) under the same cold environment during the period of ice ages when anticyclone of West Siberia caused by the glacier cover was not strong enough and the frequency of snowfall brought by the cyclone from the western part was still relatively high. The solid precipitation from the west was rich. The influence of the warm current in the gulf of Mexico, together with cold air eastward, made the regional differences strengthen.

However, the independent anticyclone system, caused by the appearance of large area of ice and snow cover, became strong enough to block moisture from west to supply glaciers when the climate in West Siberia became extremely cold. The lowest total amount of precipitation was about 20% of nowadays. At the same time, glaciers in the western part or European region were under the advantageous conditions. So it can be seen that the shifting of sea-atmosphere-glacier system from one stage to another caused largest precipitation centers changing from one place to another. Dating evidences from moraine had proved that West Siberian glacier attained its maximum at 40-50 ka BP, westward, the Novaya Zemlya-Polar Urals glacier at 30-40 ka BP, the glaciers in Eastern Europe at 18-20 ka BP and the further westward, the Western Europe at less than 16 ka BP (Figure 3).

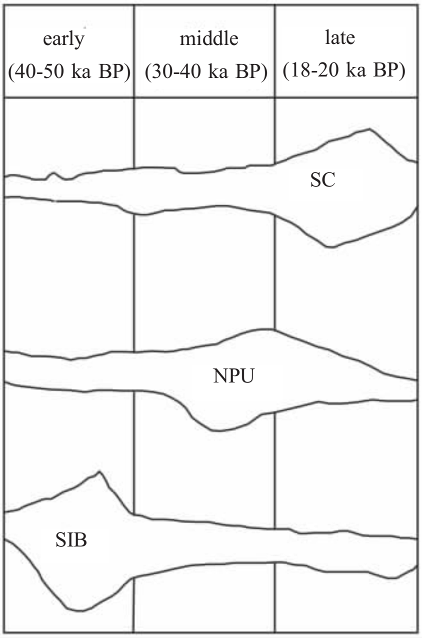

Figure 3 The time alternant system of the maximum advance extent of glaciers in Eurasia during the Last Glaciation (after Velichko, 1997) SC: Scandinavian ice-sheet; NPU: Novaya Zemlya-Polar Urals ice-sheet; SIB: Siberian ice-sheet

Although restrained by the research degree and dating precision, it is difficult to distinguish the largest glaciers advance period in the early stage or the late stage in many mountains such as the Tianshan Mountains, Qilian Mountains, Taibai Mountain, during Last Glaciation, however, it is very clear that the ice advancement in these two stages (MIS3-4) occurred prior to the LGM (Table 1).

Two opinions have been formed from the above discussion on the largest scale and the asynchronous advance of glaciers. Whether these two opinions can be connected or not depends on the selection of time scales, the opinion that supports synchronous advance of glacier maximum during the MIS3b stage gives the time range from 54 to 44 ka BP and the 10 ka time span. Data within

58-40 ka BP can be discussed within the same framework and the time span expanded to 18 ka. But the opinion that supports asynchrony provides the time range within the entire Last Glaciation. The specific time ranges include 50-40 ka BP, 40-30 ka BP and 20~18~16 ka BP and the time span is 34 ka. Although these two time spans are different, they are still in the same order of magnitude. Our premise is that all these data are credible, so we deal with the so-called error.

It can be seen that they overlay in the time range of 50-40 ka BP. If this superposition is discussed in the perspective of the synchronous opinion without considering any others, the synchrony is true. But it reduces one of the possibilities to understand the time and space evolution of the same glacial sequence. Therefore, the authors tend to combine these two viewpoints. In other words, within a certain time span, for example, within 10 ka (or shorter), synchronous glacial advance is an undeniable phenomenon. In the longer time span, for example, 20-30 ka BP, the glacier expanded asynchronously. However, the reason that causes these phenomena needs to be studied in more details. Moreover, the mountain precipitations are greatly different from the Polar regions in that the prevailing wind transports moisture of the air mass from a long distance to the mountains and nourishes the glaciers. Therefore, it is not suitable to emphasize the synchronicity between global ice-volume and glacier change.

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