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AMS radiocarbon dating of late Quaternary glacial landforms, source of the Urumqi River, Tien Shan—a pilot study of ^{14}C dating on inorganic carbon

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Abstract

Carbonate coatings on roche moutonnees and till clasts and calcite in the fine matrix of late Quaternary glacial landforms were dated by using accelerating mass spectrometry (AMS) radiocarbon dating, at the source area of the Urumqi River, Tien Shan. The values of ^{13}C and the sedimentary properties of tills and coatings show that the precipitation of inorganic carbon in calcite in the till matrix is synchronous with till formation. The carbon dating of the fine matrix of till and the coatings on till clasts can be used to determine or estimate the ages of glacial moraines, as the inorganic carbon in fine matrix and coatings may preserve well with no or little fractionation. The largest-scaled moraine near Wangfeng road maintenance station was dated to be 19–23 ka. The age of the local Last Glaciation Maximum was, therefore, coincident with the global Last Glaciation Maximum. The moraine at Glacier Observatory, which was formerly believed to be the product of Neoglaciation, seems to be the relics of a lateral moraine, also formed during the Last Glaciation.

1. Introduction

Dating till is important for reconstructing the glacial geological history of a region. However, glacial till is lacking in organic matter for direct ^{14}C dating, except for paleosols developed on till at rare sites. Many researchers have tried to use ^{14}C for dating pedogenic carbonate (e.g. Williams and Poliach, 1969; Pazdur and Pazdur, 1986; Quade et al., 1989; Wang et al., 1994). As the carbonates are not closed systems and may exchange ^{14}C with modern or dead ^{14}C after their formation, many studies failed. However, some data proved to be useful for sediment ages or explanation of paleoenvironments (Swett, 1974; Chen and Polach, 1986; Courty et al., 1994; Geyh and Eitel, 1998; Pustovoytov, 1998). Subglacial precipitation of carbonate coatings was found in carbonate rock areas (Bauer, 1961; Ford et al., 1970; Souchez and Lorrain, 1975; Hallet, 1976a, b; Fairchild and Spiro, 1990; Sharp et al., 1990). Its presence implies that subglacial calcium carbonate coatings could be used for ^{14}C dating. However, dead carbon from carbonate rock will make ^{14}C dates much older than the actual age of moraine and would make the dating of inorganic carbon in glacial moraine impossible. As well, the concentration of carbonate cement and precipitates in till is low in China. When HCl solution is added to till samples, there is no apparent reaction of carbonate with the acid, suggesting that carbonate content is less than 1%. It is therefore difficult to determine the age by mass spectrometry ^{14}C dating of carbonate because of the low carbonate concentrations. Hence, many studies on Quaternary glacial geology in China lacked absolute dating data (e.g. Yi, 1989; Cui et al., 1993). The experimental studies of this paper deal with the radiocarbon dating of subglacial precipitates in a non-carbonate rock area, which though less spectacular are probably more widespread than those on carbonate bedrock, in the source area of the Urumqi River, Tien Shan.

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2. Geological setting at sampling sites

The source area of the Urumqi River is on the northern slope of the main range of the Karauchen Mountains in the central Tien Shan (43°07′N, 86°49′E, Fig. 1). The elevation of the ridge in the region is mainly between 4100 and 4300 m asl, with the highest peak, Tianger Peak, having an attitude of 4486 m asl. The elevation of the modern snowline is about 4000–4100 m asl. Modern glaciers, including cirque glaciers, small-valley glaciers and hanging glaciers, are present at elevations of 3765–3700 m asl. The bedrock in the glaciated area comprises mainly chlorite-quartz schist, gneiss, granite, and diorite. Scattered carbonate rocks outcrop occur on the ridge to the north of Glacier 1. Wang (1981) believed that the glacial deposits that are distributed up the Wangfeng road maintenance station to an attitude of 3000 m formed since the Last Glaciation.

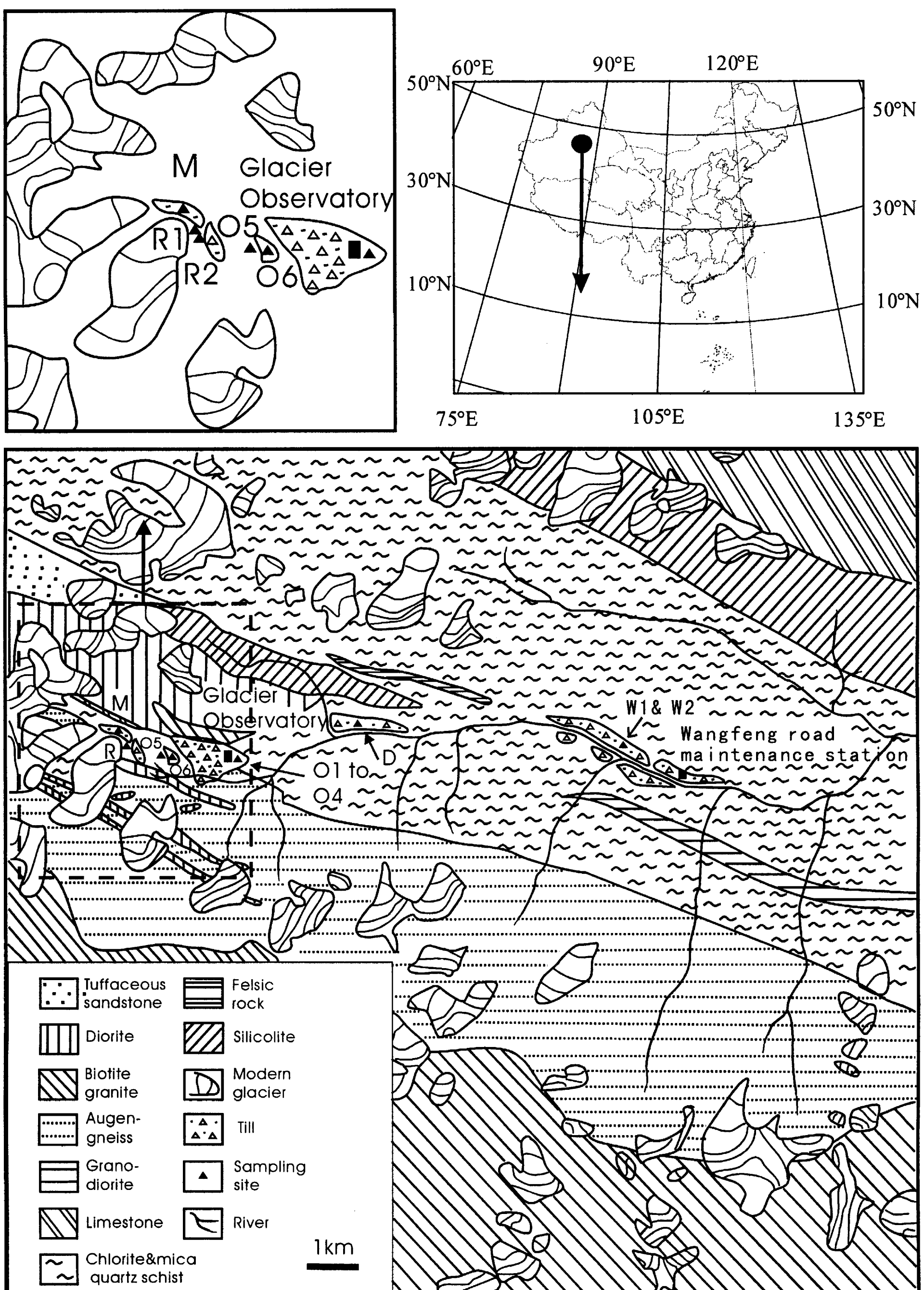

Fig. 1. Sampling sites at the source area of the Urumqi River, Tianshan Mountains.

3. Methods

3.1. Sampling

Samples W1 and W2 (W = Wangfeng) were collected from an end moraine in the Upper Wangfeng Moraine Group near the Wangfeng road maintenance station. The end moraine comprises two distinct tills, and is covered by a loess cap (Fig. 2).

The lower till (Figs. 2 and 3) is more consolidated and is finer grained, with a high silt content (Cui, 1981; Wang and Zhang, 1981). The fabrics of clasts (Feng and Qin, 1984) and of fine particles (Yi and Zhijiu, 2001) within these tills are strongly oriented, as a consequence of subglacial deformation. In the same moraine, Cui and Xiong (1989) and Xiong (1991) observed bending or folding of thin layers of fine sand to silt, about 0.5 m thick and several meters long. These layers were usually either between two large boulders or beneath boulders. The layers between large boulders appeared to be folded more than those beneath a boulder. We observed shear planes, as did Derbyshire (1984) and Feng and Qin (1984). Shear zones were several to more than 10 m long and 0.8–2 m thick, dipping upper glacier at angles of 18–28°. Feng and Qin (1984) and Derbyshire (1984) reported that the materials in these shearing zones were finer, and the sizes of clasts more uniform, than in the matrix. Feng and Qin (1984), Ma (1984), and Cui and Xiong (1989) reported that the long axes of elongate clasts in the shearing zones were parallel to the valley trend. The voids in the till were closed, surrounded by smaller particles, and most of them displayed regular disc, ellipse or worm-like shapes and had strong microfabrics (Yi and Cui, 1994; Yi and Zhijiu, 2001). Sample W1 was collected at a depth of about 14 m in an artificial exposure.

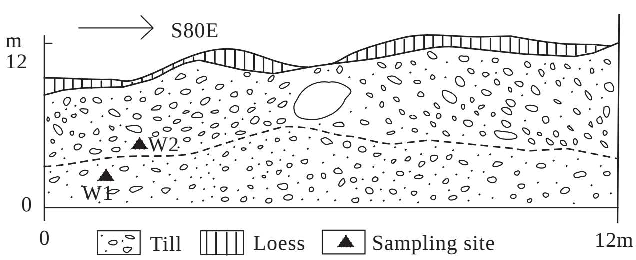

Fig. 2. Till profile at Wangfeng road maintenance station.

The upper till (Figs. 2 and 4) is loose and coarse, and has a low content of silt (Wang and Zhang, 1981) and dipping stratification of coarse to fine fragments. The rock fragments in this loose overlying till are the same lithology as the local valley sides (Li et al., 1981), and therefore this till is believed to have formed by dumping and rolling of debris from the hill slopes and from the glacier surface (Cui, 1981; Feng and Qin, 1984; Ma, 1984; Cui and Xiong, 1989; Xiong, 1991). Thus, it was likely formed by gravity flow processes. Yi and Cui (1994) reported that the voids in this till were interconnected. Most of these voids were large and irregular in shape, and were surrounded by smaller particles and the microfabrics of fine particles were strong, but those of voids were weak (Yi and Cui, 1994; Yi and Zhijiu, 2001). Sample W2 was collected at a depth of about 19 m in an artificial exposure.

There are small moraine hills (Fig. 5) on the valley side where the Glacier Observatory is located. There are no good exposures of till in the field. Samples O1–O3 (O = Glacier Observatory) were collected from the calcite coating on a till clast in the end moraine near the Glacier Observatory. O1 was scraped from the inner layer and O2 from the outer layer of the coating. O3 was a mixture. Sample O4 was collected at an artificial pit 1.5 m beneath the surface.

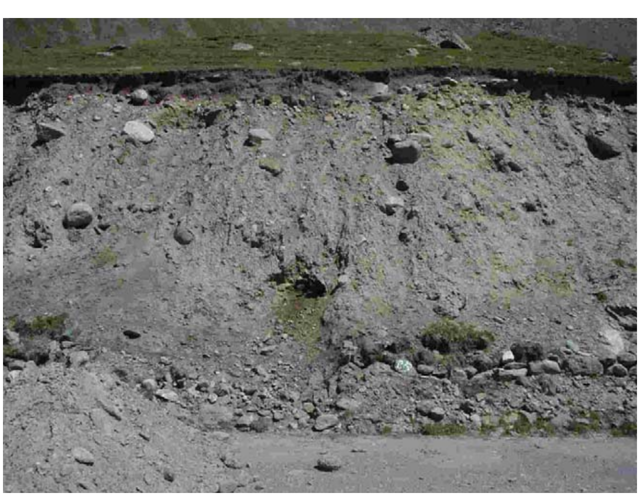

Fig. 3. Sediments in the lower till at Wangfeng road maintenance station. The former glacier flowed from left to right.

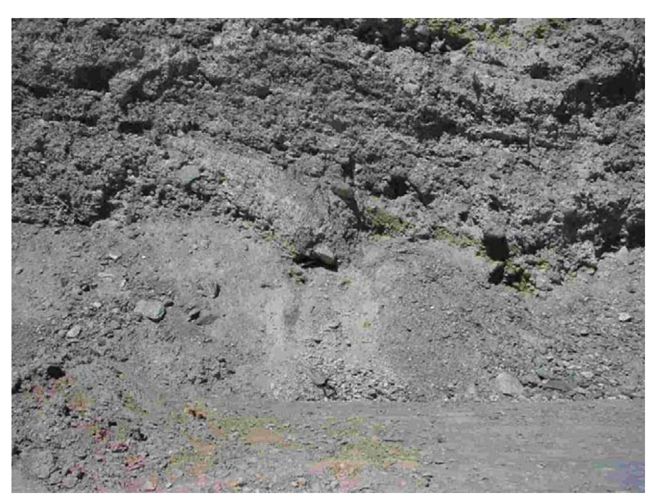

Fig. 4. Sediments in the upper till at Wangfeng road maintenance station. The former glacier flowed from left to right.

There are three end moraines between Glacier 1 and the Glacier Observatory. There are white coatings on the large boulders and roche moutonnees, with areas of 3–10 cm^2. The outer layers were scraped off and inner layers were collected for dating. O5 was collected from the coating on the top surface of a boulder over 2 m in diameter, at the foot of the third end moraine near the Glacier Observatory. O6 was collected from the coating on the lee side of a roche moutonnee near the third moraine between the third and second end moraines.

Sample D was collected on the lee side of a drumlin, which is located in the valley bottom, with a length of about 800 m and width of 200–300 m. It is between the upper Wangfeng moraine group and the Glacier Observatory.

The morphology of more than ten roche moutonnees with a height of about 3640 m, several hundred meters away from the front of Glacier 1 (Fig. 1) and the calcium precipitates on them were observed in the field. It is estimated that they were exposed to the atmosphere from 10 to 50 years ago. At this location, the bedrock comprises augen-gneiss. Samples R1 and R2 (R = roche moutonnee) were collected from a carbonate coating on two roche moutonnees several tens of meters in front of Glacier 1 (Fig. 6). Sample M (M = modern lateral moraine) was collected from the till by digging a pit in the modern lateral moraine of Glacier 1.

Fig. 5. Moraine where Samples O1–O4 were collected.

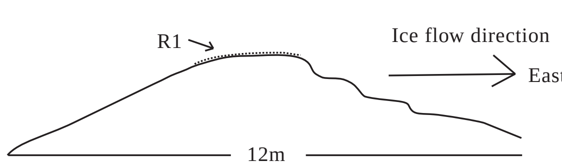

Fig. 6. Sampling site where Sample R1 was collected on a roche moutonnee in front of the snout of Glacier 1.

Primary coating or inorganic carbon as used here refers to the coating or carbon formed synchronously with till formation. Secondary coating or carbon refers to the coating or carbon after the till was formed.

3.2. Determination of morphology and mineral constituents of the coatings

The precipitate on a roche moutonnee was observed first visually under the polarizing microscope through thin sections to determine the structures and mineral constituents. Small samples were scraped from the coatings, where Samples R1, O5 and O6 were collected, and mineral constituents were analyzed semi-quantitatively using the infrared spectrophotometer at the Department of Geology of Peking University.

3.3. Dating

Tills were sifted through 100-mesh sieve, and 10 g of sieved till and 10 mg of coatings were used for preparation of carbon samples. Dilute HCl solution was added to Samples W1, W2, O1, O2, O4, D, M and R1 to decompose $CaCO_3$. Samples O5 and O6 were ignited. CO_2 gas obtained in these processes was collected and made into graphite. The sample preparation was undertaken in the Department of Archaeology at Peking University. The samples were dated using the accelerating mass spectrometry (AMS) equipment of Peking University.

3.4. Determiniation of $\delta^{13}C$ and $\delta^{18}O$

10 g of the dry till samples which were sieved through 100-mesh were ground into powder and were sifted through a 200-mesh sieve. The sifted powder and 10 mg of carbonate coatings were dried at 100°C, added to 100% H_3PO_4 solution, and put into bain marie at 25°C to induce a balanced reaction. Samples O5 and O6 were ignited. CO_2 was collected and $\delta^{13}C$ and $\delta^{18}O$ were determined using a Finnigan MAT-251 instrument.

4. Results

4.1. Morphology and mineral constituents of the coatings

Yi (1992) studied the occurrence and mineral constituents of the coatings on the roche moutonnees in the front of Glacier 1. The coatings, where Samples R1 and R2 were collected, are yellowish white and distributed on the polished top surface of the roche moutonnee. They are about 150–200 μm thick, which is observed in polarizing microscope in thin section. The maximum thickness reaches 200–300 μm. The main mineral component of the precipitate on the roche moutonnee (sample R) is calcite with minor amounts of limonite, quartz and feldspar (Table 1), as determined by infrared spectrophotometer and polarized microscope.

The coatings, where Samples O5 and O6 were collected, are white and 1–2.5 mm thick. Most were distributed on the top surface of the roche moutonnee. They cannot be decomposed in HCl solution, but can be decomposed by ignition. Their mineral constituents are mainly whewellite with minor amounts of limonite, hydromuscovite, feldspar and quartz, as determined by infrared spectrometry.

4.2. Dating results

The dating results are shown in Table 2. The dated carbon in R1, collected on a roche moutonnee, and in M, collected in modern lateral moraine, is modern carbon, indicating that the carbon was formed coincident with the till and precipitation. The end moraine at the Wangfeng road maintenance station is between 19 and 23 ka, which is about 4–8 ka older than the age dated by Wang (1981). The overlying till is about 4 ka older than the underlying till. O1 and O2, the inner layer and the outer layer of the coating, are 6.5 and 1.8 ka, respectively. However, the fine matrix of the same till (Sample O4) gives an age of 19 ka. O5 and O6 are 390–420 YBP, which is the same age as determined using lichenometric chronology (Chen, 1989). Sample D failed to give a dating age due to the low content of carbon.

4.3. Stable isotopes of carbon and oxygen

Stable isotope of carbon and oxygen are shown in Table 3. $\delta^{13}C$ values are −2.9‰ to −4.7‰ for old carbonate coating on a till clast (Samples O1, O2-1, and O2-2), 0.3‰ for modern till (Sample M), −0.8‰ to 0.6‰ for old till (Samples O4, W1 and W2), −4.1‰ to −8.2‰ for modern carbonate coating on roche moutonnees (R1 and R2), and −7.4‰ to −14.8‰ for organic coatings (Samples O5 and O6).

5. Discussion

Some ^{14}C dates for dating pedogenic carbonate proved to be useful indications of sediment ages or the explanation of the paleo-environment in arid or cold regions (e.g. Swett, 1974; Chen and Polach, 1986; Courty et al., 1994; Geyh and Eitel, 1998; Pustovoytov, 1998). The study area of this paper is also in the sub-arid and cold region with average annual temperature and annual precipitation of −5.2°C and 439.3 mm respectively (data from 1958 to 1998 at the Glacier Observatory Station). Secondary coatings are common on till clasts in the source area of the Urumqi River valley. Some dating on these coatings was tried (Wang, 1981; Gu and Li, 1990). Due to the cold and dry environments in glaciated areas in Tien Shan, some authogenic carbon in till may not exchange with other carbon sources after its formation, and radiocarbon dating can be useful. Here we discuss the possibilities of this technique, in this

Table 1
Mineral constituents of the precipitates: semi-quantitative results

Sample	Limonite	Calcite	Hydromuscovite	Whewellite	Feldspar	Quartz
R1	Less	Major	None	None	Less	Less
O5	Less	None	Less	Major	Less	Less
O6	Less	None	Less	Major	Less	Less

Table 2
Dating results of glacial deposits from the source area of the Urumqi River

Series	Sampling site	Type of deposit or moraine	Type of sample	AMS dating age (BP)
W1	Wangfeng road maintenance station	Underlying till	Till matrix	23 080 ± 510
W2		Overlying till		19 010 ± 450
O1	Glacier Observatory	Coating on till clast	Inner layer of coating	6560 ± 150
O2			Outer layer of coating	1860 ± 110
O4	Between Glacier 1 and Glacier Observatory	Lateral moraine	Till matrix	19 590 ± 130
O5		Coating on a boulder	Organic carbon coating	420 ± 150
O6		Coating on roche moutonnee	Organic carbon coating	390 ± 210
R1	Near Glacier 1	Lateral moraine	Coating	Modern carbon
M		On roche moutonnee	Till matrix	Modern carbon
D		drumlin moraine	Till matrix	Failed

Table 3
Values of $\delta^{13}C$ and $\delta^{18}O$ of carbonates in the samples[a]

Series	Sampling site	Type of sample	$\delta^{13}C$‰(PDB)	$\delta^{18}O$‰(SMOW)
O1	Glacier Observatory	Inner layer of coating on till clast	−4.65	24.39
O2-1		outer layer of coating on till clast	−2.90	24.87
O2-2			−3.03	25.03
O4		Till matrix	0.18	
O3		Coating on a boulder	−1.33	25.06
O5	Between Glacier 1 and Glacier Observatory	Organic coating on a boulder	−7.38	31.07
O6		Organic coating on roche moutonnee	−14.75	21.26
R1	In front of Glacier 1	Coating on roche moutonnee	−8.24	17.82
R2			−4.1	18.7
M		Till matrix in modern lateral moraine	0.31	23.47
W1	Road maintenance station	Till matrix in underlying till	0.6	20.8
W2		Till matrix of overlying till	−0.8	20.5

[a] W1 and W2 were determined by Dr. Yang Jinghong, Department of Geosciences of Nanjing University. O4 was provided by Dr. Liu Kexin, Institute of Heavy Ion Physics, Peking University. The rest were determined by Dr Huang Junhua, Testing Center of China University of Geosciences at Wuhan.

pilot study, to date tills by comparison of ^{14}C dates with the ages determined by other methods, $\delta^{13}C$ and some properties of till.

5.1. Carbonate coating on roche moutonnees in front of Glacier 1

The coating precipitation of carbonate calcite on roche moutonnees was found in carbonate areas and its mechanism of formation has been discussed by Ford et al. (1970), Hallet (1976a, b) and Souchez and Lorrain (1975). Hallet (1976a) and Souchez and Lorrain (1975) attribute the carbonate coatings to precipitation from chemically enriched subglacial melt-water associated with regelation processes involved in glacier sliding in carbonate areas. The carbon in the calcite formed in such a process is most probably polluted by dead carbon, which is not suitable for dating.

However, the bedrock on which the glaciers flow in the source area of the Urumqi River is dominantly noncarbonate. Glacier 1 covers augen-gneiss mingled with chlorite schist, quartz schist, and granite, and only a few small outcrops of carbonate-rich lithologies occur on the ridge to north of Glacier 1 (Fig. 1). This might not be unusual as similar carbonate coatings were found on the roche moutonnee in the Halasi river catchment in the Altay Mountains, an area that is also devoid of carbonate-rich rocks and where the bedrocks are several types of schist, sandstone and granites (Yi, 1992). Analysis of the 0.1–0.2 mm fraction of minerals in the glacial till revealed no calcite, dolomite and aragonite in that region (Yi, 1997). The carbonate distributed on the ridge to north of Glacier 1 in the study area may be dissolved into ions of Ca^{2+} and CO_3^{2-}, enters glaciers in dissolution along with slope flow, and recrystallizes on the roche moutonnee and in till. The carbon formed in such a process would be dead carbon. However, the carbon of the coating on a newly exposed roche moutonnee was dated to be modern carbon, denying the dominance of such process. As well, the $\delta^{13}C$ values of the carbonate coatings from newly exposed roche moutonnees (R1 and R2) are −4.1‰ to −8.2‰, apparently lower than that of marine carbonate which is usually 0 ± 2‰ (Zheng and Jiangfeng, 2000), suggesting the carbon may not come from limestone. These data imply that the carbon from the coatings was exchanged with the CO_2 from the atmosphere.

Calcite coatings have been reported to be present in front of retreating glaciers (Ford et al., 1970; Souchez and Lorrain, 1975; Hallet, 1976b). The calcite coatings where samples R1 and R2 were collected were distributed on polished surfaces of roche moutonnees. Their polished surface indicates that the coatings cannot be precipitated when they are shaped, otherwise precipitates would be scraped away by fragments frozen in the sole of the glacier. This suggests that calcite coatings precipitated in the front of retreating glaciers are approximately modern.

5.2. Modern till in the front of Glacier 1

The $\delta^{13}C$ value of carbonate in the till matrix of modern lateral moraine is 0.3‰, which is close to that of marine carbonate (Zheng and Jiangfeng, 2000). However, the dating showed that carbonate in the modern till matrix is modern carbon, suggesting that most of the carbon, if not all, was exchanged with the CO_2 in atmosphere in calcite formation.

As the decrease of pressure-melt point or refreezing can make ion-enriched subglacial water separate out calcite in small openings on roche moutonnees (Hallet, 1976a, b; Souchez et al., 1978; Yi, 1992), this process may also let calcite separate out on uneven surfaces or voids of till during glacial retreat, implying the carbon produced in such a way is synchronous with the till. It is significant that the inorganic carbon in till can be used for dating if the ancient glacial till was preserved well.

5.3. Old coatings on till clasts

The $\delta^{13}C$ values in old carbonate coating on till clasts (Samples O1, O2-1, and O2-2) are −1.33‰ to −4.7‰, similar to those of modern carbonate coatings. The age of the outer layer is younger than that of inner layer, demonstrating that the environment has been closed and suggesting that ^{14}C dating is useful.

Many radiocarbon dates of the coating on till clasts were reported in the source area of the Urumqi River. Wang (1981) dated the coating on till clasts of the upper Wangfeng moraine group and obtained an age of 5530 ± 220 BP. Gu and Li (1990) dated the coatings of the clasts and obtained an age of 3753 ± 179 BP for the Upper Wangfeng Group and 5312 ± 168 BP for the lower Wangfeng Group. Some carbon dates on the coatings on the till clasts near the Glacier Observatory were also made. Gu and Li (1990) obtained two dates, 3980 ± 150 and 6170 ± 120 BP. Wang (1981) obtained a date of 3949 ± 141 BP. The outer layer of the coatings was removed before they dated the samples. Based on the carbon dating age of 3.9–5.5 ka of the coatings on till clasts in the moraine near the Glacier Observatory, Wang (1981) and Gu and Li (1990) believed that the moraine was formed during the Neoglaciation. However, our results show that the ages of the coating are 1.8 ka for the outer layer and 6.5 ka for the inner layer, suggesting the environment is closed and the coating grew outwards. The carbon in the inner layer was hindered in exchanging with the environment, implying that the age of the inner layer of the coating is closer to the age of the moraine.

The age of the inner layer is 6.5 ka, suggesting the moraine was older than 6.5 ka. This date is not unusual. Gu and Li (1990) also reported a date of 6170 ± 120 BP of coating on a till pebble in the same moraine, but they supposed that the moraine in the upper valley side was the lateral moraine formed during the Last Glaciation and the till clasts might be brought in to the moraine, which was suggested to be formed in the Neoglaciation, in the lower valley side by rolling and dumping. However, the carbon dating of the fine matrix of the same moraine shows that the moraine was formed during the Last Glaciation (see below).

5.4. Organic coatings on roche moutonnee and boulder near Glacier Observatory

The main mineral constituent of the coatings on the roche moutonnee, and a boulder where Samples O5 and O6 were collected, is whewellite which is an organic compound. AMS carbon dating ages of the Samples O5 and O6 are 390–420 BP. The $\delta^{13}C$ values of carbon in whewellite coatings are the lowest among all samples, reaching −7.4‰ to −14.8‰, suggesting participation by organisms in carbon fractionation exchange. Lichen grows on the boulders of the moraines and the protruding rocks between the moraines. Based on lichenometry, Chen (1989) supposed that the lichen grew after the moraine formed and concluded that the age of the same moraine was 1538 AD. The two methods of lichenometric dating and AMS carbon dating give the same age of the moraine, which was produced in the Little Ice Age.

We observed in the field that the dead lichen was black and it left white patches after it peeled off the rock or boulders. The same phenomenon was also observed in the Halasi River catchment, in the Altay Mountains, where the main mineral constituent of calciferous precipitate on the rock moutonnee which was estimated to be formed in the Last Glaciation Maximum (Cui et al., 1993) is whewellite (Yi, 1992). Lichen can secrete oxalic acid. The process is interpreted that calcite or calciferous minerals reacted with oxalic acid ($H_2C_2O_4$) secreted by lichen and turned into whewellite (CaC_2O_4), carbonic acid or sialic acid. These two acids are not stable, readily decomposed into CO_2 and H_2O or dissolved in water.

The carbon atoms in whewellite were not easily exchanged with those in the carbon in calcite or atmosphere because of tight conjunction of their chemical bonds. The radiocarbon dating of carbon in whewellite, at least in the lower layer close to the rock, can represent the age of the lichen, thus representing the age of the moraine.

5.5. Till matrix of old moraine

Old and new carbon can influence the carbon dating accuracy. No carbonate rock fragments were found in these tills (Li et al., 1981). Thus, old carbon from carbonate rock might not get into the samples to increase dating age. Clay mineral constituents and chemical elements in tills showed that chemical weathering below 50–60 cm is not significant (Xiong, 1991). The $\delta^{13}C$ values of carbonate in old till matrix (Samples O4, W1 and W2) are between −0.8‰ and 0.6‰, close to those in modern till matrix. This does not show an apparent exchange of the carbon with other carbon sources, implying that the primary carbon in the tills may be preserved well and can be used for dating. Thus, the dates from inorganic carbon may represent the ages of the moraines.

The calcite coatings on the till clasts are widespread in this semi-arid and cold area. The annual average rainfall from 1958 to 1999 at the Glacier Observatory is 445 mm.

Though this is low, the annual average evaporation, because of high attitude and cold, is also low (~285 mm). The moraine is more than 100 m above the valley bottom and is in the vadose water zone. The depth of the illuvial horizons of soils at the source area of the valley is about 30–40 cm. The water infiltrating downward below 40 cm is saturated with the calcium ions and cannot basically dissolve calcite in sediment. When free water moves upwards due to evaporation on the surface, the concentration of calcium in groundwater increases, and calcite precipitates on the undersides of the clasts. This phenomenon is common in till, alluvium and talus. The CO_2 in the water in the zone of aeration is easily exchanged with that in the atmosphere. The carbon in the coating formed is newer than the primary carbon in till. Carbon dating of the till matrix and the coating on till clasts in this paper and others work support this concept. Voids among fine particles are smaller than those among large particles. The free water can easily pass through the large voids and the coating precipitates on the adjacent large particles. It is suggested that new carbon can influence the age of large particles and the matrix in till may preserve the primary calcite as the till was formed. The carbon dating by mass spectrometry techniques requires bulk samples, which contain large particles. Using AMS techniques, only a small amount of sample is needed and it is easy to obtain fine material through sieving, thus excluding the interference, to a large extent, of new carbon in the coatings on large particles on dating accuracy. This may explain why our dated age is older than the age of 14.7 ka determined by mass spectrometry techniques (Wang, 1981).

The AMS ^{14}C dating ages of the inorganic carbon in the moraines near the Wangfeng Road Maintenance Station, where Samples W1 and W2 were collected, are 19–23 ka, which was produced in the late stage of the Last Glaciation (equivalent to Wisconsinan in the North America or Wurm in the Alps). The ^{14}C dating of the loess cap on the moraine is 9170 ± 400 BP (Wang, 1981; Gu and Li, 1990), suggesting that the moraine was older than 10 ka and produced in the Last Glaciation. The ^{14}C dates of the charcoal in soil layer, which covered the moraine 20 cm below the surface, are 6170 ± 120 and 7035 ± 90 BP (Yuan et al., 1985). The ESR dating ages of the quartz grains in the upper till and lower till where Samples W1 and W2 were collected are 37.4 and 27.6 ka, respectively (Yi et al., 2002). Thus, the ^{14}C dating ages of the calcite in the moraines are approximately the same as those from independent dating data.

The carbon dating of the fine matrix of the moraine near Glacier Observatory at 19 ka also suggests the moraine was formed during the Last Glaciation. The moraine is located on the upper valley side 100 m above the valley bottom and there is no geomorphologically related moraine on the bottom nearby. It is suggested that the moraine is a relic of the lateral moraine formed during the Last Glacial Maximum.

6. Conclusions

Results of stable isotope carbon and radiocarbon dating, and sedimentary properties of modern till and modern coating on the roche moutonnees, suggest that the source of inorganic carbon in them is synchronous with the moraine formation. The carbon in the fine matrix of till in this non-carbonate area can be used to date the moraine age, as the inorganic carbon in till may be preserved with little or no fractionation. The paper reveals that the age of the Last Glacial Maximum is about 19–23 ka at the source area of the Urumqi River.

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