Characteristics of the subglacially-formed debris-rich chemical deposits and related subglacial processes of Qiangyong Glacier, Tibet

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Subglacially-formed debris-rich chemical deposits were found both on bedrock surface and in bedrock crevice on the edge of Qiangyong Glacier, one of the continental glaciers in Tibet. Grain size distribution, internal structures and chemical components of the chemical deposits were analyzed. It can be inferred that the temperature of some part of the ice-bedrock interface is close to the melting point and there exists pressure melting water under Qiangyong Glacier. Debris, especially those from continental aerosols, can release Ca++ in the water. At the lee-side of obstacles on glacier bed the CO_2 in the melting water might escape from the water and the melting water might refreeze due to the dramatically reduced pressure, making the enrichment and precipitation of $CaCO_3$. The existence of subglacial melting water and the process of regelation under Qiangyong Glacier indicate that sliding could contribute some proportion to the entire movement of Qiangyong Glacier and it belongs to multiplex cold-temperate glaciers.

Characteristics of the subglacially-formed debris-rich chemical deposits and related subglacial processes of Qiangyong Glacier, Tibet LUO Risheng, CAO Jun, LIU Gengnian, CUI Zhijiu (College of Environmental Sciences, Peking University, Beijing 100871, China) 1 Introduction The physical-chemical processes at the interface between glacier and bedrock are responsible for the formation of eroded landform on glacial bed and its characteristics. The common method to study these processes is to dig tunnels into glaciers and make direct investigations (Huang et al., 1987; 1994). However, for the poor conditions in cryosphere, in most places this direct investigation is difficult to put on an action. After the retreating of modern glaciers, chemical deposits could be found on the exposed bedrock surface, particularly in carbonate-bedrock area (Ford et al., 1970; Page, 1971). Subglacially-formed chemical deposits are intimately related to the physical-chemical processes under the glacier and thus thought to be a good proxy to study subglacial environment. A quantity of investigations were carried out worldwide in the 1970s-1980s, including the temperate Alpine glaciers at low-mid latitudes (Hallet, 1975; 1976; 1979; Hanshaw et al., 1978; Souchez et al., 1985) and the ice-sheets at high latitudes (Bjerke et al., 1977; Aharon, 1988). Most of the modern glaciers in China belong to continental glaciers (Liu et al., 2000), which flow slowly with weak subglacial water film and subglacial processes. Thus there were few reports on subglacial chemical deposits in China except one found in Urumqi Riverhead, Tianshan Mts. and Hanasi catchment, Altay Mts. (Yi, 1992). During field work in the summer of 2001, debris-rich chemical deposits were found on the edge of Qiangyong Glacier, Tibet. Samples of the deposit were collected and then laboratory analysis was conducted. Based on the physical-chemical characteristics of these deposits, the formation mode and the related subglacial processes are discussed, which might be helpful to understand the subglacial environment of the continental glaciers in China. 2 Developing environment and properties of Qiangyong Glacier Qiangyong Glacier is located in Yangzhuoyong (Yamzho) Lake´s drainage area, between Himalayas and Yarlong Tsangbo River (Figure 1). The glacier flows northward, with a length of 4.9 km, a maximum width of 2.8 km and an area of 7.7 km2. The records at Langkazi (Nagarze) weather station (4460 m asl) in this drainage area show that the average annual rainfall from 1961 to 1975 is 373.6 mm, 90% of which falls in the summer (June to September). The average annual evaporation is 2089.4 mm, about 5.6 times as much as the rainfall. The average annual temperature is 2.4oC, with the coldest month (January) -5.5oC and the warmest month (July) 10oC. These characteristics show that the climate of Yangzhuoyong Lake´s drainage area is very continental. This climate condition is not suitable for the development of glaciers. Thereby, Qiangyong Glacier develops with a high altitude. The snow line is about 5600 m asl and the terminal of Qiangyong Glacier is 5000-5100 m asl. With l

ittle mass supply and high altitude, the glacier is cold and moves slowly. It has been classified to be a sub-continental glacier (Lai et al., 1990). 3 Sampling and analysis method The debris-rich chemical deposits disperse on the lee-side of the exposed bedrock near Qiangyong Glacier and they could be found both on the bedrock surface and in the bedrock crevice. The deposits on bedrock surface are larger and the largest one is about 30 cm2. They are dark gray with lots of debris. Laminae can be seen from the section, yet there is no crystal form to be found. The thickness of this kind of deposits is 3-10 mm. Samples were collected in an area from 200 m to 3 m apart from the glacier. Altogether 10 samples were collected. The deposits in bedrock crevice are light gray in color, with crystal forms in them. The thickness is only 1-2 mm. This kind of deposits was difficult to be found and sampled for the hard bedrock, so only one sample with bedrock was sampled. Besides, we sampled the bottom ice of the glacier and melted it in sampling bottle. We analyzed them in the following procedures: (1) Grain size analysis for the debris in the deposits on bedrock surface. In order to measure the grain size of the debris in the debris-rich deposits, HCl and H2O2 were used to get rid of the carbonate cementation and organic matter, respectively. The size distribution of the dispersed debris was measured on the Master Sizer 2000 produced by Malvern (Feng et al., 2002). (2) Investigation on slices of the deposit samples with polarizing microscope. (3) Chemical components analysis on the bedrock, deposits on bedrock surface, suspensions in the melting water and the water itself. The solid materials were alkali-fused and measured with ICP (Li et al., 2002). The concentration of the cations and anions in water samples was measured with ICP and quantitative titration. (4) Electron probe analysis for the deposits in bedrock crevice. We use the electron probe micro area (EPMA) analysis (Zheng, 1994) to measure chemical components of different layers in the deposits. In addition, we selected one line across the whole section to make a linear scanning analysis (Yang et al., 1998) to test the chemical content variations in the section. 4 Grain size distribution of the debris in debris-rich chemical deposits on bedrock surface The grain size distribution and the cumulative percentage for grain size probability of the debris in debris-rich chemical deposits from Qiangyong Glacier (Figures 2 and 3) show that the mode size is 8 ?滋m. Silt and clay (<50 ?滋m) amounts for 98% of the total mass and clay (<5 ?滋m) occupies 32%. This fine-grain characteristic indicates that the water carrying these debris is weak in velocity or energy. The debris in the chemical deposits comes from two main sources: (1) continental aerosols preserved in the glacial ice; and (2) the debris abraded from the bedrock by the glacier. The grain size of the continental aerosols in the glaciers of the Tibetan Plateau ranges between 1 ?滋m and 13 ?滋m and it decreases as the distance becomes longer from the dust source (arid Northwest China) (Li et al., 2000). Qiangyong Glacier lies on the south edge of the Tibetan Plateau, which should have finer aerosol debris. Thus at least a portion of the total debris in the deposits, especially the coarser debris >13 ?滋m (about 30%), comes from the abraded debris. This means that there is intensive abrasion and crashing process under the glacier. 5 Internal textures and structures of debris-rich chemical deposits In the debris-rich chemical deposits developed on bedrock surface, there are clear parallel laminae which are parallel to the bedrock surface. The laminae can be distinguished by their colors, although the boundaries are not very clear. In some of the samples, there are S-shaped distortion (Figure 4). The distorted laminae usually have an inclination of 10-30o to the normal laminae, which is the proof of extrusion process after the deposits formed. In the chemical deposits developed in bedrock crevice, there are also parallel laminae which are parallel to the stretching direction of the crevice (Figure 5). The laminae are thicker than the ones on bedrock surface with the maximum about 100 μm. The boundaries are clear, with dark debris-rich layers and light crystal layers appearing alternatively. 6 Chemical components of debris-rich chemical deposits, bedrock and melting water The major element contents of the bedrock and the deposits on bedrock surface (Table 1) show that the major component of the bedrock is SiO2, which accounts for 52% of the total mass. While in chemical deposits, the most significant component is CaO, which is quite different from the bedrock and indicates that the deposits are not composed just by the bedrock debris, but chemical deposits rich in CaCO3. The suspensions in the melting water and the debris in the chemical deposits should have similar sources. It is argued that in the northern part of the Tibetan Plateau the major component of the aerosol dust is "CaCO3+Ca(HCO3)2" (Xiao et al., 2002) and that all the glaciers north to the Himalayas have similar aerosol grains (Li et al., 2000). Thereby, the higher content of CaO in the suspensions than the bedrock (Table 1) might be due to the contribution of the Ca-rich aerosol grains. Comparing the debris-rich chemical deposits and the suspensions in melting water, it can be seen that the deposits have more CaO than the suspensions (Table 1), which means that the fine-grains in glacial ice could not form the deposits themselves, either. CaCO3 precipitates and cements the debris when they melt out and deposit from the glacier ice. The SiO2/(Al2O3+Fe2O3) ratios are close to 1.02 both in the suspensions and the deposits, which means that the debris in the deposits comes from the suspensions in the bottom ice. When the debris accumulates into the deposits from melting glacial ice, there is no other complicated chemical partition process except the precipitation and cementation of CaCO3. The concentration o

f the major ions in the melting water (Table 2) shows that the predominant cation and anion are Ca++ and HCO3-, respectively. The concentration of Ca++ is an order of magnitude higher than the other cations, while in the suspensions we cannot see such a significant difference (Table 1). This might be the result of a large quantity of Ca++ moving into the melting water which has a high concentration of CO2 (Weiss et al., 1972) and a relatively low pH value. 7 Chemical content variations in debris-rich chemical deposits in bedrock crevice The linear scanning analysis result (Figure 6) shows that the relative contents of Si, Al and Fe are high when the relative content of Ca is low. In the depositional process, the content of Ca is negatively correlated to the content of other contents. In the dark debris-rich layers, more debris rich in Si, Al and Fe deposits appears, making these layers richer in Si, Al and Fe and depleted in Ca. While in the light crystal layers, the situation is conversed. The EPMA analysis result (Table 3) shows that the debris-rich layers (signed with odd number) have less CaCO3 and more other components than the crystal layers (signed with even number). This result is consistent with that of linear scanning analysis which shows the negatively correlated relation between the content of Ca and other components. Compared with the chemical deposits on bedrock surface, it can be seen that either the debris-rich layers or the crystal layers in the deposits in bedrock crevice have higher content of CaCO3. This indicates the situation in bedrock crevice is more suitable for the enrichment and precipitation of CaCO3. 8 Discussion 8.1 Formation of the debris-rich chemical deposits and subglacial chemical processes The bedrocks that Qiangyong Glacier covers are Mesozoic metamorphic sandstone, shale and slate. There is no carbonate bedrock and thereby it can be inferred that the bedrock has relatively small contribution to the sources of Ca in the deposits compared with the chemical deposits found in carbonate areas (Ford et al., 1970; Page, 1971; Hallet, 1976; 1979; Bjerke et al., 1977; Hanshaw et al., 1978; Souchez et al., 1985). The Ca-containing silicates abraded from the bedrock and the calcite from the aerosols are the main sources of the Ca++ in the melting water. It is a common reaction for the calcite to release Ca++ in CO2-containing water, which also exists in cryosphere (Ford et al., 1970; Page, 1971; Hallet, 1976; 1979; Bjerke et al., 1977; Hanshaw et al., 1978; Souchez et al., 1985; Cui et al., 2002). On the other hand, Ca-containing silicates can also react in the cryosphere with water and the CO2 in it (Aharon, 1988). For instance, Ca-feldspar can react with water and CO2 which could be expressed below: $CaAl2Si2O8 + H2O + 2H^+ \rightarrow Al2Si2O5(OH)4 + Ca^{++}$ (1) $CaAl2Si2O8 + 3H2O + 2CO2 \rightarrow Ca^{++} + 2HCO3^- + Al2Si2O5(OH)4$ (2) The above reactions release Ca++ and HCO3-. Other cations can also be released from silicates in a similar way. However, Ca++ is the predominant cation in melting water, indicating that the Ca-containing minerals can release Ca++ most easily. The aerosol calcite which can decompose and release Ca++ easily might explain this. Continental aerosol dust is an important source for the calcium in the melting water and the chemical deposits. This is an exceptional phenomenon in the Tibetan Plateau and Northwest China affected by Asian dust. With the contribution from aerosols, a large quantity of Ca++ appears in the water, providing the material for precipitation and cementation. At the lee-side of the glacier bed, where pressure from the glacier decreases dramatically, the melted water refreezes, making the Ca++ concentrated (Hallet, 1976), the CO2 escapes from the water, reducing the solubility of CaCO3 and thus the CaCO3 precipitates, forming the chemical deposits. 8.2 Depositional environment difference between the chemical deposits on bedrock surface and the ones in bedrock crevice There are debris-rich chemical deposits both on the bedrock surface and the bedrock crevice, yet they have different characteristics (Table 4), which might owe to different depositional environments. During the formation of the deposits on bedrock surface, the water film flows on their surface, carrying lots of debris and unloading them quickly. Thus the deposits are rich in debris that conceals the growing of calcite crystals. For this reason, the deposits have less CaCO3 and crystal characteristics could not be seen. Meanwhile, as the deposits form at the interface between glacier and bedrock, they have large probability to be extruded and destroyed by the above flowing glacier. It is suggested that the deposits in the crevice are formed when the subglacial water leaked into the crevice, where the water flow is weaker with less debris flux. This situation is more suitable for the crystals to grow and thus the deposits have more CaCO3 and crystal layers. 8.3 Temperature and flowing mechanisms of Qiangyong Glacier According to the temperature, glaciers can be classified into cold glacier, temperate glacier and multiplex cold-temperate glacier (Huang, 2000). Major proportion of the temperate glacier is close to the melting point and there is a quantity of pressure melting water under the glacier which provides helpful media for chemical weathering and element transference under the glacier. This might be an important factor for the formation of numerous chemical deposits under the temperate glaciers in North America and Europe besides the favored carbonate bedrock. However, most of the modern glaciers in China belong to continental glaciers developed at high altitudes with low ice temperature except the glaciers in southeastern edge of Tibet (Liu et al., 2000). Qiangyong Glacier is one of those continental glaciers. The decomposition process of the Ca-containing minerals, the release of Ca++ and the precipitation of CaCO3 under Qiangyong Glacier inevitably need the liquid water as their media. Thereby, the discovery of the calcareous chemical deposits formed subglacially

y is the proof of the existence of pressure melting water under Qiangyong Glacier. Part of the glacier bottom (at least 200 m inferred from the distribution of the deposits) is close to the melting point, forming a subglacial melting area. Thus Qiangyong Glacier should be classified to be a multiplex cold-temperate glacier. Glacier moves forward with two different mechanisms: ice deformation and sliding at the bottom. Sliding of glaciers includes regelation and increased viscous flowing (Weertman, 1957; 1964). Under the temperate glaciers, sliding plays a key role in the whole movement while for the cold glaciers, ice deformation is more important. The melting area and regelation process under Qiangyong Glacier indicates that sliding can also contribute a part to the whole movement of continental Qiangyong Glacier. The flowing mechanisms of Qiangyong Glacier also present a multiplex property. 9 Conclusions Based on the investigations on the physical-chemical characteristics of subglacially-formed debris-rich chemical deposits from Qiangyong Glacier, Tibet, some clues about the subglacial processes can be inferred below: (1) The temperature of some part of the glacier bottom is close to the melting point and there exists pressure melting water and melting area under Qiangyong Glacier. The water acts as the media of chemical weathering. Debris in the glacier, both from the abrasion and continental aerosols, can release Ca++ in the subglacial water. The aerosols are very important for the concentration accretion of Ca++, this is an exceptional process in the area affected by Asian dust. (2) The CO_2 in the melting water might escape from the water and the melting water might refreeze due to the dramatically reduced pressure at the lee-side of obstacles on glacier bed under the glacier. Both these processes could be the reasons for $CaCO_3$ precipitation which cements the silt and clay, forming debris-rich chemical deposits. (3) The chemical deposits on the bedrock surface are different from the ones in bedrock crevice due to different environments. With a relatively steady position and a small debris flux, the deposits in bedrock crevice are better crystallized. Conversely, the deposits on bedrock surface are developed with a larger debris flux and distortion from the above glacier, forming distorted laminae without crystallized characteristics. (4) The existence of melting area and the process of regelation under Qiangyong Glacier indicate that sliding could contribute some proportion to the whole movement of Qiangyong Glacier and it belongs to multiplex cold-temperate glaciers. Thus, the chemical deposits could be a useful tool to understand the properties of the glaciers in China and then classify them into different types.