Calcrete crust formation on the lateral moraine of Batura glacier, Northern Pakistan

Tetsuya Waragai

Department of Geography, Nihon University, Sakurajyosui Setagaya-ku Tokyo, 156-8550, JAPAN

For correspondence. E-mail: waragai@chs.nihon-u.ac.jp

Calcrete crusts, which are cementing gravels, are observed on the surface of lateral moraine on the circumference of the Batura glacier, northwestern Karakoram Mountains. Although calcretes generally develop from arid and semi-arid environments with an annual precipitation of 500 mm or less, they are also found in cold climatic regions such as permafrost environments (Swett 1974, Lauriol and Clark 1999). It is thought that the calcrete crust formation in cold environments is involved in carbonate dissolution on the permafrost table and calcite production near ground surfaces, which are derived from the temperature-induced solubility differential of calcium carbonate ($CaCO_3$). With regard to geochronological studies, calcrete and calcic soils can provide accurate dating and useful paleoenvironmental information by stable isotope analysis using ^{14}C, $^{230}Th/U$ and $\delta^{18}O$ (e.g., Sharp et al. 2003). This study considers the formation processes of the calcrete crusts in the cold environment around Batura glacier terminals through their mineralogical and chemical compositions and ^{14}C dating by an accelerator mass spectrometry (AMS).

In the study area (**Figure 1**), the Batura, Pasu and Ghulkin glaciers are going down to around the altitude of 2,500 m of glacier terminals from mountain peaks exceeding 7,000 m such as Batura peak I (7,794 m asl). There are distributed Pasu limestone and Pasu slate of the Palaeozoic, and granodiorites composed of Hunza plutonic complex of the Cretaceous around the Batura glacier terminals (Crawford and Searle, 1993). On the other hand, according to Waragai (1998, 1999) who carried out air temperature measurements at the lateral moraine located in the Batura glacier snout from July 1994 to July 1996, maximum and minimum temperatures were 43.7 and -13.7 degrees C, respectively. Annual average precipitation in Gilgit (1,490 m), located about 70km south of the study site, is 131.6 mm.

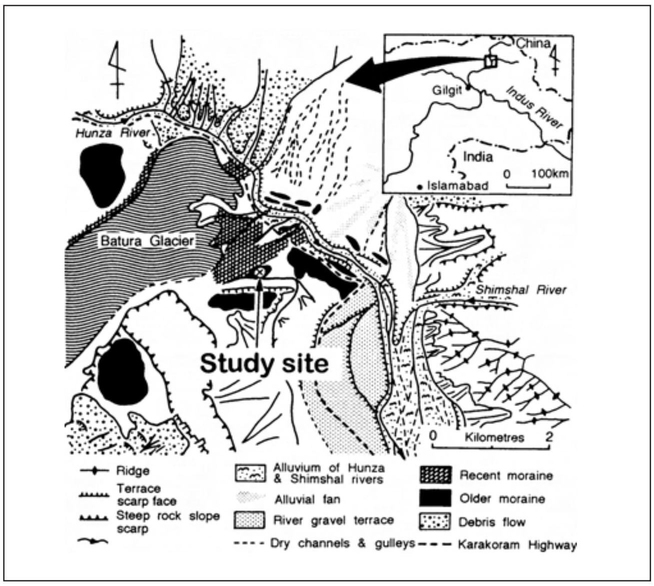

FIGURE 1. Location of a study site and geomorphological map at Batura glacier snout

Description of the calcrete crust

The calcrete crust develops on the ground surface (about 2,700 m) of the lateral moraine's ridge that was probably formed in the Batura glacial stage (Owen et al. 2002). Analysis was carried out for pebble calcretes (**Plate 1**) that accumulate on the ground under a granodiorite boulder (3.0x2.5x1.5 m^3) near the ridge of the lateral moraine. This sample, highly indurated, is composed

PLATE 1. Pebble calcretes formed under a boulder

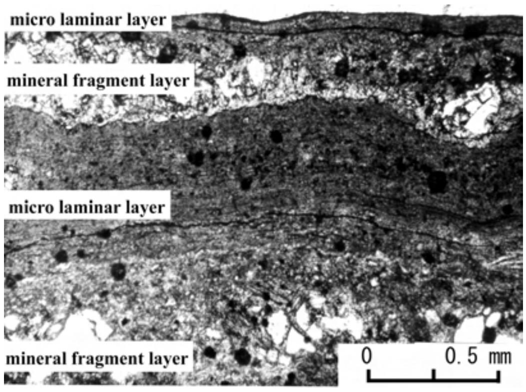

PLATE 2. The outermost layer of the calcrete crust showing laminar structure

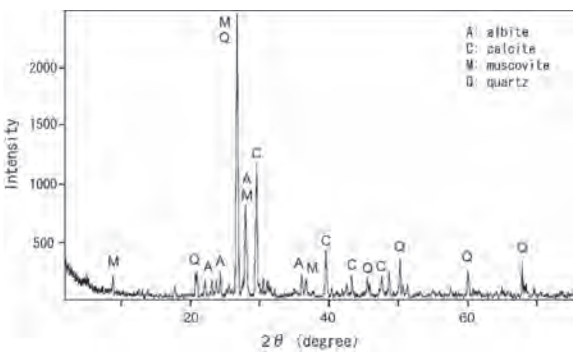

FIGURE 2. An X-ray diffraction pattern of the outermost layer of the calcrete crust

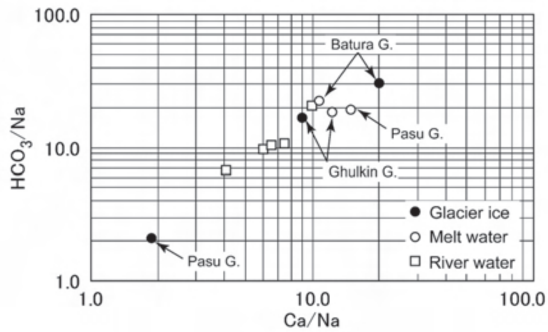

FIGURE 3. Ca and HCO_3 concentration of some glacier ice and waters

of pebbles and porous cementing materials as a matrix. Cements overlapped on pebbles form a micro-relief reflecting the surface morphology of pebbles and are cream in colour.

In order to investigate the structure of the calcrete crust, a sample was prepared, which was cut from the surface to a depth of about 2 cm, and a thin section was made. The microscopic structure from the surface of the crust to a depth of 1.5 mm is shown in **Plate 2**. According to the plate, the calcrete crust can be distinguished into mineral fragment layers and micro laminar layers developing by turns. The mineral fragment layer consists of some rounded mineral grains with a maximum diameter of 0.2 mm. Since the mineral fragment layer tends to place large particles in a lower part, it is recognized that this layer shows a slight grading bedding structure. Thus the boundary between upper parts of the mineral fragment layer and the lower parts of the micro laminar layer is relatively conformable. However, the micro laminar layer obviously borders the mineral fragment layer at its upper part. This shows that the outermost part of the calcrete crust has several sequences of layers joining both layers together.

1) Mineralogical and chemistry compositions

The mineralogical composition of the outermost part of the calcrete crust was examined with X-ray diffractometer (XRD). Quartz, albite, muscovite, and calcite crystals were identified **(Figure 2)**. This result indicates that the mineral fragment layer shown in **Plate 2** is composed of quartz, albite, and muscovite crystals, while the micro laminar layer consists of calcite ($CaCO_3$).

Since the micro laminar layer is characterized by a striped pattern, the chemical composition for micro spots (quantitative point analysis) and element distribution (qualitative mapping analysis) for this layer was examined by electron- probe microanalysis (EPMA). A polished specimen, which was extracted from the surface to a depth of 2 cm, was used for these analyses. As a result of the qualitative mapping analysis for an analysed area of about 650 μm^2, it was revealed that a high concentration of Ca was present compared with Mg, Al, and Si in the micro laminar layer. In addition, it was surmised that the laminar structure reflects the difference of Ca concentration. Quantitative analysis for a spot (3 μm in diameter) showed about 60 % of CaO and about one percent of MgO. Total major element composition for the micro laminar layer was about 63 % by weight, and the remaining about 37 % was estimated to be H_2O content.

2) ^{14}C age of the calcrete crust

Since the outermost part of the calcrete crust dominantly consists of calcium carbonates ($CaCO_3$), ^{14}C age by AMS was measured at the Institute of Geological & Nuclear Sciences Limited, New Zealand. An outermost thin layer of the calcrete crust was carefully removed with tweezers, then the carbon compound subjected to acid treatments was extracted from the outermost portion. The result of the measurement was the specimen indicated 7,358±57 yBP (NZA9243, $\delta^{13}C$=6.7‰).

Conclusion

According to Owen et al. (2002) who carried out the cosmogenic radionuclide (CRN) age determination for boulders on moraines around the present study site, the Batura glacial stage to which glaciers advanced is placed to 9.0-10.8 ka (yBP). This Batura glacial stage corresponds to the glacial advance period which is widely accepted in the Himalaya and Karakoram mountains between late Pleistocene and early Holocene (8 – 11 ka). The age for the outermost portion of the crust in this study (7,358 ± 57 yr) clearly places it in the later age of the Batura glacial stage. It is considered that the calcrete crust was formed under the warm climate when the Batura glacier was retreating about 7,000 years ago.

Meanwhile, the chemical reaction in connection with formation of calcite ($CaCO_3$) which is the dominant ingredient of calcrete crusts, is described as follows:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Precipitation of the carbonates due to supersaturation mainly results from the evaporation and freezing of water, decreases in CO_2 partial pressure, CO_2 degassing, and biological activities. Since Pasu limestone is widely distributed around Batura glacier terminals, the presence of high Ca^{2+} is supposed in groundwater and surface water around the study area. Results of chemical analysis by the Ion Chromatography analyser demonstrate that the glacier ice and melt water of the Batura glacier have a high concentration of Ca^{2+} and HCO_3^- (**Figure 3**). Particularly, cold climatic environments during glacial stages are effective in formation of $CaCO_3$, because $CaCO_3$ is more soluble at lower temperatures. The climatic warming following the glacial stage may have accelerated $CaCO_3$ precipitation accompanied by decreases in CO_2 partial pressure from the glacial ice pressurized. It is concluded that the calcrete crusts precipitated by decreases in CO_2 partial pressure and evaporation of water including high concentration of Ca^{2+} under the climatic warming at the place between moraines and glacial ice bodies.

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