Journal of the Korean Geographical Society, Vol. 42, No. 2, 2007(165~176)

Absolute Age Determination of One of the Oldest Quaternary(?) Glacial Deposit (Bunthang Sequence) in the Tibetan Plateau Using Radioactive Decay of Cosmogenic ^{10}Be and ^{26}Al, the Central Karakoram, Pakistan: Implication for Paleoenvironment and Tectonics

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방사성 우주기원 동위원소를 이용한 티벳고원에서 가장 오래된 제4기(?) 빙성퇴적물인 Bunthang sequence의 절대 연대측정과 이의 고환경 및 지반운동에 대한 의미

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Abstract : Absolute age of the deposition of 1.3 km-thick Bunthang sequence within the Skardu intermontane basin of the Central Karakoram was determined using radioactive decay of cosmogenic ^{10}Be and ^{26}Al burial dating. The Bunthang sequence deposited around 2.65 Ma, which is the oldest glaciation in the region. The timing of deposition of the Bunthang sequence is consistent with the previous suggestion that the basin filling took place between Brunhess and Matuyama chrons. Four major sedimentary facies interfinger within the Bunthang sequence: glacial diamict, lacustrine, fluvial and lacustrine facies upward. This sedimentary distinctiveness and the lack of evidence on the faults for alternative pull-apart basin model around the Bunthang sequence, suggest that the depressional basin was formed by deep subglacial erosion during the extensive Bunthang Glacial Stage and subsequently the sediments underlain by basal diamict, was quickly deposited by proglacial and paraglacial processes. Temporary ponding of the Indus River due to tectonic uplift in the downstream or blockage by mass movements might make the basin filling more possible. The hypothesis that the single ice sheet developed on the Tibetan Plateau during the global last glacial cycle should be refuted by the existence of the older extensive Bunthang glacier. Furthermore, the extensive glaciation during the early Quaternary (and thus progressive decrease in extent with time) suggests that there may have been significant uplift of the Pamir to the west and Himalaya to the south, which would have reduced the penetration of westerlies and Indian summer monsoon and hence moisture supply to the region.
Key Words : the Central Karakoram, cosmogenic burial dating, Quaternary, Plio-Pleistocene boundary, glaciation, till.

요약 : 티벳고원의 서쪽, 중부 카라코람의 인더스 강이 지나는 Skardu 근처에서 발견된 약 1.3km의 두께를 보이는 Bunthang 시퀀스의 절대 연대측정을 우주 기원 동위원소인 ^{10}Be과 ^{26}Al의 비를 이용해서 측정했으며 약 2백 65만년전에 급격하게 퇴적된 것으로 확인되었다. 이러한 퇴적시기는 지금까지 발견된 가장 오래된 직접적인 빙하활동의 증거로서 이전의 고지자기 연구와도 일치한다. Bunthang 시퀀스는 아래에서부터 빙퇴석, 호성 퇴적물, 하천 퇴적물 그리고 다시 호성 퇴적물로 이루어지며 어떠한 단층운동의 증거도 발견되지 않는 점으로 미루어 볼 때 분지의 생성은 빙하의 하방침식에 의해서 만들어졌으며 빙하의 후퇴와 더불어 proglacial

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과 paraglacial 프로세스에 의해서 생성된 것으로 판단된다. 이 지역에 있어서 신생대의 활발한 지반 활동은 인더스 강의 구배를 변형시킴으로써 연구지역과 같은 국지적인 호소퇴적층의 활발한 퇴적을 용이하게 하였으며 또한 지반운동과 빙하의 침식에 의한 사면의 불안정성은 이러한 국지적 퇴적 작용을 더욱 촉발시켰을 것으로 판단된다. 이전의 연구와 본 연구의 결과로써 지난 제4기 동안 빙하의 활동이 약해진 것으로 보건데 지난 마지막 빙기 최성기를 정점으로 티벳고원에 커다란 빙상이 존재했다는 가설은 틀린 것으로 보인다. 이 지역에서 제4기 동안의 빙하 활동의 축소는 희말라야 산맥과 카라코람 산맥 중심의 급격한 융기로 인해 Indian monsoon의 유입이 줄어든 것에서 기인한 것으로 추측된다.
주요어 : Bunthang 시퀀스, 중부 카라코람, 우주기원 동위원소, 매몰연대 측정, 제4기, Plio-Pleistocene 경계, 빙하, 빙퇴석.

1. Introduction

The Central Karakoram Mountains, near K2 in Pakistan, exhibits complex topography and a complex interplay of surface processes that have not been adequately studied. Impressive landforms such as moraines, alluvial fans, flood deposits, are present within the valleys and intermontane basins, although there have been conflicting interpretations of landform features (e.g., moraines versus rock avalanche; Owen, 1988; Hewitt, 1998, 1999; Seong *et al.*, 2007a, b, c). In addition, the timing of geomorphic events that significantly govern landscape evolution in selected portions of the western Himalaya was not clearly understood. Consequently there is a need for geomorphological mapping and geochronological assessment of landscape evolution dynamics in the Central Karakoram.

Over the last decades, there has been severe debate on the Pliocene-Pleistocene boundary (Aguirre, and Pasini, 1985; Berggren *et al.*, 1995; Partridge, 1997; Ding *et al.*, 1997). One of the suggestions is to lower the onset of the Quaternary to the boundary between Gauss and Matuyama chrons (Ding *et al.*, 1997; Raymo, 1994). The suggestion is based on the big shift of the records from Chinese loess and deep sea sediments. Around 2.75 Ma, Chinese loess deposition becomes widespread and is substantially different in character to the underlying Red Clay (Ding *et al.*, 1997) and deep sea oxygen isotope records show the culmination of a series of cycles of increasing glacial intensity, also associated with the first major inputs of ice rafted debris to the North Atlantic (Raymo, 1994). For many proxy records, this marks the beginning of the "Quaternary ice ages". It also marks a change from precession-dominated to obliquity-dominated climate forcing (Raymo, 1994).

The relative chronology of the continental Plio-Pleistocene deposits has generally been deduced from the biostratigraphic data (Aguirre and Pasini, 1985). In many cases it is impossible to obtain reliable radiometric dates. Specifically, this research tries to determine the absolute age of the Bunthang sequence (possibly formed around plio-pleistocene boundary) near Skardu, which has been under debate on its age and relationship with glaciation and tectonics (Seong *et al.*, 2007a). Cosmogenic radionuclides (CRN) burial dating is applied to define the age of the glaciofluvial deposits underlain by glacial diamict. Collectively the results are synthesized to develop a conceptual model of landscape evolution for the middle Indus Valley near Skardu and the initiation of Quaternary in Tibet.

2. Central Karakoram

1) Physical setting

Tectonically the Karakoram Mountains represent a continental-continental collision zone between India and Asia plates (Searle, 1991; Figure 1A). The northwesterly orientation of the basin parallels the local structural grain of the enclosing Karakoram Mountains, which skirts a promontory of the Indian Plate called the Nanga Parbat-Haramosh syntaxis (Figure 1B). This dynamic tectonics as well as glacier activities resulted in intense denudation, producing thick valley fills which frequently exceeds hundreds meters in thickness. One of the striking deposits is found near Skardu in the Central Karakoram. Skardu is an intermontane basin situated at the junction of Indus River and Shigar River which originates from K2 - the second highest peak in the world (8611 m). The climate of the region is transitional between central Asian mid-latitude (dominated by the mid-latitude westerlies) and Indian summer monsoon types, and has considerable microclimatic variability influenced by multiscale topographic factors (Owen, 1988; Hewitt, 1989).

At Skardu (Figure 1; 35°18' N, 75°41' E, 2181 m asl), the average annual temperature is 11.5°C and the mean annual precipitation is 208 mm (averaged for the period 1951 to 1989 from Miehe *et al.*, 2000). The highest precipitation occurs during spring as the mid-latitude westerlies advance into the region. Two-thirds of snow accumulation on the Central Karakoram occurs in winter and spring, supplied by mid-latitude westerlies, while the other one-third is supplied from the Indian monsoon during summer (Hewitt, 1989).

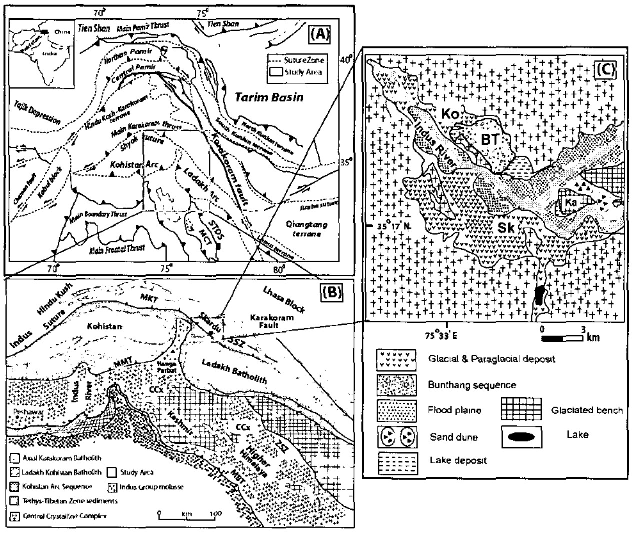

Figure 1

Figure 1. Geologic content of the western Himalaya-Tibetan orogen. (A) Tectonic map of the western end of the Himalayan-Tibetan orogen (modified from Robinson *et al.*, 2004; STDS-South Tibetan Detachment, MCT-Main Central Thrust). (B) Geologic map of the central Karakoram (after Parrish and Tirrul, 1989; MBT-Main Boundary Thrust, CCx-Central Crystalline Complex of Higher Himalaya,, ZSZ, Zanskar Shear Zone, MMT-Main Mantle Thrust, MKT-Main Karakoram Thrust, SSZ-Shyok Suture Zone, AKB-Axial Karakoram Batholith, and BG-Baltoro Granite). (C) Geomorphic map of the Skardu. BT means Bunthang, Sk is for Skardu, Ko is for Komara, and Ka is for Karpochi Rock.

2) Previous study

Due to physical inaccessibility and lack of methodology, few geomorphic and stratigraphic studies have been undertaken in the Skardu Basin (Oestrich, 1906; Dainelli, 1922; Burgisser *et al.*, 1982; Cronin, 1989; Cronin *et al.*, 1989; Owen, 1988; Owen and Derbyshire, 1988; Seong *et al.*, 2007a; b; c). Oestrich (1906) first suggested that the Indus Valley above Skardu had initially been eroded to its bedrock floor, then filled with sediment to roughly 200 m above its present level, and then reexcavated by glaciers and the Indus River. Dainelli (1922) described a thick exposure of sedimentary strata along the northern rim of the basin. These strata have been coined the Bunthang sequence (Cronin *et al.*, 1989). They described a 1.3-km-thick sedimentary succession that is located in the NW corner of Skardu basin, which they named the Bunthang Sequence (Figure 2, 3). This sequence comprises a basal diamicton overlain by lacustrine and glaciofluvial sediments. Based on paleomagnetic studies they suggested that the basal till started to accumulate towards the end of the Matuyama chron (ca. 0.72 Ma). On the basis of their similar locations, elevations, stratigraphic positions, and induration, they correlated it with the till exposed on Karpochi Rock (Figure 1C).

Owen (1988) undertook a study of the Quaternary geology of the Skardu basin and provided a reconstruction of the history and

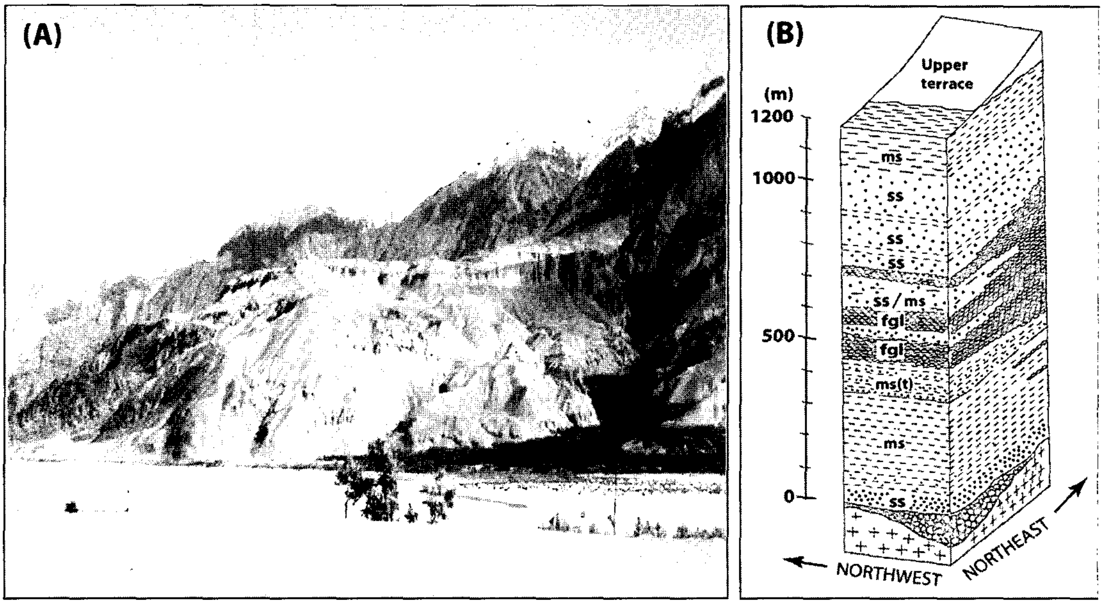

Figure 2. The stratigraphy of the Bunthang sequence. (A) The view of Bunthang sequence near Skardu, looking northwest from the Karpochi Rock. The width of Bunthang outcrop in the view is ~5 km. The Indus River in the foreground flows from right to left. The vegetated area on the alluvial fan is the village of Komara. Pale horizontal stratified bed at top of the outcrop comprises interfingering glaciofluvial and lacustrine sediments, which overlie darker alluvial gravel deposit. The alluvial gravel units thin toward the Indus River. (B) Schematic summary of the physical stratigraphy of the Bunthang Sequence (after Cronin *et al.*, 1989). Lithologic abbreviations: ms is mudstone; ms (t) is rhythmically-bedded mudstone; ss is sandstone; fgl is fanglomerate.

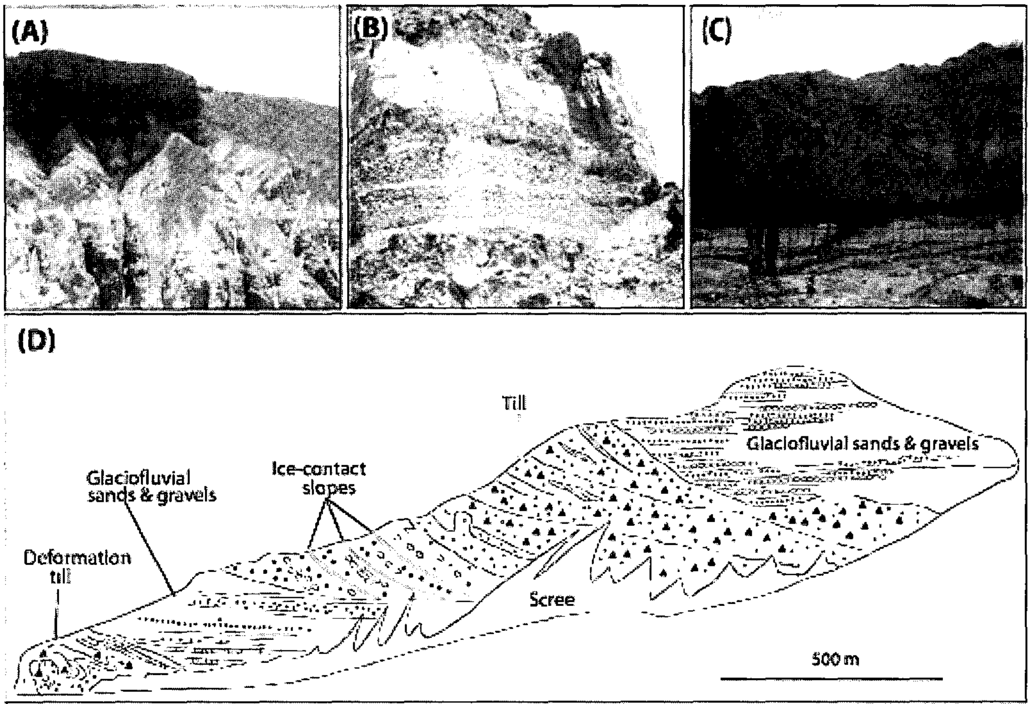

Figure 3. Closer views of Bunthang sequence. (A) The upper unit of Bunthang sequence which consists of stratified lake deposit and fine glaciofluvial deposit. (B) View of the middle unit from which the cosmogenic burial samples were taken. (C) Wet-sediment deformation structure developed within the Bunthang sequence. View looking south from the village of Komara. D) Modified version of Owen and Derbyshire's (1988) log showing the structures in the lower part of the Bunthang sequence viewed south from the village of Komara (35°24.087' N, 75°31.576' E).

extent of glaciation. He recognized four major glacial surfaces throughout the Skardu basin and in the Shigar valley. He attributed these to different glaciations, but did not name them. Seong *et al.* (2007a) found four glacial stages and defined three of them using CRN surface exposure dating and optically stimulated luminescence (OSL) dating. They noted glaciation decreased in extent from extensive (> 150 km long) valley glacier during the penultimate glacial to 80 km during the Lateglacial to restricted (few kilo meters beyond the present snout of the glacier) valley glacier during the Holocene.

3. Bunthang Sequence

The Bunthang basal till is overlain by 1.3 km thick succession of fluvial/glaciofluvial, lacustrine, and alluvial sediments (Cronin, 1989; Cronin *et al.*, 1989; Figure 2, 3). The Bunthang Sequence of Cronin *et al.* (1989) was examined near the village of Komara (Figure 2). At this location, basal till is dark gray with patchy brown oxidized areas. It is texturally very coarse, unstratified, and contains matrix-supported boulders up to several meters in diameter. The till unconformably overlies the bedrock (Figure 2C). The till and associated sediments are deformed into folds (Figure 3D). Similar deformation structures are present throughout the Skardu basin and for a considerable distance along the Shigar valley within younger sediments (Burgisser *et al.*, 1982; Cronin *et al.*, 1989). Owen (1988) explained the wet-sediment deformation of the Skardu fluvial and lacustrine beds by glaciotectonic deformation resulting from tributary valley glaciers advancing over wet and probably frozen sediments during glacial times.

The Bunthang sequence can be divided into lower, middle, and upper units, based on remarkable textural differences in the strata (Figure 2, 3). The lower unit consists of massive sand, massive clay and stratified clay beds. The basal sand layer is a planar and cross bedded, locally with conglomerate. It grades upward into a massive, light gray, clayey silt bed to silty clay bed. The massive mud bed is approximately 300 m thick, and becomes progressively less sandy upward. The middle unit consists of boulderly layer interbedded with sand bed and clay bed. The clast size ranges up to several meters in diameter, although most of the coarse fractions are less than 0.25 m in diameter. Most of the clasts are subround to angular and the matrix consists primarily of dark, metamorphic lithics. The upper unit consists of sandstones and mudstone. The sediment unit onlapps the uppermost fan surface that marks the top of the middle Bunthang sequence. The angular discordance between flat-lying upper Bunthang strata and the top of the middle Bunthang fanglomerate reflects primary, undeformed bedding orientations characteristic of different depositional environments.

Owen and Derbyshire (1988) interpreted the Bunthang sequence as a succession of sediments that had undergone glaciotectonic deformation. Re-examination of these sediments confirms that the basal till was deformed by glaciotectonic processes. The apparent discontinuities throughout the overlaying sediments were interpreted by Owen and Derbyshire (1988) to be faults. However, these discontinuities are more likely to be ice-contact depositional surfaces down which sediment was deposited from a large glacier that filled the Indus valley at this location (Figure 3D). These are similar in form to those described by Benn and Owen (2002). Cronin (1989) and Cronin *et al.* (1989) showed that the basal till is predominantly reversely magnetized, implying the thick, extensive glacier occupied the Indus Valley between initial continental glacial advances and prior to the present Brunhes normal chron, i.e., between 2.75 and 0.72 Ma. However, since this till is deformed and in places is inverted, the validity of the reversed magnetism might be questionable.

4. Method

A recently, widely used method for dating buried materials employs the concentration ratio of cosmogenic radionuclides such as ^{26}Al and ^{10}Be (Lal, 1991; Granger and Smith, 2000; Granger and Muzikar, 2001). These cosmogenic nuclides are produced in quartz with the top few centimeters of the earth's surface by secondary cosmic rays and can be used to constrain the exposure age of geomorphic surface (Seong and Kim, 2003; Kim, 2005). Burial dating is based on the assumption that a clast has been exposed to cosmic rays for sufficient time to acquire an inventory of various cosmogenic nuclides from hillslopes and transported through river systems. The clast is then buried (or shielded from secondary cosmic rays) quickly, so that cosmogenic nuclide production effectively stops and then each radionuclide (e.g. ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl) begins to decay with the appropriate half-life. By measuring the concentrations of several (at least two) radionuclides, it can be determined how long the clast has been buried.

At a time t later the concentrations of ^{26}Al and ^{10}Be are determined by Eq. (1):

$$N_{Al}(t)=N_{Al}(0)e^{-t/\tau Al}; \qquad N_{Be}(t)=N_{Be}(0)e^{-t/\tau Al}$$

Where $N_{Al}(0)$ and $N_{Be}(0)$ are inherited concentration at burial, $\tau_{Al}=1.02\pm0.04$ Myr and $\tau_{Be}=2.18\pm0.09$ Myr. If sediment is then buried deeply enough (typically >10 m) that cosmic rays are shielded, nuclide production drastically slows and effectively stops and thus the radionuclides begin to decay exponentially. Because ^{26}Al decays roughly twice as fast as ^{10}Be, the inherited nuclide ratio $(N_{26}/N_{10})_0$ decreases exponentially over the time according to the following successive Eqs. (2) and (3):

$$\frac{N_{Al}}{N_{Be}}=\left(\frac{N_{Al}}{N_{Be}}\right)_0 e^{-(1/\tau Al-1/\tau Be)} \qquad (2)$$

$$\tau=-\frac{\tau Al\tau Be}{\tau Be-\tau Al}=ln\left(\frac{P_{Be}N_{Al}(t)}{P_{Al}-N_{Be}(t)}\right) \qquad (3)$$

where P_{Be} and P_{Al} are the production rates (atoms g^{-1} yr^{-1}) of ^{10}Be and ^{26}Al at the locations. $^{26}Al/^{10}Be$ ratios in buried sediments may be used to determine burial ages from ~0.3 to 5.5 Ma (Granger and Muzikar, 2001). Burial dating utilizes only quartz, a common mineral on the surface, and can help determine absolute ages for coarse sediments without relying on correlation.

Two coarse sediment samples (BT-1 and BT-2) for cosmogenic burial dating were collected from the gravel bed (buried as deep as > 500 m) which belongs to the middle Bunthang sequence. Locations were chosen where there was apparent evidence of stratigraphic continuity. The quartz-rich pebble was chosen to help increase the effective concentration of cosmogenic nuclides.

All the samples for cosmogenic burial dating were prepared in the geochronology laboratories at the University of Cincinnati. First, the samples were crushed and sieved. Quartz was then separated from the 250 - 500μm particle size fractions using the methods of Kohl and Nishiizumi (1992). After the addition of ^{9}Be and ^{27}Al carriers, Be and Al were separated and purified by ion exchange chromatography and precipitated at pH>7. The hydroxides were oxidized by ignition in quartz crucibles. BeO and Al_2O_3 was mixed with Nb (for Be) and Ag (for Al) and loaded into stainless steel cathodes for the determination of the $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios by accelerator mass spectrometry (AMS) at the Center for Accelerator Mass Spectrometry in the Lawrence Livermore National Laboratory for Be analysis and in the University of Tokyo, Japan for Al analysis, respectively. Isotope ratios were compared to ICN ^{10}Be and NIST ^{26}Al standards prepared by K. Nishiizumi (pers. comm. 1995), using half-life of 1.5×10^{6} yr for ^{10}Be and 0.71×10^{6} yr for ^{26}Al. Al concentrations were determined by ICP mass spectrometry at the Inter-University Laboratory of Seoul National University. The measured isotope ratios were converted to cosmogenic concentrations in quartz using the total ^{10}Be and ^{26}Al in the samples and the sample weights. Total cosmogenic ^{10}Be and ^{26}Al concentrations were then converted to burial ages using sea level high

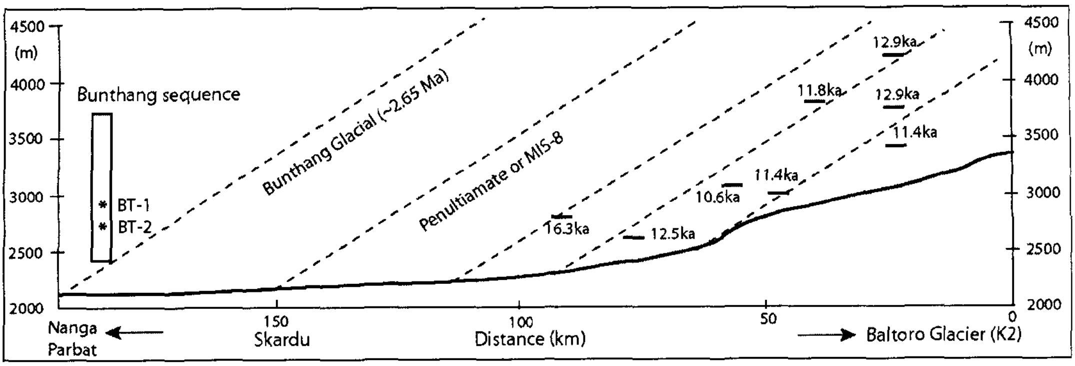

Figure 4. Reconstructed paleo-valley profile. The glacier profiles (dotted lines) during the Lateglacial and the Penultimate Glacial redrawn from Seong *et al.* (2007a) and the profile of the extensive valley glacier for Bunthang Glacial is reconstructed for this study. The solid line is for the modern river longitudinal profile. The column is the Bunthang sequence with the locations (*) for cosmogenic burial samples. The Shigar River merges into the Indus River around Skardu, which flows toward Nanga Parbat.

latitude (SLHL) production rate of 4.98 atom/g of quartz/year for ^{10}Be and 31.1 atom/g of quartz/year for ^{26}Al (Stone, 2000; Balco and Stone, 2007). Cosmogenic production rates were scaled to the latitude and elevation of the sampling sites using the scaling factors of Stone (2000) with 3% SLHL muon contribution.

5. Result and Discussion

1) Age of the Bunthang sequence

The (glacio-)fluvial sediments (BT-1 & BT-2) taken from the middle unit of the Bunthang sequence yielded burial ages of 2.64±0.13 and 2.67±0.14 Ma (Table 1). Despite of the lack of sample numbers, both samples shows the clustering age around 2.65 Ma (±0.13). Therefore, it is likely that the whole sediments quickly deposited during the deglaciation. Furthermore, the decreased age with elevation above modern Indus River, provides more reliability on the data. Based on the reversed magnetic-polarity, Cronin *et al.* (1989) suggested the Bunthang sequence was most probably deposited after the initial glaciation of the northern Hemisphere (<3.2 Ma) and before the end of the Matuyama chron (0.73 Ma). The age range of this study is likely to fall to the Matuyama chron.

This study provides the first numerically defined chronology of the sediment related to the oldest Quaternary (?) glaciation for the Central Karakoram. The Bunthang Glacial Stage might be broadly correlated with Karewa Group of the Kashimir Basin, 150 km southwest of the Skardu Basin (Burbank and Johnson, 1982) and with the Peshawar Basin sequence (Burbank and Tahirkheli, 1985). As Schafer *et al.* (2001) and Owen *et al.* (2005) pointed out, the presence of glacial deposits that are well preserved and predate the last glacial cycle in the western Tibet provides evidence that an extensive ice sheet, as proposed by Kuhle (e.g. 1985, 1988, 1991, and 1995), could not have existed on the Tibetan Plateau during the last glacial cycle. Had such an ice sheet developed, the glacial landforms and associated deposits from earlier glaciations would have been eroded away. This study's data for the

Table 1. Cosmogenic radionuclides data, burial ages, and river incision rates from Bunthang sequence located in the middle Indus River near Skardu, Pakistan

Sample ID	Latitude (N)	Longitude (E)	Altitude (m asl)	Elev. (m)*	^{26}Al (10^4 atoms/g)	^{10}Be (10^4 atoms/g)	^{26}Al/^{10}Be	Burial age (Ma)†	Min. incision rate (mm/yr)‡	Max. incision rate (mm/yr)
BT-1	35°23.900'	75°33.260'	2830	679	7.28 ± 0.14	4.72 ± 0.19	1.54 ± 0.08	2.64 ± 0.13	0.26	0.5
BT-2	35°23.802'	75°33.168'	2701	550	12.24 ± 0.19	8.07 ± 0.24	1.51 ± 0.07	2.67 ± 0.14	0.21	

* Reported elevations are sample elevations above modern Indus River.

† Burial ages calculated by iterative solution of Eqs. (3) (4) (5), assuming sea level high latitude (SLHL) neutron spallation production rates of P_{26} = 31.1 atoms g^{1} yr^{1} and P_{10} = 5.1 atoms g^{1} yr^{1} (Stone, 2000), and SLHL stopped muogenic production rates of P_{26} = 0.80 atoms g^{1} yr^{1} and P_{10} = 0.10 atoms g^{1} yr^{1} (Heisinger *et al.*, 2002)

Uncertainties represent 1δ measurement uncertainty with systematic uncertainty in production rates (~20%).

‡ Minimum incision rates are based on the age and elevation for each sample.

§ Maximum incision rate is generated from the assumption on that time duration of the whole sequence deposition was relatively short (as 0.1 Ma).

Bunthang Glacial Stage confirms the view that an extensive ice sheet did not exist on Tibetan Plateau during the last glacial cycle.

This study shows that the Bunthang glaciation was most extensive and confirms the view by Seong *et al.* (2007a) that glaciation in the Central Karakoram has decreased in extent through time; from extensive valley glaciers (> 180 km long) to restricted valley glaciers (a few tens of kilometers). This likely represents a significant reduction of the moisture flux to the region over the Quaternary, which is needed to maintain positive glacier mass balances. This possibly reflects a change in regional climatic forcing that might be the result of the progressive surface uplift of the Himalayan ranges on the south and the Pamir to the northwest, which progressively uplifted and restricted the supply of moisture by the monsoon and westerlies to the region.

2) How did the Bunthang sequence form?

Given the sedimentary characters and its relationship with basal glacial diamict, it can be drawn that a depositional basin was developed at Skardu as a result of the deep subglacial erosion of a closed depression. Since the extensive glacier retreated from the Komara (i.e. around the Bunthang sequence), the depression might be subsequently filled with sediments by proglacial and paraglacial processes. Then, this closed basin was filled with a cyclic succession of coarse glacial and alluvial detritus and fine lacustrine sediment. Later, the whole sequence would be exhumed by the incision of the modern Indus River.

Alternatively, the intermontane basin development for the Bunthang sequence could be made by a pull-apart mechanism like the upper Sutlej River Basin, approximately 400 km southeast of Skardu (Ni and Barazangi, 1985). However, no direct evidence of normal or strike-slip faulting that may be related to extensional basin development. Thus, the tectonic model for the Bunthang sequence should be speculative. Furthermore, fission-track data from the bedrock around Komara provided younger ages than the surrounding rocks (Zeitler, 1985). This indicates that the depositional basement of the Bunthang sequence is experiencing an increase in elevation comparable to that of the surrounding region. Long-term maximum (effective) incision rate of

0.5 mm/yr over the last 2.67 Ma, deduced from the cosmogenic burial ages of the terraced sediments (i.e. Bunthang sequence) is similar to the fission-track data reported from long-term thermoch-ronology data (Zeitler, 1985).

6. Conclusion

The first new cosmogenic ^{10}Be and ^{26}Al burial dating defines the timing of deposition of the Bunthang sequence near Skardu in the Central Karakoram. The age data is consistent with previous paleomagnetic study (Matuyama reversal chron). The depositional basin within which sediments accumulated to a thickness of more than 1.3 km around 2.65 Ma, which is possibly the Pliocene-Pleistocene boundary based on the view that Quaternary is ice age. Given the sedimentary characteristics and the lack of faults evidence around the Bunthang sequence, the sediments underlain by basal till was deposited within the depression formed by deep subglacial erosion during the Bunthang Glacial Stage and subsequently filled by proglacial and paraglacial sediments. The existence of the extensive Bunthang glacier refutes the hypothesis that the big ice sheet developed on the Plateau during the last glacial cycle and suggests that there may have been significant uplift of the Pamir to the west and Himalaya to the south, which would have reduced the penetration of westerlies and Indian summer monsoon and hence moisture supply to the region.

Acknowledgements

I would like to acknowledge the long-term and highly fruitful relationship with the late Syed Hamidullah, former Director of the Centre of Excellence at Peshawar University, who did so much to help me with this project. I would also like to thank his students, Faisal Khan and Mohammad Shahid, for their excellent assistance in the field. This field research was supported by funding from the National Geographic Society and the US National Science Foundation (Grant BCS-0242339). Special thanks to Dr. Hiroyuki Matsuzaki (at Department of Nuclear Engineering and Management, The University of Tokyo) for his sincere help with AMS measurement of the ^{26}Al samples.

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Received May 7, 2007
Accepted June 5, 2007