

RADIOMETRIC CHRONOLOGY OF CHANGME-KHANGPU GLACIER, SIKKIM

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ABSTRACT. The ^{32}Si concentration in a sample of surface ice from the snout of Changme-Khangpu glacier is 0.36 disintegrations per minute/tonne compared to the fall-out value of 0.7 d.p.m./tonne. If this decrease is assumed to be solely due to decay of ^{32}Si , an age of c. 100 years is estimated for the surface ice of the snout, leading to an average flow velocity of c. 40 m/year for the past century. A vertical profile of ^{210}Pb in a core taken at an altitude of 5040 m shows two horizons where this isotope is enriched, one between 3 and 4 m and another between 11 and 12 m, indicating that the primary concentration of ^{210}Pb can change by physico-chemical processes like adsorption on dust. None the less, a longitudinal profile along the glacier shows a systematic decrease of ^{210}Pb activity with decreasing altitude, the surface ice of the snout giving a value of 0.2 d.p.m./l, corresponding to an age of 100 years which is concordant with the ^{32}Si age. This surface flow-rate of the glacier is much larger than the average contemporary flow-rate (c. 13 m/year). The difference can be understood in terms of the past history of advance and recession of the glacier as revealed by the geomorphic evidence.

RÉSUMÉ. Chronologie radiométrique du glacier Changme-Khangpu, Sikkim. La concentration en ^{32}Si d'un échantillon de surface près du front du Changme-Khangpu est de 0,36 d.p.m./tonne alors que celles des précipitations est de 0,7 d.p.m./tonne. Dans le cas où cette variation n'est due qu'à la décroissance du ^{32}Si , on estime à 100 ans l'âge de la surface près du front, ce qui donne des vitesses moyennes d'écoulement de 40 m/an sur le dernier siècle. Un profil vertical du ^{210}Pb pour une carotte prélevée à 5040 m d'altitude montre deux horizons d'enrichissement isotopique, l'un vers 3-4 m, l'autre vers 11-12 m, indiquant que la concentration originelle du ^{210}Pb peut être modifiée par des processus physico-chimiques tels que l'adsorption sur les poussières. Enfin un profil longitudinal montre une

décroissance systématique de l'activité du ^{210}Pb avec l'altitude, avec 0,2 d.p.m./l au front, ce qui correspond à un âge d'un siècle en concordance avec celui du ^{32}Si . Par contre la vitesse d'écoulement est beaucoup plus élevée que celle actuelle (c. 13 m/an). Cette différence peut être attribuée à l'histoire passée du glacier avec des avances et reculs qui sont révélés par des évidences géomorphologiques.

ZUSAMMENFASSUNG. Radiometrische Chronologie des Changme-Khangpu-Gletschers, Sikkim. Die ^{32}Si -Konzentration in einer Probe des Oberflächeneises aus der Zunge des Changme-Khangpu-Gletschers beträgt 0,36 d.p.m./t, während der Niederschlagswert 0,7 d.p.m./t ist. Wenn diese Abnahme lediglich dem Zerfall von ^{32}Si zugeschrieben wird, so ergibt sich für das Zungeneis ein Alter von etwa 100 Jahren, woraus eine mittlere Fließgeschwindigkeit von circa 40 m pro Jahr für das letzte Jahrhundert abgeleitet werden kann. Ein Vertikal-Profil von ^{210}Pb in einem Kern aus einer Höhe von 5040 m weist zwei Horizonte mit Anreicherung dieses Isotopes auf, eines zwischen 3-4 m und ein anderes zwischen 11-12 m; dies lässt darauf schliessen, dass die ursprüngliche ^{210}Pb -Konzentration infolge von physiko-chemischen Prozessen wie der Aufnahme von Staub schwanken kann. Trotzdem zeigt ein Längsprofil über den Gletscher eine systematische Abnahme der ^{210}Pb -Aktivität mit der Höhe, wobei das Oberflächeneis der Zunge einen Wert von 0,2 d.p.m./l ergibt; dies entspricht einem Alter von 100 Jahren, in Übereinstimmung mit dem Wert aus der ^{32}Si -Analyse. Die oben genannte Fließgeschwindigkeit des Gletschers ist weit höher als die derzeitige mittlere Fließgeschwindigkeit (c. 13 m pro Jahr). Der Unterschied kann aus dem historischen Ablauf von Vorstößen und Rückzügen des Gletschers erklärt werden, der sich aus geomorphologischen Beobachtungen ergibt.

INTRODUCTION

Changme-Khangpu glacier is located in the Tista river basin, in the upper catchment of one of its major tributaries, Lachung Chu, in the Sebu valley of north-east Sikkim. It is a transverse valley glacier trending north-south, having a length of 5.87 km and width varying between 600 m to 1 km. The glacier originates from the southern slope of Gurudongmar peak (lat. $27^{\circ}58'N$, long. $88^{\circ}42'E$) which is an integral part of the Khangchengyao-Pauhri massif. The melt water of the glacier feeds into the Sebu Chu, a tributary of Lachung Chu.

The areal coverage of the glacierized part of the Changme-Khangpu basin is about 12.85 km², of which 10.35 km² comes under perennial ice cover and the rest is covered by rock surfaces only. The ratio between the accumulation and ablation zone areas is 5:7. Almost the entire ablation zone of the glacier is under a thick mantle of supraglacial morainic debris (Bhattacharya, unpublished). The terminal part of the glacier is completely buried under the moraine which has generated enormous amounts of dust which is present everywhere. Presence of englacial dust is also well documented in the darker ice bands exposed in the vertical to sub-vertical faces. The lowest part of the snout is located at an altitude of 4850 m a.s.l. This part, when exposed from the supraglacial debris, is about 3 m in height and 7 m in width.

The Geological Survey of India has been studying the annual mass balance on this glacier since 1977. In order to obtain the flow rates of ice we have dated the snout using the isotope ^{32}Si produced by cosmic rays (Lal and Peters, 1962). In addition, we have measured the longitudinal and vertical profiles of ^{210}Pb . Nuclear debris, mainly from the Chinese nuclear tests, was detected in fresh snow (Bhandari and others, 1982) and its vertical profile in the accumulation zone enabled us to determine the net accumulation rate of ice in this glacier to be 70 cm/year (Shukla and others, 1983). The results are discussed here in terms of glacier dynamics and its past history as determined from the geomorphological studies.

EXPERIMENTAL TECHNIQUES

Three types of samples were collected for the present study. Samples of snout ice (2.38 tonnes) and of snout water (1.64 tonnes) were collected and processed for ^{32}Si and ^{210}Pb (Table 1). Small samples of surface ice were also collected from some locations for ^{210}Pb , and $\delta^{18}\text{O}$ analysis (Fig. 1). A core was taken at 5040 m altitude and one metre sections of ice were melted in plastic bottles for analysis of ^{210}Pb , total dissolved solids, total beta activity, some chemical constituents, and isotopic ratio of oxygen. On the night of 28 August 1978, snow precipitation occurred all over the glacier. Samples (nominally

TABLE I. EXPERIMENTAL DATA ON ^{32}Si MEASUREMENTS IN SNOUT SAMPLES FROM CHANGME-KHANGPU GLACIER, SIKKIM

Sample code ^a	Nature	Altitude m	Distance ^b from A.Z. km	Water collected tonnes	Net ^{32}P c.p.h.	^{32}Si ^c d.p.m./tonne	Mean ^{32}Si d.p.m./tonne	^{32}Si ^d apparent age years
CK-36 -1 m	Snout water	4850	4.66	1.64	7.9	0.68±0.07	0.61±0.05	21
CK-36 -2 m					10.5	0.56±0.05		
CK-38 -1 m	Snout ice	4850	4.66	2.38	3.73	0.34±0.03	0.36±0.03	101
CK-38 -2 m					2.7	0.38±0.04		

^a 1 m = first milking of ^{32}P , 2 m = second milking of ^{32}P .

^b A.Z. = accumulation zone.

^c The statistical errors are less than 5% but a nominal error of 10% is given except when larger uncertainty is expected in chemical estimation.

^d Half-life of ^{32}Si taken for calculation is 105 years.

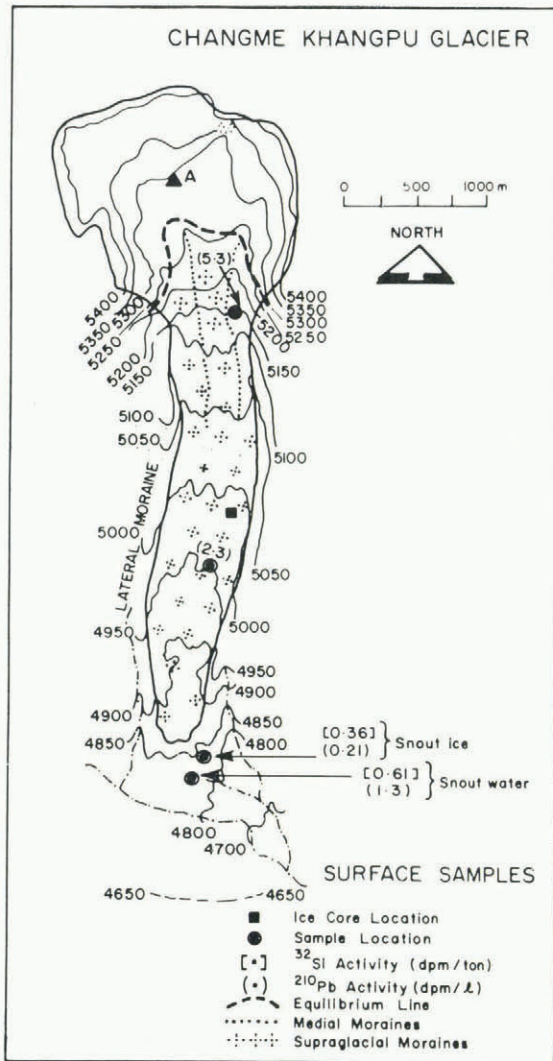


Fig. 1. Distribution of ^{32}Si and ^{210}Pb activity in surface samples of Changme-Khangpu glacier. The sample distance from the accumulation zone has been determined from point A which is the centre of the accumulation zone.

1 g) of this fresh snow were collected for ^{210}Pb and $\delta^{18}\text{O}$ studies, Fig. 2. Here we only discuss ^{210}Pb and ^{32}Si data. The other data relating to nuclear debris and $\delta^{18}\text{O}$ have been reported elsewhere (Shukla and others, 1983; Bhandari and others, 1983; Nijampurkar and Bhandari, in press).

The chemical procedures and techniques of measurement are similar to those described by Nijampurkar and others (1982). ^{32}Si was estimated by analysis of its daughter ^{32}P and ^{210}Pb by its daughter ^{210}Bi . The daughters were radiochemically purified, counted on low-background Geiger-Müller counters, and their decay was followed for several half-lives. The counting efficiencies of ^{32}P and ^{210}Bi were around 35%. The chemical efficiency of extraction of phosphorus was about 50% and of bismuth about 80% except for a few cases of low yield of up to 20%. Replicate measurements made in some samples gave consistent activity.

The results of ^{32}Si measurements are given in Table I. Measurements of ^{32}P in a second extraction in both snout ice and snout water samples agree within the errors of measurements. In both the cases the silica recovered was more than expected from the content of dissolved silica as estimated from spectrophotometry. It was therefore not possible to determine the actual chemical extraction efficiency of silica. Based on our experience in analysis of similar samples, the efficiency of extraction of silica is assumed to be 95%.

RESULTS AND DISCUSSIONS

The ages of various ice samples can be calculated from the observed activity, given in Tables I and II, using the radioactive decay equation, the values of their half-lives, and their fall-out values, if it is assumed that the change of activity is entirely due to decay. The average fall-out values in the past are difficult to estimate, although measurements over the past two decades are available at several geographic locations (Georgieva and Dimchev, 1977; Lal and others, 1979; and Nijampurkar and others, 1982). The ^{210}Pb values in the precipitation of 28 August 1978 suggest an increase in activity with altitude (Fig. 3) except for one value of 2.9 d.p.m./g at 5400 m altitude which does not fit this pattern. An increase of ^{210}Pb with altitude was also observed by Georgieva and Dimchev (1977). The measurements in other snow samples collected during 1981 at 5200 m yield a value of 8.7 d.p.m./g for ^{210}Pb and 0.8 d.p.m./tonne for ^{32}Si . Taking these observations into account and based on arguments given earlier (Nijampurkar and others, 1982; Bhandari and others,

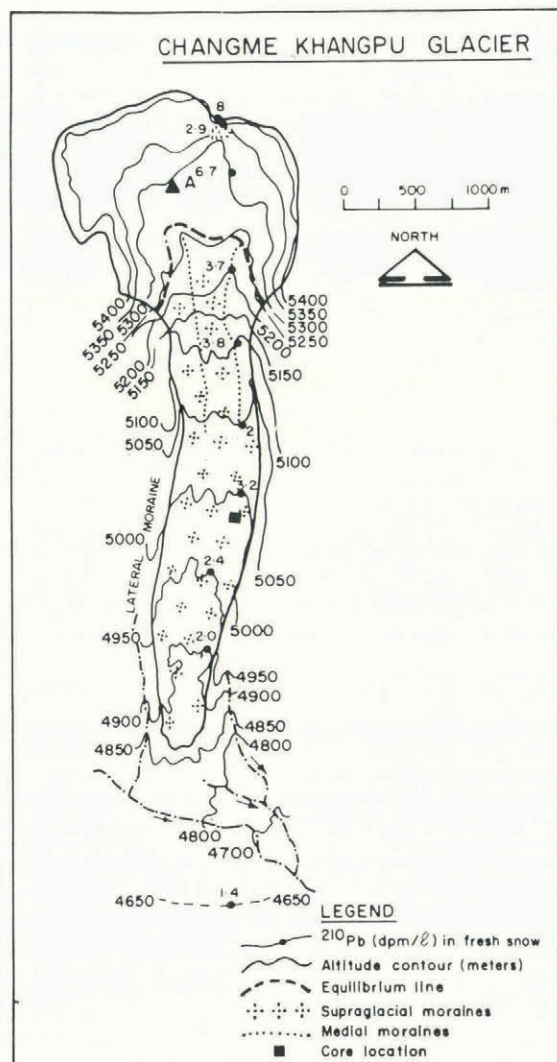


Fig. 2. Distribution of ^{210}Pb activity (d.p.m./l) in fresh snow samples on Changme-Khangpu glacier. The sample distance from the accumulation zone has been determined from point A which is the centre of the accumulation zone.

1981), we assume the fall-out values to be 8 d.p.m./l for ^{210}Pb and 0.7 d.p.m./tonne for ^{32}Si for the purpose of calculating ice ages. Probable errors in these values assumed for fall-out do not significantly alter the conclusions regarding ages of ice samples or flow rates discussed later on. An uncertainty of a factor of two in the fall-out value of ^{210}Pb changes the age of the snout by only 22 years whereas a 20% uncertainty in fall-out value of ^{32}Si changes the age by about 50 years. Thus in spite of the fact that the fall-out value may be changing in each precipitation and that there is possibly some uncertainty in the annual fall-out, the chronology derived here should be qualitatively correct. The half-life values for ^{32}Si measured recently by Elmore and others (1980) and Kutschera and others (1980) are 108 ± 18 years, and 101 ± 18 years whereas so far a value of 300 years has been used, based on geophysical arguments given by Clausen (1973) and Demaster (1980). We here adopt a value of 105 years for ^{32}Si and the value for ^{210}Pb is 22.3 years.

The apparent ages of about 100 years, calculated

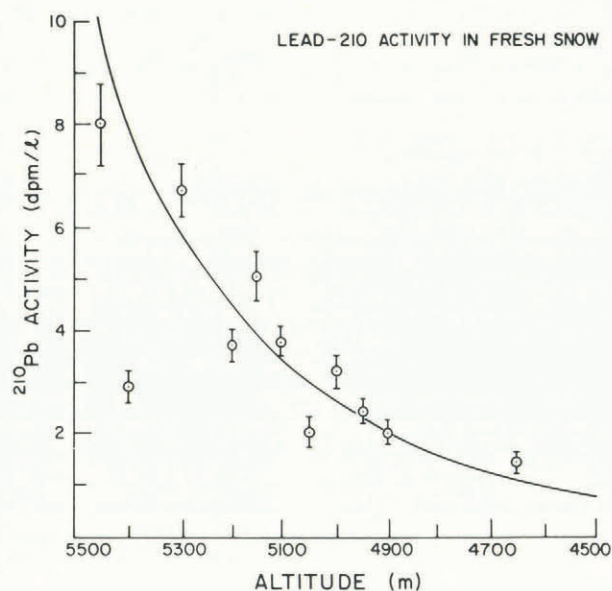


Fig. 3. Altitude dependence of ^{210}Pb activity in precipitation (fresh snow) of 28 August, 1978.

TABLE II. EXPERIMENTAL DATA ON ^{210}Pb MEASUREMENTS IN SURFACE AND FRESH SNOW SAMPLES FROM CHANGME-KHANGPU GLACIER, 1978

Sample	Altitude m	Nature of sample	Volume of water processed l	Net counting rate c.p.m.	^{210}Pb d.p.m./l	^{210}Pb age years
CK-33, 34,35	5300-5450	Fresh snow	-	-	5.9	0
CK-3-81	5200	Fresh snow	33	38.0	8.7 ± 0.9	0
CK-22	5150	Surface ice	0.138	1.8	5.3 ± 0.5	13
CK-18	4950	Surface ice	0.214	0.31	2.3 ± 0.2	40
CK-37	4850	Snout water	100.0	33.84	1.3 ± 0.1	59
CK-39	4850	Snout ice	60.0	2.85	0.21 ± 0.02	117

from ^{32}Si and ^{210}Pb activity in snout ice are consistent. Snout water, on the other hand, shows younger age of 21 ± 13 years based on ^{32}Si and of 59 ± 4 years based on ^{210}Pb which may agree with each other within two standard deviations. Younger ages for snout water as compared to ice are of course expected since the melt water contains contributions from all over the glacier. Significantly young ages, as observed here, indicate a major contribution to the melt water from the upper reaches of the glacier, i.e. from recent precipitations. There are, however, many complications as far as the "closed box" assumption is concerned. The core samples (Table III) show ^{210}Pb activity of 0.5 d.p.m./ ℓ in all horizons except between 3 and 4 m and again between 11 and 12 m. The value of 7.5 d.p.m./ ℓ at 3 to 4 m is much higher than expected as it yields an apparent age of 10 years and is overlain by very old ice (>100 years). Such inversions have also been encountered in Neh-nar glacier in two core samples collected during 1977 and 1978 (Nijampurkar and others, 1982; Bhandari and others, 1981). The enrichment of ^{210}Pb can occur in many ways, from nuclear weapons testing, due to absorption on dust or due to chemical exchange or contribution from the *in situ* radiogenic ^{210}Pb present in the dust. Percolation of melt water can also play an important role in modifying ^{210}Pb concentration, particularly in temperate glaciers (Glen and others, 1977). None of these sources can, however, completely explain all the observations (Shukla and others, 1983). In spite of these possible uncertainties, the observed longitudinal profile of ^{210}Pb in surface ice shows a systematic decrease with decreasing altitude (Fig. 4), and can be attributed to decay of ^{210}Pb with time. For ^{32}Si it is known that such processes are much less important (Nijampurkar, unpublished) and can probably be ignored. The ^{32}Si ages should therefore be more reliable.

FLOW RATES

The ^{210}Pb ages in ice, subject to the corrections for other processes, can be used to determine the flow rates of the glacier in various regions. The three measurements at 5150 m, 4950 m, and 4800 m yield apparent average flow rates of 80 m/year and 20 m/year between the two altitude intervals respectively. The ^{32}Si and ^{210}Pb data in surface ice from the snout yield an average flow rate from the accumulation

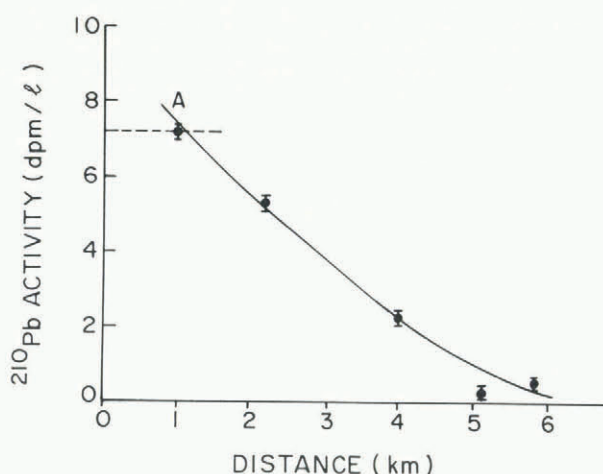


Fig. 4. Longitudinal profile of ^{210}Pb in surface ice samples. ^{210}Pb activity (d.p.m./ ℓ) is plotted against (km) from the top of the accumulation zone. Point A is the mean value for the fresh snow (fall-out) based on several samples and is expected to be uniform through out the accumulation zone (dotted line).

zone to the terminus of 40 m/year for the Changme-Khangpu glacier.

These values can be compared with contemporary flow rates which have been determined by the Geological Survey of India and the Survey of India (Ghosh and Sengupta, unpublished; personal communication from R. Nahak in 1980) for several years during summer. These velocities vary between 1 m/year around altitude of 4850 m to 58 m/year at the equilibrium line, at an altitude of 5250 m, and decrease again towards the accumulation zone, being 40 m/year at an altitude of 5300 m. No measurements have been made above this altitude but flow rates are expected to be low in the accumulation zone. These contours give an average area-weighted flow rate of 13 m/year, which can be treated as an upper limit considering that the accumulation zone is not included in this analysis. This value is much less than the 40 m/year obtained by

TABLE III. EXPERIMENTAL DATA ON ^{210}Pb MEASUREMENTS IN CORE SAMPLES OF CHANGME-KHANGPU GLACIER, 1978

Core	Depth m	Volume of water m ℓ	^{210}Pb counting rate c.p.m.	Chemical efficiency	^{210}Pb d.p.m./ ℓ
CK-1*	0-1	510	<0.05	0.90	<0.33
CK-3*	2-3	530	<0.06	0.94	<0.36
CK-4*	3-4	690	1.52	0.90	7.5
CK-5*	4.7-5.7	1390	<0.06	0.83	<0.15
CK-7	6.7-7.7	1620	<0.08	0.91	<0.2
CK-8	7.7-8.7	1000	0.14	0.99	0.45
CK-9*	8.7-9.25	1000	0.08	0.84	0.29
CK-10*	9.25-10.25	1270	0.09	0.90	0.24
CK-11*	10.25-11.25	1810	0.56	0.88	1.07
CK-12	11.25-12.25	490	<0.13	0.50	<1.6

*These samples were remilked and the activity was confirmed by counting ^{210}Pb .

radiometric methods, which is averaged over the mean life of ^{32}Si , i.e. about a century.

The discrepancy is probably significant enough to suggest that contemporary and past flow rates are different indicating that the glacier is not in a steady state at present. We therefore examine the geomorphic observations to see if this can give some clues to the past history of the glacier. This is particularly important since the glaciers of this valley are, in general, in the process of recession at present.

GEOMORPHIC EVIDENCE FOR GLACIAL ACTIVITY OF CHANGME-KHANGPU GLACIER

The available glacier geomorphic evidence indicates that this part of the higher Himalayan morphogene had undergone multiple glacial episodes. Four, if not more, glacial phases and inter-phases are well documented from the multiple landscape around Changme-Khangpu glacier (Bhattacharya, unpublished; Ghosh and Sengupta, unpublished) though the glacial landforms of the valley are generally obliterated or covered by the consequent geomorphic processes.

During the earliest advancing phase, Changme-Khangpu glacier, the largest of the ten glaciers in the Sebu valley, possibly had occupied the entire valley width and had advanced up to the Dongkyachu valley, where it coalesced with the trunk glacier. This advance probably had resulted in erosion of the *roches moutonnées* which already existed at Yume Samdong along the course of the trunk glacier. The old tillites lying over these *roches moutonnées* were likely to be the medial moraines separating the trunk glacier (Dongkya glacier) from the tributary glacier (Changme-Khangpu). Glacially eroded valley walls and the unpaired benches that one sees here nearly 200 m to 300 m higher up from the present valley floor are evidently due to this glacial episode. In the following advance, Changme-Khangpu glacier did not advance far enough to cover the entire valley width and length. However, a glacier advance at least up to the hot springs about 1 km down-stream of the present snout position could well be postulated. Lower level terraces noted between 100 m and 150 m higher than the present valley base and a set of dissected tillites are apparently remnants of old end moraines and represent this glacial phase. During the third advance, available field evidence indicates that the glacier occupied the western part of the upper reaches of the valley. As a result, a glacial trench developed between the eastern margin of the glacier and the eastern valley wall. During this advance of the glacier, however, the glacier abutted against its southern valley wall and was diverted to the south-east. The glacially eroded western valley wall of the Sebu valley as well as the swerving latero-terminal moraine ridges of Changme-Khangpu glacier corroborate this observation. During these phases this glacier evidently still acted as a barrier to the advance of other glaciers like Sebu or Changme-Khang. As a result, these glaciers during this advance either coalesced or abutted against Changme-Khangpu glacier.

In the recent past, the glacier had another advance which could be deciphered from the evidence still preserved nearly 300 m down-stream of the present terminus. The exact extent of the advance could not be pinpointed as much of the glacial deposits are eroded away by the consequent fluvio-glacial activities. Similar phenomena are also noted in some other glaciers in the valley. The maximum extension of Sebu glacier in the recent past is well indicated by its end moraines. Within the depression between the present position of this glacier and the end moraines the lake Sebu Cho is located. A small hanging glacier located to the south of Changme-Khangpu glacier also demonstrates clearly the advance that this glacier had in the recent past. In the case of Changme-Khangpu glacier the advance in recent time

is noted from the half-truncated end-moraine deposits located nearly 750 m from the present ice limit of the glacier. Due to the rather rapid recession, this glacier has already transformed into a cirque glacier with no outflow (tongue) at all.

The smaller present-day surface velocity is therefore consistent with the recession of the glacier and the high velocity over the past century is probably related to the previous advancing phase. The radioisotopic tracers thus provide a method of determining the past behaviour (advance or recession) of glaciers. Using isotopes with different half-lives one can construct the past history of glaciers.

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