Basal flow rate of Changme-Khangpu glacier, Sikkim Himalaya based on ^{32}Si and ^{210}Pb chronology

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MS received 5 January 1985; revised 22 March 1985

Abstract. Using environmental radioisotopes silicon-32 and lead-210, the radiometric ages of ice at the surface and at 5 m depth at the snout of the Changme-Khangpu (CK) glacier have been calculated to be 100 and > 650 years respectively. Based on i) these age estimates, ii) a net uniform accumulation rate of 0.7 m/yr of ice in the accumulation zone; and iii) applying a simple ice flow model assuming melting of ice of 1 cm/yr at the base of the glacier, it is demonstrated that the average basal flow rate of the CK glacier is much smaller (at least by a factor of three) than that of 40 m/yr estimated for the surface ice. This observation is in good agreement with the earlier work on basal flow rates and indicates that the deeper ice near the bed rock travels much slower than the surface ice.

Keywords. Himalaya; basal flow; environmental radioisotopes.

1. Introduction

The Himalayas form one of the most important temperate glacier systems on the earth. The annual mass budget of these glaciers controls to a large extent the dynamics of ice and plays a vital role in meltwater contributions to north Indian rivers. Direct measurement of glacier flow rates and accumulation and ablation rates of some selected Himalayan glaciers have been made in the past using conventional methods of monitoring the stakes installed at shallow depths in different parts of the glacier over a period of a few months (Geological Survey of India 1984; Raina *et al* 1977).

It is known since three decades, both from mathematical models and from a number of bore-hole experiments (Paterson 1981) that the motion of ice in a glacier slowly decreases with increasing depths and reduces to minimal level near the bed rock. Basal flow rate, which contributes significantly to the understanding of average flow rate of the glacier, depends on many factors like nature and slope of the bed, thickness of the glacier, impurities and suspended material trapped within the ice. Estimation of ice movement by conventional methods at depths is usually cumbersome and gives information only about short term flow rates. The modern radioisotopic techniques, however, provide a unique approach to investigate flow rates over a period of a few centuries (Bhandari *et al* 1982; Nijampurkar *et al* 1982, 1984). An attempt is made in this paper to estimate the past average basal flow rate of the Changme-Khangpu glacier using natural radioisotopes like cosmogenic silicon-32 (half-life = 105 years; Kutschera *et al* 1980) and radiogenic lead-210.

Changme-Khangpu glacier, a small valley glacier in the Sikkim Valley of the eastern Himalayas, is located in the Tista river basin at 27°58' N, 88°42' E and is situated at altitudes ranging from 4850–5800 m above sea level. The glacier is 5.8 km long with a surface area of about 4.6 km². The average thickness of the glacier ice is about 70 m

which thins down to about 5 m at the terminus of the glacier. The surface of the glacier is very dirty and covered with a thick supraglacial morainic debris in its entire ablation area. The glacier has shown a negative mass balance of $2 \times 10^3 \text{ m}^3/\text{yr}$ since 1978 and a receding trend for the past few years. There is strong geological evidence that this glacier has gone through at least four cycles of advance and recession in the past. The geological and geomorphological details are discussed elsewhere in detail (Nijampurkar *et al* 1984).

Results of analysis of the basal ice flow rate of the CK glacier are reported here and are compared with the surface flow rates determined by Bhandari *et al* (1982) and Nijampurkar *et al* (1984). The findings are discussed in terms of glacier movement.

2. Sample collection and analytical techniques

Three deep ice samples (CK-2, CK-5 and CK-7), at the snout of the CK glacier, close to the bed-rock at 5 and 12 m depth (tables 1, 2) along with eight other samples of different types (fresh snow, surface ice and meltwater emerging out from the terminus of the glacier) were collected during two glacier expeditions to the CK glacier in 1978 and 1981 (tables 1, 2 and figure 2). These samples were processed for ^{32}Si and ^{210}Pb activities using analytical procedures described by Nijampurkar *et al* (1982). In short, ^{32}Si and ^{210}Pb activities were extracted from a few tons and a few litres of meltwaters respectively, using $\text{Fe}(\text{OH})_3$ as a scavenger. The respective radioactive daughters ^{32}P and ^{210}Bi (of ^{32}Si and ^{210}Pb respectively) were radiochemically separated, purified and counted as $\text{Mg}_2\text{P}_2\text{O}_7$ and BiPO_4 for several half-lives, using low background (0.8 cph) GM detectors with a NaI(Tl) active anticoincidence shield (Bhandari 1969). A typical decay curve of ^{32}P in fresh snow sample is shown in figure 1.

Table 1. Experimental data on measurements of ^{32}Si in snow and ice samples of CK glacier, Sikkim

Sample code	Nature/date of collection	Altitude (m)	Water collected (L)	Net ^{32}P (cph)	^{32}Si (dpm/ton)	$^{32}\text{Si}^*$ apparent age (yrs)
CK-1-81	Fresh snow 30.7.81 to 6.8.81	5200	800	10.5	0.88 ± 0.09	0
CK-2-81	Snout ice (at 5 m depth) 7.8.81 to 10.8.81	4850	1035	<0.1	<0.01	>650
CK-36-78	Snout melt water	4850	1640	9.0	10.5 ± 0.05	51
CK-38-78	Surface snout ice (0-30 cm) 28.8.78 to 7.9.78	4850	2380	3.7	10.34 ± 0.03	109

* Half-life of ^{32}Si taken for calculation is 105 years; † Average value of repeat milkings. The corrected ^{32}Si activity for freshwater contribution, using the two component models (Nijampurkar *et al* 1982) has been taken for calculation of age.

Table 2. Experimental data on measurements of ^{210}Pb in snow and ice samples of CK glacier, Sikkim

Sample code	Nature	Date of collection	Altitude (m)	Volume processed (L)	^{210}Pb		
					Total ^{210}Bi activity (cpm)	Activity dpm/L	Age (yr)
CK-3-81	Fresh snow	6.8.1981	5200	33	37.95	8.50 ± 0.90	0
CK-4-81	Snout ice (0-30 cm)	9.8.1981	4850	10	0.38	0.33 ± 0.02	100
CK-5-81	Snout ice at 5 m depth	9.8.81	4850	50	0.63	0.08 ± 0.01	150
CK-6-81	Surface ice (0-30 cm)	10.8.81	4900	14	0.72	0.58 ± 0.06	85
CK-7-81	Deep ice at 12 m depth	10.8.81	4900	9.5	0.12	0.088 ± 0.03	145
^t CK-39-78	Snout ice (0-30 cm)	3.9.78	4850	60	2.85	0.21 ± 0.02	115
CK-37-78	Snout water	5.9.78	4850	100	33.85	1.3 ± 0.10	60

^tFrom Nijampurkar *et al* 1984.

Figure 1. Observed decay plot of ^{32}P activity (cph) for the samples fresh snow (CK-1-81) and the snout ice at 5 m depth (CK-2-81). The dashed line represents the background.

3. Results

3.1 Dating of surface and deep ice samples by radioisotopes

The intercomparison of the past flow rates with contemporary flow rates can best be done by dating the surface and deep ice samples of the glacier using radioisotopes such as ^{32}Si , ^{210}Pb . Additionally, bomb-produced ^{137}Cs in an ice core can be used as a time marker to date deep ice samples and estimate past accumulation rates of ice. Dating of snow, firn and glacier ice by radioisotopes requires proper knowledge of their half-life values and average fallout values in the precipitation. Based on various considerations, discussed in detail by Nijampurkar *et al* (1982), the apparent ages of the surface and deep ice samples have been calculated using appropriate half-lives for cosmogenic ^{32}Si (105 yr) and radiogenic ^{210}Pb (22.3 yr). Mean weighted fallout values in precipitation of 0.7 dpm/ton for ^{32}Si and 8 dpm/L for ^{210}Pb are adopted in the present work for calculation of age (Nijampurkar *et al* 1982). The ^{32}Si and ^{210}Pb activities in one year's fallout of fresh snow samples (CK-1, CK-3) were found to be 0.88 ± 0.09 dpm/ton and 8.5 dpm/L respectively which are a little higher than the values adopted for age calculations and those reported in the literature (Bhandari *et al* 1982; Clausen *et al* 1967; Nijampurkar *et al* 1982, 1984). The ages of these samples are, therefore, assumed to be zero for calculation of ice flow rates.

Results from table 1 clearly show that the ^{32}Si activity in the surface ice sample of snout (CK-38) has decayed by 50 % and that of snout ice at 5 m depth (CK-2) by over 95 % (figure 2). The age of the deep snout ice, estimated to be > 650 years using ^{32}Si (table 1) is thus older than that of the surface ice sample by at least 550 years.

The ^{210}Pb ages of surface samples CK-6 (150 m away from the snout in the ablation zone) (figure 2) and CK-4 (snout ice) are estimated to be 85 ± 10 and 100 ± 10 respectively which are in good agreement with that of the snout ice (CK-38, about 100 ± 10 years), obtained earlier through ^{32}Si measurements. A very low activity of 0.08 dpm/L may be contributed by non-fallout process (i.e. due to *in situ* production in

Figure 2. Distribution of ^{32}Si activity (dpm/ton) and ^{210}Pb activity (dpm/L) in snow, surface and deep ice on CK glacier. The ^{210}Pb activities (5.3) and (2.3) of surface ice shown in the map (not discussed in text) and melt water (1.3) emerging from terminus (i.e. snout water) are given for comparison with those of fresh snow and snout ice.

dust) and therefore the ages of the deep ice samples CK-5 (150 years) and CK-7 (145 years) obtained by ^{210}Pb method can be taken as a lower limit of the age estimates (table 2).

The meltwater collected near the snout at the glacier is much younger (55 ± 5 years for CK-36 and CK-37) than the surface snout ice (tables 1, 2 and figure 2). Its age estimate has been given only for comparison with that of the ice samples, and to show that the average residence time of meltwater in the glacier is much smaller than that of deep ice at snout.

4. Discussion

The general pattern of flow of surface and deep ice in a glacier has been studied earlier by field experiments and theoretical considerations (Bhandari *et al* 1982; GSI 1984;

Figure 3. Variation of horizontal velocity and ice flow model ages with depth; a) Probable horizontal velocity profile in CK glacier based on past average surface and basal ice flow rates assuming vertical velocity gradient of Paterson (1981); b) Age of ice in the accumulation zone of CK glacier as a function of the distance y from the bottom (bed-rock) calculated using the modified formula for the ice flow model ages [see text (1)].

Hutter 1982; Lliboutry 1976; Paterson 1981; Paterson and Waddington 1984). These studies indicate that the deepest ice at the terminus of the glacier ice is fed by the deeper ice from the accumulation and ablation zones and would, therefore, be the oldest. For calculation of basal flow rates one requires estimates of the ice ages of the deeper ice in accumulation zone. In view of practical difficulties that arise in getting deeper ice samples from accumulation zones of temperate Himalayan glaciers and the limitations of the isotopes ^{32}Si and ^{210}Pb to date the ice samples layer by layer, indirect methods based on (i) bomb-produced ^{137}Cs as a time marker and (ii) ice flow models, are employed to obtain the ages of the deeper ice.

Using the depth profile of bomb-produced ^{137}Cs in an ice core from the accumulation zone, a net accumulation rate of ice of 0.7 m/yr has been calculated for the high altitude region over the CK glacier (Shukla *et al* 1983). Assuming a uniform deposition rate of snow over a period of past few decades, the radiometric age of the ice at 70 m depth near the bed rock has been estimated, as a first approximation (as lower limit), to be 100 years.

Considering the thinning of ice with depth (Paterson and Waddington 1984) and applying a simple ice flow model, assuming a constant vertical strain rate and melting rate of 1 cm of ice per year at the base of the glacier (which corresponds to an average geothermal heat flux and a deformational heat production caused by a sliding velocity of 10 m/yr), the ages of the deeper ice in the accumulation zone are calculated using Nye's formula (1963), modified by Hammer *et al* (1978).

$$t_{\text{yr}} = (H + \Delta H) / \lambda H \ln (H + \Delta H) / (y + \Delta H) \quad \dots \quad (\text{I})$$

where H and λH are the mean thickness (m) of ice in accumulation zone and net

accumulation rate of ice (m/yr), y is the distance (m) from the bed rock, λ_0 is the annual ablation (cm/yr) from the bottom at $y = 0$ and $\Delta H = (H\lambda_0)/(\lambda H - \lambda_0)$.

The ages of the deeper 10 m ice lying over the bed rock (from $y = 0$ –10 m) lie in the range of 200–430 years (figure 3b). Based on these age estimates and that of the deep ice at snout, the average basal flow rate of the glacier ice has been found to be much smaller (< 13 m/yr) than that of the average surface flow rate of about 40 m/yr calculated for the past century (Nijampurkar *et al* 1984). Figure 3b also shows the most probable velocity profile with depth drawn on the basis of only two points (assuming horizontal velocity gradient of Paterson 1981), obtained by radiometric and flow model age estimates for the surface and deep ice samples. This clearly indicates that sliding velocity in this glacier is not more than 30% of the surface velocity, and that the travelling time of deeper ice from accumulation zone to the terminus of the glacier is at least 3 times longer than that for the surface ice.

Acknowledgement

I thank Professors David J Demaster, M Kuhn and N Bhandari for their critical comments and suggestions. My thanks also to Shri V M K Puri, Shri Sanjay Sharma, Mr S Chatterjee and other members of the CK glacier expedition. I also thank Mr Kameswara Rao for his technical assistance.

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