# Sudden warming epochs during 42 to 28 ky BP in the Himalayan region from stable isotope record of sediment from a relict lake in Goting, Garhwal, North India

**Prosenjit Ghosh[#,†] and S. K. Bhattacharya***

[#]Max-Planck-Institute for Biogeochemistry, Winzerlaer Str. 10, 07745 Jena, Germany
*Physical Research Laboratory, Navarangpura, Ahmedabad 380 009, India

**$^{18}O/^{16}O$ variations of the precipitation recorded in carbonate sediments of a high-altitude Himalayan lake have been investigated by analysing samples from a varve deposit in Goting, Garhwal Himalaya. $^{14}C$ ages of four samples from different depths suggest that the sedimentation in the lake started ~ 42 ky BP and continued till ~ 28 ky BP. Fluctuations in $d^{18}O$ values are interpreted in terms of water-source variations. A trend showing the enrichment of $d^{18}O$ values between 32 and 28 ka indicates slow cooling as one approaches the Last Glacial Maximum (LGM). There are six strong $d^{18}O$ excursions (depleted ratios) coinciding with low $^{13}C$ values at around 40.2, 38.2, 36.2, 34.2, 32.8 and 29.4 ky BP, denoting enhancement of the southwest monsoon. In addition, three positive shifts at around 40.7, 37.2 and 35.2 ky BP were observed, which indicate weakening of the southwest monsoon. Fourier analysis of the $d^{18}O$ time series shows a significant ~ 740 year periodicity, similar to that reported in the Arabian Sea and South China Sea.**

THE history of global climate change during the last glacial cycle is faithfully recorded in two repositories, i.e. deep-sea sediments and ice sheets[1]. From these records it has been established that the slow cooling and warming phases in this cycle were punctuated by several relatively short-term events signifying instabilities in the climate system. However, such variation in the continental climate is relatively less clear because of absence of suitable archives preserving continuous record. In this context, palaeo-lakes have special importance. Lakes are smaller water bodies compared to oceans and ice sheets, and are, therefore, sensitive to even small climatic fluctuations; may contain records of sudden environmental changes in their sediments. However, continuous sedimentary sequences from lakes are rare, especially from the tropical region. Recent discovery of a varve sediment deposit in Goting palaeo-lake, Garhwal Himalaya by Pant *et al.*[2] has led to the possibility of deriving past climatic information from a study of the layers of the deposit. Geological evidences indicate that this deposit, presently exposed as a standing column, formed in a lake with fluctuating margins. It is believed that the lake originated as a result of impounding of the river Dhauli-Ganga by landslides (Figure 1) and drained out later when the breach got removed due to another phase of tectonism. Based on morphological features and $^{14}C$ dates, Pant *et al.*[2] argued in favour of a continuous sedimentation during the life of the Goting lake (from about 42 to 28 ky BP). Magnetic susceptibility studies along its length showed marked enhancement of susceptibility at about 36.5 ka (ref. 2). Increase in the magnetic susceptibility coincided with increase in the occurrence of limonitic bands comprising hematite and goethite minerals. Since formation of these

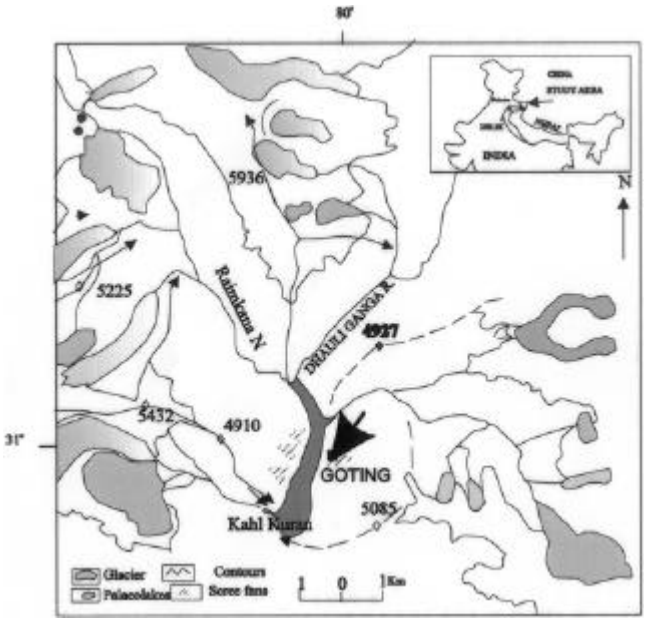


**Figure 1.** Location of the Goting relict lake deposit in Garhwal Himalaya. The glaciers at higher reaches (> 1000 ft w.r.t. the Goting basin) feeding the stream Dhauli–Ganga and sampling site (denoted by a box) are also shown.

[†]For correspondence. (e-mail: pghosh@bgc-jena.mpg.de)

minerals is favoured in warmer conditions, the 36.5 ka event was interpreted[2] as a period of climatic amelioration.

A major component of the Goting sediments consists of marly carbonates and offers the possibility of carbon and oxygen isotope analysis in the annual layers to infer about the water source and its variation. As in the other Himalayan rivers from this region, the river Dhauli–Ganga receives its water from monsoonal rainfall, winter snowfall and melting of glacier. These sources of water are expected to have different stable (O, H) isotopic composition and, therefore, any variation in their relative supply would lead to isotopic variation in the Goting lake and in the contemporary authigenic carbonate phase. Our study was motivated to decipher such variation in the geological history of the lake, with possible connection to climate change in this region.

## Materials and methods

A 15 m thick sedimentary pile comprising alternate bands of coarse and fine marly sediments (Figure 2) from a cliff face was chosen for sampling. Samples were collected starting from ground level up to a height of 12 m (Table 1). Adequate precaution was taken while sampling to avoid recent contamination and cross-contamination between two neighbouring samples. About 200 samples were collected from different layers (fine- and coarse-grained). Thin-section study of some chips showed that the samples are composed of detrital (quartz and feldspar) material with micritic carbonate as cementing matrix having grains less than 100 micron in size. The fine-grained nature of the matrix, the layered structure and absence of features suggesting re-precipitation of carbonates indicate that they are primary precipitates and have not suffered any alteration subsequent to precipitation. An additional confirmation for this is provided by the nature of the isotopic data itself, displaying large differences in adjacent layers. Ages of six samples (bulk organic phase) at different depths were determined earlier using radiocarbon technique[2]. Oxygen and carbon isotopic composition of the carbonate cement was measured after crushing the sample chips to fine powder (~ 200 mesh) and reacting with 100% phosphoric acid at 25°C for 12 h. The carbon dioxide produced by the reaction was cleaned and purified cryogenically and analysed in a VG Micromass 903 mass-spectrometer. Water samples, collected from snowmelt, rainfall and river were also analysed following the procedure of $CO_2$ equilibration at 25°C (ref. 3). A number of samples were re-analysed to check the sample heterogeneity. The isotopic ratios of carbon and oxygen are presented in the usual $d$ notation in units of per mil (‰) w.r.t. V-PDB and are reproducible within 0.1‰ at 1 $s$ level. The oxygen isotopic ratios of the water samples are expressed w.r.t. V-SMOW.

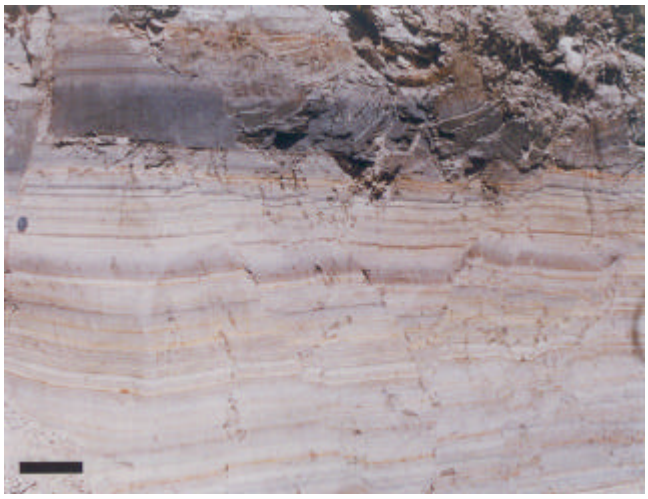

**Figure 2.** Exposure of rhythmite showing alternate laminations of fine (dark colour) and coarse (light colour) material at Goting (bar 20 cm in length).

### *Chronology of the Goting sediments*

Pant *et al.*[2] determined $^{14}C$ ages for six samples from the same Goting section (Table 2). These ages were obtained from the organic fraction of the sediments, but were not corrected for variation in radiocarbon production function in the past. This needs to be done in order to make reliable inter-comparison with other proxy climate data. A calibration curve based on tree ring, varve counting and coral dating is available for the period 0–24 ky BP (ref. 4). Beyond 24 ky BP, a calibration has been proposed by Bard *et al.*[5] based on U–Th dates and $^{14}C$ ages of coral samples. According to this, the true age is 1.168 times the measured $^{14}C$ age. This factor is used here for estimating the correct ages of the six Goting samples (Table 2). Out of the six ages, two are found to deviate from a linear trend probably due to contamination by younger carbon[2]. Four corrected ages were plotted against the sample depths and a linear regression line was drawn. An average annual sedimentation rate of 1.2 mm/yr is obtained from the slope of this line. This estimate is higher than the earlier estimate of 0.7 mm/yr obtained by Pant *et al.*[2] using all the six uncalibrated ages.

## Results

The oxygen and carbon isotopic ratios of the carbonate cements are plotted in Figure 3 *a* and *b* along with the estimated ages of the samples. The samples are not strictly equally spaced and the time difference between two adjacent samples ranges from 60 to 100 yrs. The average $d^{18}O$ value based on 193 samples (rejecting the values of seven samples with outlier values) is – 14‰ with a 1 $s$ range of ± 2.3‰. The corresponding mean $d^{13}C$ value is – 0.8‰, with a 1 $s$ range of ± 1.0‰. The oxygen isotopic

**Table 1.**

| GS sample | Depth (cm) | Cal age (BP year) | $d^{13}$C (PDB) | $d^{18}$C (PDB) |
|---|---|---|---|---|
| 1 | 5 | 42546 | – 1,6 | – 15,0 |
| 2 | 12 | 42460 | 0,0 | – 11,2 |
| 3 | 15 | 42423 | – 1,2 | – 15,1 |
| 4 | 23 | 42325 | – 2,1 | – 17,0 |
| 5 | 32 | 42315 | – 2,9 | – 17,3 |
| 6 | 43 | 42081 | – 1,4 | – 13,9 |
| 7 | 58 | 41897 | – 1,8 | – 16,0 |
| 8 | 68 | 41775 | – 1,0 | – 14,5 |
| 9a | 79 | 41640 | – 1,1 | – 15,5 |
| 9b | 74 | 41701 | – 1,0 | – 13,7 |
| 10 | 86 | 41554 | – 0,2 | – 11,9 |
| 11 | 93 | 41469 | – 2,2 | – 15,8 |
| 12 | 98 | 41407 | – 1,6 | – 14,2 |
| 13 | 103 | 41346 | – 1,5 | – 15,6 |
| 14 | 108 | 41285 | – 1,6 | – 12,3 |
| 15 | 112 | 41236 | – 1,8 | – 16,2 |
| 16 | 115 | 41199 | – 0,8 | – 12,6 |
| 17 | 117 | 41175 | – 1,0 | – 14,8 |
| 18 | 123 | 41101 | – 0,4 | – 10,9 |
| 19 | 128 | 41040 | – 0,0 | – 12,4 |
| 20 | 132 | 40991 | – 0,8 | – 15,3 |
| 21 | 137 | 40930 | 0,3 | – 11,6 |
| 22 | 143 | 40857 | – 0,4 | – 12,5 |
| 23 | 150 | 40771 | – 2,4 | – 19,1 |
| 24 | 158 | 40673 | – 1,8 | – 17,1 |
| 25 | 166 | 40575 | – 1,0 | – 14,4 |
| 26 | 174 | 40477 | – 1,3 | – 15,4 |
| 27 | 186 | 40330 | – 0,9 | – 13,6 |
| 29 | 204 | 40110 | – 2,3 | – 11,6 |
| 30 | 214 | 39988 | – 0,3 | – 13,3 |
| 31 | 222 | 39890 | – 2,1 | – 19,2 |
| 32 | 236 | 39718 | – 1,1 | – 13,9 |
| 33 | 246 | 39596 | – 0,5 | – 12,4 |
| 34 | 260 | 39425 | – 1,7 | – 18,4 |
| 35 | 278 | 39204 | – 1,0 | – 14,2 |
| 36 | 284 | 39139 | – 1,9 | – 16,8 |
| 37 | 291 | 39045 | – 1,5 | – 15,5 |
| 38 | 299 | 38947 | – 0,3 | – 12,6 |
| 39 | 307 | 38849 | – 0,3 | – 13,0 |
| 40 | 316 | 38739 | – 0,0 | – 12,6 |
| 41 | 326 | 38617 | – 1,1 | – 14,5 |
| 42 | 336 | 38494 | – 0,3 | – 12,0 |
| 43 | 347 | 38360 | – 2,3 | – 14,4 |
| 44 | 356 | 38250 | – 2,2 | – 17,6 |
| 45 | 365 | 38139 | – 1,6 | – 16,6 |
| 46 | 375 | 38017 | – 2,9 | – 12,0 |
| 47 | 385 | 37895 | – 2,6 | – 15,5 |
| 48 | 395 | 37772 | – 2,8 | – 18,5 |
| 49 | 405 | 37650 | – 1,9 | – 17,3 |
| 50 | 415 | 37527 | – 0,2 | – 12,0 |
| 51 | 425 | 37405 | – 0,1 | – 12,4 |
| 52 | 431 | 37332 | – 0,5 | – 12,0 |
| 53 | 436 | 37270 | – 0,4 | – 13,2 |
| 54 | 445 | 37160 | – 1,2 | – 14,3 |
| 55 | 455 | 37038 | – 0,8 | – 13,1 |
| 56 | 461 | 36964 | 0,6 | – 10,1 |
| 57 | 466 | 36903 | – 0,2 | – 11,8 |
| 58 | 471 | 36842 | – 2,8 | – 19,6 |
| 59 | 474 | 36805 | – 0,9 | – 13,8 |
| 60 | 478 | 36756 | – 1,5 | – 13,4 |
| 61 | 482 | 36707 | – 1,4 | – 16,5 |
| 62 | 486 | 36658 | – 0,9 | – 13,7 |
| 63 | 491 | 36597 | – 0,6 | – 13,4 |
| 64 | 496 | 36536 | – 0,3 | – 13,5 |
| 65 | 502 | 36463 | – 1,4 | – 15,8 |
| 66 | 507 | 36401 | 0,0 | – 11,2 |
| 68 | 515 | 36303 | – 0,4 | – 12,5 |
| 69 | 519 | 36254 | – 2,1 | – 19,0 |
| 70 | 526 | 36169 | – 2,2 | – 19,1 |

(**Table 1.** *Contd*.)

| GS sample | Depth (cm) | Cal age (BP year) | $d^{13}$C (PDB) | $d^{18}$C (PDB) |
|---|---|---|---|---|
| 71 | 532 | 36095 | – 1,2 | – 15,1 |
| 72 | 539 | 36010 | – 2,1 | – 16,4 |
| 73 | 545 | 35936 | – 0,2 | – 10,2 |
| 74 | 552 | 35851 | – 0,3 | – 13,7 |
| 75 | 565 | 35691 | – 0,1 | – 11,0 |
| 76 | 575 | 35569 | – 2,1 | – 16,9 |
| 77 | 582 | 35483 | – 0,6 | – 12,6 |
| 78 | 588 | 35410 | – 0,4 | – 12,1 |
| 79 | 592 | 35361 | – 0,9 | – 13,9 |
| 80 | 597 | 35300 | 0,4 | – 11,0 |
| 81 | 601 | 35259 | – 2,0 | – 16,8 |
| 82 | 603 | 35226 | – 0,1 | – 12,2 |
| 83 | 607 | 35177 | – 0,5 | – 12,3 |
| 84 | 612 | 35116 | 0,2 | – 11,5 |
| 85 | 617 | 35055 | – 1,0 | – 14,3 |
| 86 | 621 | 35006 | – 0,8 | – 12,4 |
| 87 | 624 | 34969 | – 0,9 | – 13,9 |
| 88 | 629 | 34908 | 0,8 | – 10,5 |
| 89 | 633 | 34859 | – 3,1 | – 18,4 |
| 90 | 638 | 34798 | – 0,3 | – 9,0 |
| 91 | 642 | 34749 | – 0,3 | – 13,8 |
| 92 | 647 | 34688 | – 0,2 | – 12,9 |
| 93 | 652 | 34627 | – 2,4 | – 17,9 |
| 94 | 658 | 34553 | – 1,2 | – 14,9 |
| 96 | 667 | 34443 | – 0,7 | – 13,8 |
| 97 | 672 | 34382 | – 1,4 | – 13,8 |
| 98 | 678 | 34308 | – 2,2 | – 19,9 |
| 99 | 686 | 34210 | – 0,7 | – 13,8 |
| 100 | 690 | 34161 | – 0,4 | – 12,0 |
| 101 | 697 | 34076 | – 2,5 | – 20,2 |
| 102 | 706 | 33966 | – 0,1 | – 13,9 |
| 103 | 713 | 33880 | – 1,1 | – 15,9 |
| 104 | 718 | 33819 | 0,6 | – 11,5 |
| 105 | 723 | 33757 | – 1,6 | – 18,0 |
| 106 | 727 | 33709 | 0,1 | – 12,6 |
| 107 | 731 | 33660 | 0,0 | – 13,6 |
| 108 | 734 | 33623 | 0,1 | – 12,8 |
| 110 | 741 | 33537 | 0,4 | – 12,2 |
| 111 | 746 | 33476 | – 1,8 | – 17,1 |
| 112 | 752 | 33403 | 0,3 | – 11,7 |
| 113 | 757 | 33341 | 0,2 | – 13,4 |
| 114 | 762 | 33280 | 0,0 | – 12,0 |
| 115 | 766 | 33231 | 0,7 | – 14,0 |
| 116 | 771 | 33170 | 0,5 | – 12,0 |
| 120 | 788 | 32962 | – 0,8 | – 14,2 |
| 121 | 792 | 32913 | – 2,5 | – 16,7 |
| 122 | 796 | 32864 | – 1,8 | – 14,5 |
| 123 | 799 | 32827 | – 4,4 | – 18,5 |
| 124 | 802 | 32791 | – 2,7 | – 17,3 |
| 125 | 806 | 32742 | – 3,4 | – 18,0 |
| 127 | 816 | 32619 | – 1,7 | – 16,5 |
| 128 | 820 | 32570 | – 1,1 | – 11,4 |
| 129 | 827 | 32485 | – 0,1 | – 12,4 |
| 130 | 832 | 32423 | – 0,2 | – 12,9 |
| 131 | 837 | 32362 | – 1,5 | – 15,0 |
| 132 | 840 | 32325 | – 0,2 | – 12,9 |
| 133 | 844 | 32276 | – 1,5 | – 16,2 |
| 134 | 848 | 32227 | – 1,2 | – 12,7 |
| 135 | 852 | 32179 | – 1,1 | – 13,0 |
| 136 | 855 | 32142 | 3,1 | – 9,4 |
| 137 | 859 | 32093 | 0,3 | – 11,5 |
| 138 | 863 | 32044 | – 0,9 | – 14,2 |
| 139 | 868 | 31983 | – 0,2 | – 13,2 |
| 140 | 871 | 31946 | – 0,5 | – 11,7 |
| 141 | 874 | 31909 | – 0,3 | – 12,4 |
| 142 | 879 | 31848 | – 0,9 | – 14,0 |
| 143 | 883 | 31799 | – 1,8 | – 14,8 |
| 144 | 888 | 31738 | – 0,6 | – 13,6 |
| 145 | 892 | 31689 | – 1,0 | – 15,6 |

(**Table 1**. *Contd*.)

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| GS sample | Depth (cm) | Cal age (BP year) | $d^{13}$C (PDB) | $d^{18}$C (PDB) |
|---|---|---|---|---|
| 146 | 896 | 31640 | 0,4 | – 11,0 |
| 147 | 901 | 31579 | – 0,1 | – 13,8 |
| 148 | 907 | 31505 | – 1,1 | – 15,6 |
| 149 | 914 | 31420 | – 0,5 | – 13,4 |
| 150 | 921 | 31334 | – 1,5 | – 15,7 |
| 151 | 928 | 31248 | – 0,6 | – 12,8 |
| 152 | 935 | 31163 | 0,2 | – 12,1 |
| 153 | 939 | 31114 | – 0,7 | – 13,8 |
| 154 | 944 | 31052 | – 1,1 | – 14,4 |
| 155 | 951 | 30967 | – 0,9 | – 15,6 |
| 156 | 958 | 30881 | – 0,3 | – 11,7 |
| 157 | 963 | 30820 | 0,6 | – 11,0 |
| 158 | 968 | 30759 | – 0,2 | – 14,0 |
| 159 | 973 | 30697 | – 0,2 | – 13,2 |
| 160 | 977 | 30649 | – 1,7 | – 16,8 |
| 161 | 981 | 30600 | – 0,7 | – 15,0 |
| 162 | 985 | 30551 | – 0,4 | – 14,0 |
| 163 | 988 | 30514 | 1,1 | – 10,2 |
| 164 | 992 | 30465 | 0,0 | – 13,1 |
| 165 | 997 | 30404 | – 0,8 | – 13,9 |
| 166 | 1002 | 30343 | – 1,2 | – 16,4 |
| 167 | 1007 | 30281 | 0,7 | – 11,0 |
| 168 | 1012 | 30220 | 0,4 | – 12,2 |
| 169 | 1017 | 30159 | – 1,6 | – 17,7 |
| 170 | 1020 | 30122 | 0,2 | – 12,0 |
| 171 | 1027 | 30037 | – 0,7 | – 14,0 |
| 172 | 1035 | 29939 | 0,4 | – 11,1 |
| 173 | 1042 | 29853 | 1,5 | – 9,5 |
| 174 | 1046 | 29804 | – 0,6 | – 13,9 |
| 175 | 1051 | 29743 | – 0,2 | – 13,8 |
| 176 | 1056 | 29682 | – 0,7 | – 11,7 |
| 177 | 1061 | 29620 | – 1,4 | – 16,2 |
| 178 | 1065 | 29571 | – 0,4 | – 14,7 |
| 179 | 1069 | 29522 | – 1,5 | – 16,2 |
| 180 | 1074 | 29461 | – 0,4 | – 14,1 |
| 181 | 1080 | 29388 | – 0,8 | – 14,9 |
| 182 | 1087 | 29302 | – 0,8 | – 15,0 |
| 183 | 1094 | 29216 | 0,0 | – 13,2 |
| 184 | 1102 | 29119 | – 0,5 | – 14,2 |
| 185 | 1108 | 29045 | 0,2 | – 12,7 |
| 186 | 1112 | 28996 | 1,0 | – 10,9 |
| 187 | 1126 | 28825 | – 1,3 | – 15,8 |
| 188 | 1134 | 28727 | 0,5 | – 11,0 |
| 189 | 1141 | 28641 | – 0,9 | – 16,1 |
| 190 | 1147 | 28562 | 0,8 | – 11,9 |
| 191 | 1152 | 28507 | – 1,0 | – 12,7 |
| 192 | 1156 | 28458 | 0,5 | – 12,0 |
| 193 | 1165 | 28347 | – 1,1 | – 12,0 |
| 194 | 1173 | 28249 | – 1,5 | – 17,0 |
| 195 | 1178 | 28188 | – 0,9 | – 15,7 |
| 196 | 1185 | 28103 | – 0,7 | – 14,0 |
| 197 | 1193 | 28005 | – 0,4 | – 14,6 |
| 198 | 1203 | 27882 | 0,4 | – 12,1 |
| 199 | 1210 | 27797 | – 0,9 | – 16,4 |
| 200 | 1218 | 27699 | 0,0 | – 13,3 |

composition of various possible sources of water in this region was also measured for comparison with past values. Samples of fresh snow, river water and glacier melt-water close to the Goting section have $d^{18}$O values of – 13.5, – 13.0, and – 20.3‰ (mean of two samples), respectively. The $d^{13}$C values of the cements vary typically from – 3 to 1‰ (Figure 3 *b*). Variation in the case of carbon is smaller compared to that of oxygen. The depth variation of both $d^{18}$O and $d^{13}$C is characterized

**Table 2.**

| Sample | Depth (cm) | Age (Pant *et al*.[2]) | Calibrated age (Bard *et al*.[5]) |
|---|---|---|---|
| 9a | 79 | 36,000 ± 2880 | 42,048 ± 2880 |
| 55 | 455 | 38,410 ± 4130 | 44,863 ± 4130 |
| 9 | 519 | 32,760 ± 2370 | 38,264 ± 2370 |
| 135 | 852 | 20,420 ± 1710 | 23,851 ± 1710 |
| 169 | 1017 | 26,610 ± 2370 | 31,080 ± 2370 |
| 197 | 1193 | 24,230 ± 1550 | 28,301 ± 1550 |

by sharp oscillations numbering about 40 over the whole section. While there is a large variation in amplitude and duration of the oscillations, the average amplitude for $d^{18}$O oscillation is about 7‰ and that for $d^{13}$C is about 2‰. The average duration of oscillation is about 200 yrs.

## Discussion

The oxygen and carbon isotopic compositions of the carbonate phase in lake sediments are determined by composition of these isotopes in water and the temperature of precipitation. The sedimentary sequence of Goting represents a continental record corresponding to the glacial stage 3 (Oxygen Isotope Stage 3 is 60,000–25,000 [CAL] years ago) of the marine oxygen isotope record in the last glacial cycle. During this stage, carbonates were precipitated from the lake water along with the lake sediments (composed of detritals). These carbonates act as a firm binding material and allow preservation of dark and light lamination in the sedimentary column. Dark bands represent cold, non-turbulent conditions when the lake water constituents (bed load) are mainly fine particles, like clays along with organics. In contrast, light bands are mainly composed of slightly coarser particles free of organic matter, reflecting turbulent, high-discharge condition. The same is reflected in the isotopic composition. The proportion of carbonate in the dark bands is smaller (5–10%) compared to the light band (20–25%). We next describe the significance of the isotopic variations of carbonate in terms of climatic changes in this region.

### *Mean oxygen isotopic composition of lake water*

It is important to note that despite the large range in $d^{18}$O values (– 9 to – 22‰) majority of the values fall in a cluster and follow a Gaussian pattern with minor spread (~ 2.3‰). This allows calculation of a representative mean (– 14‰) and also to deduce a mean value for the pore-water composition which can be used to estimate the average composition of the precipitation during that period. To estimate the composition of water from the $d^{18}$O value of the carbonate, the temperature of precipitation of calcite at the lake bottom needs to be assessed. The Goting basin is located in the Himalayan region

where mean annual temperature is 13.5°C (from meteorological data (ref. 6) at Mukteswar, Kumaun). We assume this value as the mean temperature of water in the Goting lake and derive the fractionation factor $a$ between carbonate and water from the Friedman and O′ Neil[7] equation ($10^3 \ln a = 2.78*10^6/T^2 - 2.89$) as $a = 1.0314$. $a$ is related to $d^{18}O$ of calcite by: $a = (d^{18}O_{calcite} + 1000)/(d^{18}O_{water} + 1000)$. Using the mean $d^{18}O$ value of Goting carbonate (– 14‰ w.r.t. V-PDB or 16.4‰ w.r.t. V-SMOW), the estimated isotopic composition of pore-water ($d^{18}O_{water}$) is – 14.6 ± 2.3‰ w.r.t. V-SMOW.

The estimated composition of the lake water differs only slightly (0.9 and 1.6‰) from present-day snow and river water composition, whereas the difference is large for glacial melt-water (5.7‰). This suggests that the major source of water in the lake was rain or snow. The glaciers occurring at higher reaches (> 1000 ft above the Goting basin) receive snowfall with depleted isotopic composition because of their altitude. Since the Goting lake formed in a cooler period (Glacial Stage 3) the contribution from glacier melt was probably not significant.

### *Isotopic oscillations*

The isotopic depth profile contains approximately 40 oscillations with extreme values of $d^{18}O$ varying from – 9 to – 21‰. The alternate dark and light bands, denoting material deposited during cold and warm intervals caused such oscillations. This was validated by analysis of a few selected light bands showing depleted values compared to the dark bands. These oscillations took place typically over timescale of a few hundred years. To explain such large amplitude (about 7‰) oscillations, one needs to invoke either a change in temperature, amount of rainfall and enhanced supply of glacial melt water. Interestingly, in a region dominated by monsoon, all these factors are positively correlated while delivering the final isotopic composition in the water or resultant carbonate. An increase in land temperature tends to bring more rainfall and also increase the glacial melt-water supply. They also work in tandem in changing the carbonate isotopic ratio. For example, increase in temperature, glacial melt-water and rainfall all have the effect of depleting the heavy isotope, the temperature acting through the fractionation factor and the rainfall through the amount effect. Nevertheless, if we ascribe 7‰ variation solely to a temperature change, the estimated change in regional air temperature would be unacceptably large (about 28°C using 0.25‰/°C as the temperature coefficient of fractionation between precipitating calcite and water medium). However, a small temperature effect of 2–3‰ (for change in temperature of ~ 8–12°C based on CLIMAP estimates[8]) cannot be ruled out. The rest of the depletion is, therefore, associated with change in water composition which, in turn, is due to change in amount of rainfall or greater supply of glacial melt-water. IAEA data on rainfall and isotopic composition of mean monthly precipitation from a station in New Delhi yield an estimate of 0.34‰ decrease in $d^{18}O$ for 10 mm increase in mean monthly rainfall. If we assume this value as the representative coefficient for monsoonal rainfall, the amplitude of $d^{18}O$ variation (7‰) would give an estimate of 200 mm change in mean monthly rainfall. However, it is difficult to estimate the exact contribution of the above factors based on oxygen isotopic composition of carbonates. A comparative study was done by Thompson *et al.*[9], who observed oscillations of similar magnitude in an ice core record from the Tibetan Plateau (Guliya) and interpreted them in terms of variations in the strength of the southwest monsoon.

### *Periodicity of small oscillations*

Power spectrum analysis[10] of $d^{18}O$ values from the Goting section reveals the presence of periodicity of ~ 275, ~ 300, ~ 465, ~ 530, ~ 740 yrs (Figure 3 *c*), with strongest power in the 740 ± 20 yr period. Recently, two isotopic studies based on planktonic foraminifera from the Arabian Sea sediments[11] and South China Sea sediments[12] have shown the presence of periodicities of 700 and 775 yrs comparable to the present 740 yr cycle.

### *Source of dissolved inorganic carbon in the lake*

The carbon isotopic composition of the Goting carbonates is determined by contribution from two sources: $CO_2$ dissolved from the soil zone and dissolution of old marine carbonates (Tethys Himalayan sediments) in the river catchment. Production of $CO_2$ in the soil zone is mainly from decomposition of vegetative matters with average $d^{13}C$ values of – 27 and – 12.5‰ for $C_3$ and $C_4$ type plants, respectively[13]. Earlier studies on the carbon isotopic composition of organic matter in the Pleistocene sediments from Karewa region, Kashmir (~ 300 km northwest of Goting) showed that this region was dominated by $C_4$ type vegetation[14]. Since the soil $CO_2$ generated by plants is about 4.5‰ heavier than the plant biomass, the dissolved $CO_2$ would be characterized by $d^{13}C$ value of – 8‰ (ref. 13). In contrast, dissolved bicarbonates derived from dissolution of old marine carbonates have $d^{13}C$ values between – 2 and 1% (ref. 15). The mean $d^{13}C$ of – 0.8‰ for the Goting carbonate is consistent with its derivation dominantly from Himalayan carbonates. The negative excursions would then correspond to occasional increase in the soil-derived component.

The carbon and oxygen isotopic ratios of the Goting carbonates are strongly correlated (Figure 4) as often found in sediments of a closed basin[16]. The positive correlation (correlation coefficient of 0.8) indicates a common causal origin in their variations. For example, during warm

periods (extended summer) this area is expected to receive high rainfall (enhanced summer monsoon with lower $d^{18}O$ in rains) which would allow enhanced growth and decay of vegetative matter. As a result, there would be larger contribution of $CO_2$ from the soil zone to the aqueous medium, leading to depleted isotopic values of carbon. In contrast, during the low rainfall season, the biogenic source would be less important and the dominant contribution of carbon would be from marine carbonates occurring in the river channel. Such a scenario would lead to covariation of $d^{18}O$ and $d^{13}C$ values in the carbonate.

### *Long term climatic change between 28 to 42 ky BP*

As mentioned before the sampling resolution for the present study varied between 60 and 100 yrs and large-amplitude oscillations of $d^{18}O$ are observed over time-scales of a few centuries. The Goting record can be compared with a climatic record based on $^{18}O/^{16}O$ ratios in an ice core at Guliya on the Tibetan plateau[9]. However, since the Guliya record is of lower resolution, to compare the two records, the moving average of $d^{18}O$ values of successive 10 points (representing about 500 yrs) in the Goting record is calculated and a curve is drawn through these average values plotted against the average age (Figure 5 *a* and *b*). The resultant curve filters out high-frequency signals and brings out the longer term variations in $d^{18}O$ and $d^{13}C$ between 42 and 28 ky BP. These two curves show a systematic increasing trend (shown by a line in Figure 4 *a* and *b*), indicating about 1‰ increase in both $d^{18}O$ and $d^{13}C$ while going from 42 to 28 ky BP. This increase is consistent with the expectation, since while going from 42 to 28 ky BP one is approaching the Last Glacial Maximum (LGM) (~ 20 ky BP) and, therefore, towards a colder regime with consequent increase in $d^{18}O$ of precipitating carbonate in colder lake water. Figure 5 *a* also shows six epochs (around 40.2, 38.2, 36.2, 34.2, 32.7 and 29.4 ka) when $d^{18}O$ of carbonates decreased rapidly from the average trend. Each epoch is shown by an arrow in Figure 5 *a* and marks a minima in the $d^{18}O$ curve. Hatched regions in Figure 5 *a* demarcate the zones with lower than normal values (estimated from the trend line). These excursions are characterized by nearly symmetrical decrease and recovery of $d^{18}O$ values in all the epochs. These epochs probably represent short-duration events of increased rainfall caused by regional warming, with warmer intervals ranging from 1000 to 2000 yrs. It is of interest to compare these events with seven Dansgaard–Oeschger warming events during this time interval recorded in Greenland ice core, which occurred around 29, 30.2, 32, 34.8, 36.9, 37.8, and 39.5 ky BP (ref. 17). Adjusting for slight mismatch in timing, the number of events matches closely with the number obtained here and could have a common cause. As expected from correlation between oxygen and carbon isotope ratios, $d^{13}C$ values also become more negative during these intervals (Figure 5 *b*), signifying increased contribution of bio-

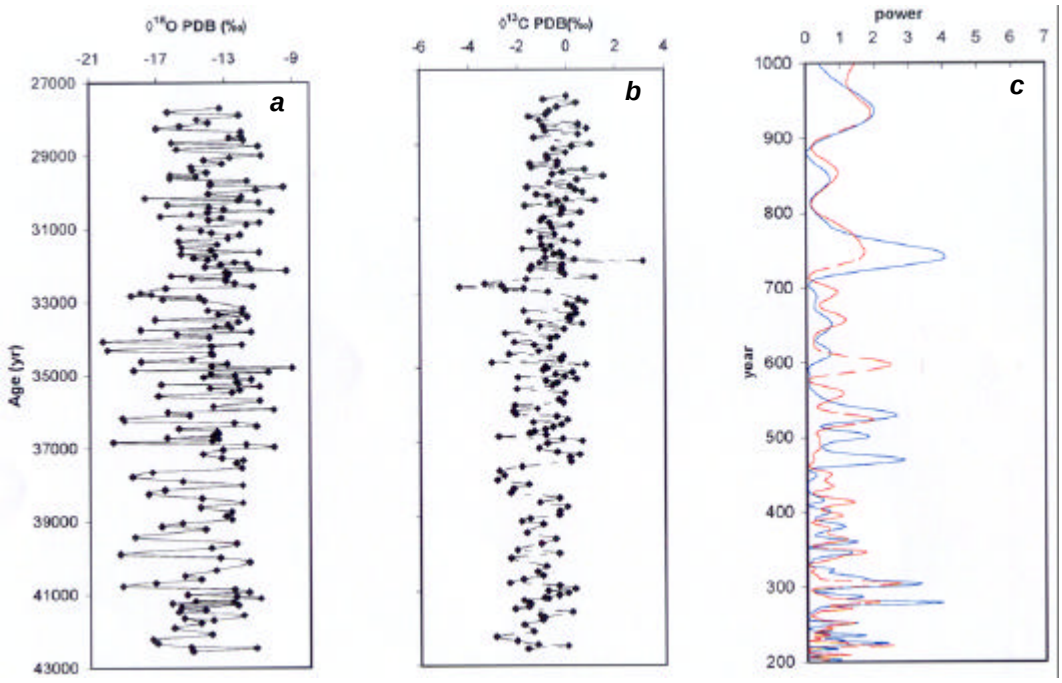


**Figure 3.** ***a***, Variation of oxygen isotope ratio in the carbonate cement (w.r.t. PDB); ***b***, Variation of carbon isotope in the carbonate cement (w.r.t. PDB). $d^{18}O$ values show large magnitude of variation compared to $d^{13}C$; ***c***, Power spectrum of the measured $d^{18}O$ and $d^{13}C$. Note six significant periodicities of which 740 year period has highest power.

genic $CO_2$ through increased rainfall, and marking intervals of major climatic amelioration. The magnitude of the excursions increases from older to younger epochs (from ~ 1 to 2‰), probably indicating increasing instability and associated variability as one approaches the LGM.

In Figure 5 *c*, existing oxygen isotope record between 42 and 28 ky BP from Guliya ice core is plotted for comparison. Broadly, the two patterns are not similar.

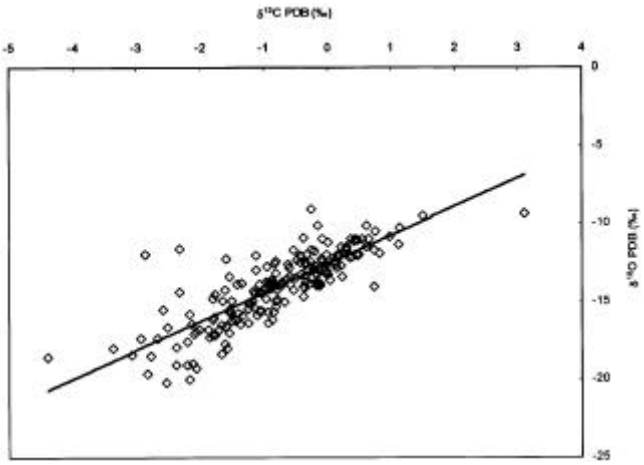


**Figure 4.** Covariation plot of oxygen and carbon isotopic ratios in micritic calcite cements of varve. Strong positive covariance ($g = 0.82$) is noted.

However, in the Guliya record the period between 42 to 34 ky BP contains three major epochs (40.7, 37.2 and 35.2 ka), when there is clustering of data points with depleted $d^{18}O$ values (encircled in Figure 5 *c*); and these have corresponding changes in the Goting record. These depletions probably denote periods when strong northeasterly wind brought moisture from continental sources or oceanic sources from long distances[9]. If these periods indicate short spells of intense cool intervals, we expect enriched $d^{18}O$ phases in corresponding periods in the Goting record, as indeed is the case (indicated by P1, P2 and P3 in Figure 5 *a*). However, limitation of resolution and time assignment in the Guliya core[9] does not allow finer comparison.

The period between 34 to 28 ky BP shows systematic drop in $d^{18}O$ values in the ice core samples (Figure 5 *c*). Such a drop probably indicates strengthening of NE monsoon carrying depleted moisture from long distances as one is approaching the LGM. The corresponding increase in $d^{18}O$ of the carbonates during this interval indicates a drop in temperature and is consistent with the above hypothesis. During the above period, two major epochs (34.2 and 32.8 ka) of negative $d^{18}O$ are observed in the Goting record. These epochs are absent in the Guliya record. We propose that these epochs indicate periods with abrupt increase in precipitation caused by enhanced SW monsoon. Such changes in precipitation would show

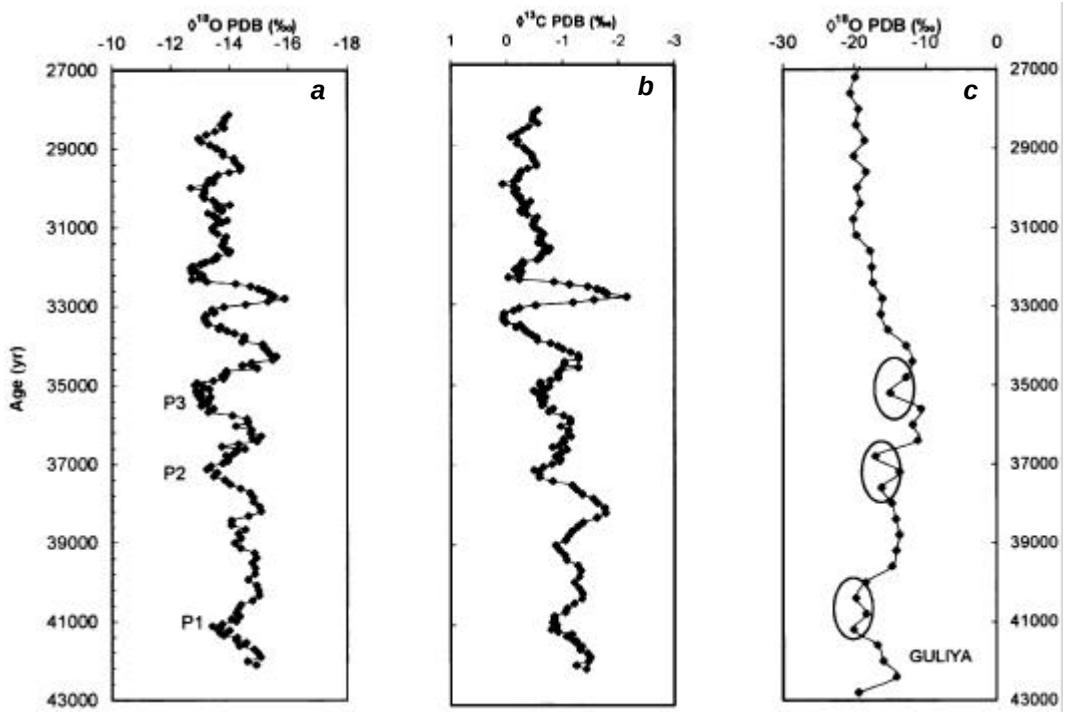


**Figure 5.** ***a***, Ten-points moving average curve based on 10 sequential oxygen isotope values of carbonate cements. Note overall trend of increase in $d^{18}O$ in the younger samples as one approaches the LGM; ***b***, Ten-points moving average curve based on 10 sequential carbon isotope values in the carbonate cements; ***c***, Proxy data from Guliya ice core record of Tibetan plateau (L. G. Thompson, pers. commun.) plotted for comparison. Note epochs of low $d^{18}O$ values denoted by P1, P2 and P3 signifying cold events in the contemporary lake record.

up in the Goting record, but not in Guliya which falls in a region controlled more by NE monsoon.

## Conclusions

Section of a varved, sedimentary column has been recently discovered[2] from a relict lake in Goting locality, Garhwal Himalaya, which contains marly carbonate (calcite) grains. These sediments were deposited during the interval 42 to 28 ky BP based on $^{14}C$ ages. Oxygen and carbon isotope ratios in the calcite were measured to understand the variation in the water composition of the lake and infer the causes of variation in terms of changes in climate during the stage 3 of the last glacial cycle. There is systematic increase in both the isotope ratios, indicating gradual cooling with time. The time variation of the isotope ratios shows short-term oscillations with periods of a few hundred years similar to the Dansgaard–Oeschger events in Greenland ice core records. Power spectrum analysis shows that a periodicity of $740 \pm 20$ yr has the strongest power. This is consistent with periodicity of 700 and 775 yrs based on foraminiferal isotope record from the Arabian Sea and South China Sea, respectively. The record also shows six epochs (40.2, 38.2, 36.2, 34.2, 32.7 and 29.4 ky BP) where sharp, negative shifts in $d^{18}O$ and $d^{13}C$ of carbonates were observed. These epochs indicate intervals of enhanced southwest monsoon associated with increased rainfall. In addition, there are three epochs (41.5, 37 and 35 ky BP) of short positive shifts in $d^{18}O$ values indicating weakening of southwest monsoon, which coincides with enhancement of northeast monsoon in this region based on an ice core record from Guliya.


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