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Climate instability during last glacial stage: Evidence from varve deposits at Goting, district Chamoli, Garhwal Himalaya, India

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The varve deposits at Goting, district Chamoli, Garhwal Himalaya have recorded climate history of the Last Glacial Stage (LGS). ¹⁴C chronology indicates that the deposition commenced around 40 ka BP and continued till the glacial maxima (about 20 ka). The magnetic susceptibility of the varve succession matches well with the lithological climate record. The varves are alternating dark and light grey bands of sub-millimeter scale separated by limonitic (pale yellow) bands and ice rafted dropstone debris. The mineral magnetic measurements show susceptibility enhancement corresponding to the limonitic beds. The enhancement of susceptibility has been attributed to accelerated weathering in the source area resulting from the temporary climatic shift from intense glacial cold to short-lived cool and wet periods. Such episodes were frequent during the LGS.

THE varve deposits at Goting (30°49'30" N; 79°49'E), District Chamoli, were first reported by Sastri and others¹ between Malari and the Niti pass and stand out distinctly as ash grey columns against the lush green U-shaped valley floor. These workers have identified two levels of moraines intercalated with varve deposits and therefore, an interglacial stage has been assigned to the varves. This view is supported by the pollen analysis carried out on two samples that show a predominance of

conifers over the pteridophytes and angiosperms, indicating a temperate climate comparable to horizon younger than the Middle Siwalik microflora¹. However, our findings are at variance with the conclusions arrived at by these workers.

Geologically, the Goting basin is delimited by two fault planes, both trending NW–SE². The southern fault line passes south of Goting along the Khal Kurans ridge, which is a subtle surface expression of the Tethyan Thrust that separates the Central Crystalline rocks from those of the Tethyan Group (Figures 1 and 2). Undifferentiated Pre-Cambrian gneisses and schists are exposed to the south of the thrust and towards the north these are juxtaposed against a succession of Maroli Group of rocks including rocks of Ralam and Garbyang formations of Cambrian age². The Khal Kurans ridge rises abruptly above the surroundings and forms the southern limit of the Goting basin. Further towards NW this fault has generated a series of fault scarps and has created numerous rockfall debris in the basin (Figure 1). This rock debris has mixed with the Quaternary clays and has been wrongly identified as moraines by the earlier workers¹. The Dhauliganga flows in N–S direction with a gentle gradient till Khal Kurans and cuts across it with a sharp bend in NW–SE direction following the fault line. The river has cut a 500 m deep gorge while emerging out of the basin at Khal Kurans (Figure 3). To the north of the basin, there exists a NW–SE trending fault in the Garbyang Formation marking the northern boundary of the basin.

Geomorphologically, the Goting is a north–south oriented basin with a narrow opening towards south through which the Dhauli drains out. The basin is bound by two ridges on either flank which form a crescentic rim (Khal Kurans ridge) towards south where it attains a general elevation of 3888 m. The valley floor has a gentle gradient (Figure 3) and has an average altitude of 3820 m but at the base of the Khal Kurans ridge it is 88 m deep. The western margin of the basin is very steep and abounds in extensive scree deposits (Figure 1). The Khal Kurans ridge acts as geomorphic barrier and has played an important role in controlling the advancement of the glacier. The narrow gorge of Dhauliganga was blocked by the moraines dumped against this barrier, forming a proglacial lake in which the varves were laid down. Erosion has left behind a single outcrop of varves in the valley. However, the periphery of the basin has a thick veneer of ash coloured clays, indicating the extension of the proglacial lake.

The precipitation regime in the Himalaya controls the spatial extent of the glaciers. In the Garhwal Himalaya, Nanda Devi massif acts as a geomorphic barrier and the precipitation regimes are different on its either side. The marked difference between the two areas is the density of ice or snow. The high density of lofty snow clad peaks along the Nanda Devi massif supports huge

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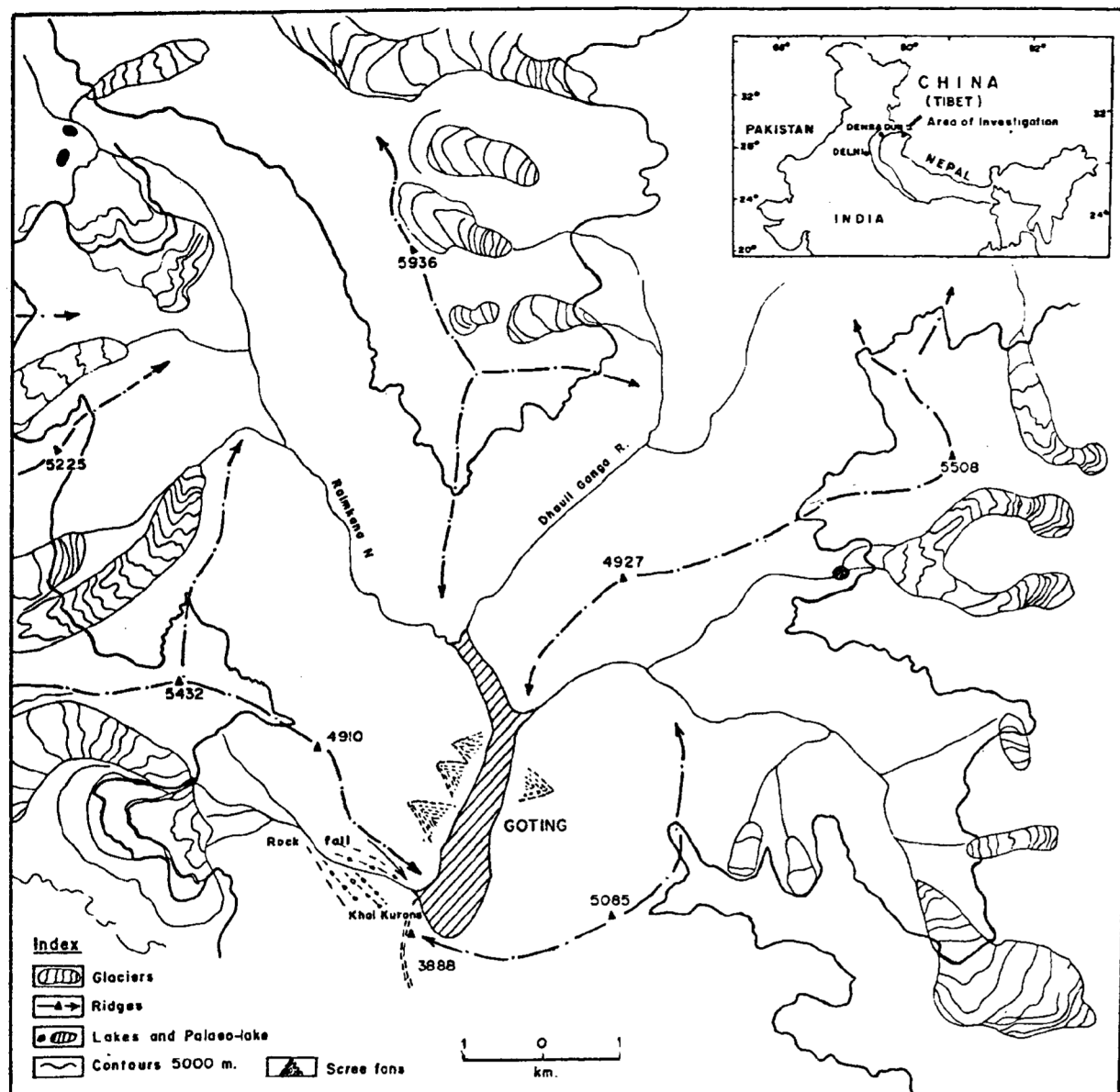


Figure 1. Geomorphological map of Goting basin.

glaciers which act as feeders to many glaciers. In contrast, there are mostly hanging cirque-type glaciers and few snow peaks (Figure 1) to the north of the massif and there are no glaciers on the northern side of the Indo-Tibetan water divide in this sector. The decrease of snow or ice from south to north is an indication of decreasing moisture and increasing aridity. This is also reflected in the behaviour of the snow-line in the two regions. While the equilibrium-line-altitude (ELA) of the glaciers to the south of the massif varies between 4700 m and 4500 m, ELA for most of the glaciers to its north are located around or above 5000 m altitude (Figure 1).

Figure 4 (not to scale) shows the Quaternary succession in the basin. The basal part of this stratigraphic

column is composed of ground moraines. Lateral moraines are absent in this part of the basin or are concealed under the talus debris and the clay drapes referred to above. However, lateral moraines could be traced all along the hanging cirque-type glaciers on either flank of the basin down to the confluence of Dhauli and Raimkane which forms the northern end of the palaeo-lake as was evidenced by the occurrence of varved clays in contact with the moraines. The moraines are overlain by a thick varve succession. These varves are in turn overlain by a 8 to 10 m thick fluvial gravel that constitutes the topmost lithofacies in the basin.

Ground moraines appear at the base of the massive columns of undisturbed varves and show distinct

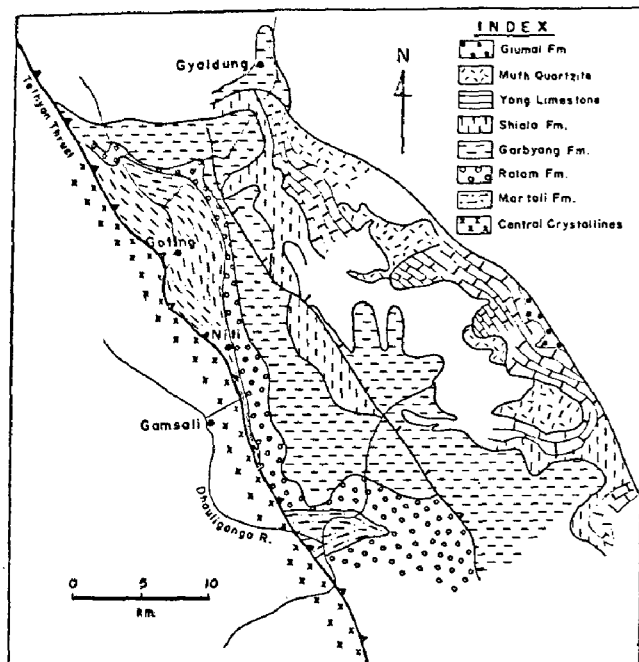


Figure 2. Geological map of the area around Goting.

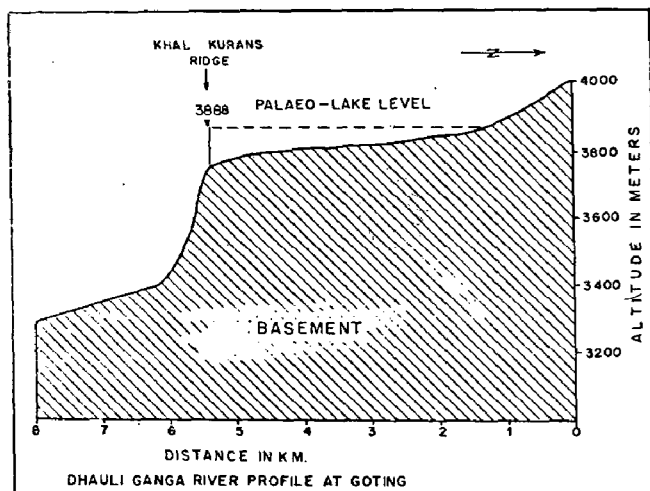


Figure 3. Profile of Dhauliganga in Goting basin.

subglacial features of a lodgment till incorporating huge boulders with smoothened convex tops having grooves and striations showing N-S orientation. At places the lodged diamicts also show shear surfaces. In general the moraines are deformed and contain undifferentiated diamicts. These have, therefore, been described as ground moraines (Figure 4). However, the lodged and other forms of diamicts definitely suggest that the glacier must have extended up to the Khal Kurans ridge which formed a natural barrier. In addition, there are huge deposits of push or end moraines seen on either

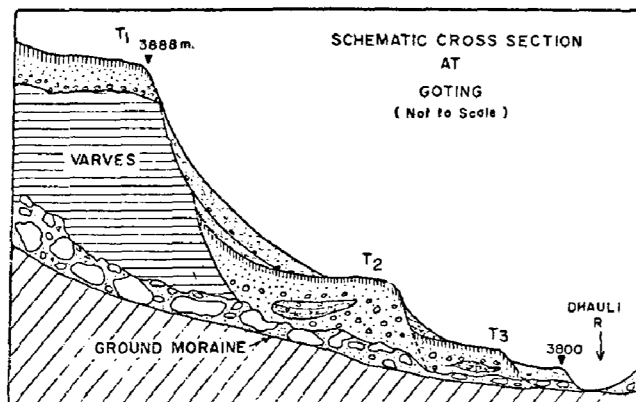


Figure 4. T₁, T₂ and T₃ terraces post dating during the varve deposit capped by fluvial gravel.

side of the Dhauliganga gorge covering the base of the ridge and riding over it. It, therefore, suggests that the narrow opening of the Dhauliganga was blocked by the end moraines aided by the natural rampart formed by the Khal Kurans ridge. It appears that lacustrine conditions prevailed after the partial recession of the ice cover to the confluence of Dhauli and Raimkana considering the position of the lateral moraines as discussed above. The Goting lake thus formed was fed by the sediment-laden glacial melt water resulting into accumulation of thick pile of varved clays.

Remnants of the varve deposits extend up to 20 m in thickness (Figure 5). The exposed parts of these columns show alternating bundles of internally laminated ash gray, and fine silty limonitic horizons appearing regularly at 5–8 cm intervals. A single varve consists of millimeter to sub-millimeter scale couplet of a dark and a light-coloured laminae composed exclusively of fine silt and clay and completely devoid of sand and coarse silt. At most of the places, laminae have fused together as a thick bed of clay and it is difficult to recognize their true character in the hand specimen. However, the separation between the individual varves is very distinct under microscope and SEM.

Normally, varves are laid horizontally (Figure 5a) but at places the beds show distortions or convolution that appear at various intervals in the succession (Figure 5b). The laminae are never horizontal as in the case of typical varves. Slump structures are common. At places these form loops and at others have lenticular forms. Distorted wave patterns with plunging basal laminae are other common features. In general, the patterns appear as contorted mosaic of dark and gray varve sediments. Three possible processes can be considered for these deformations. Firstly, such features are found in periglacial soft sediments due to cryoturbation caused by freezing and thawing and frost heaving in permafrost regions³. We are not aware of such features developing

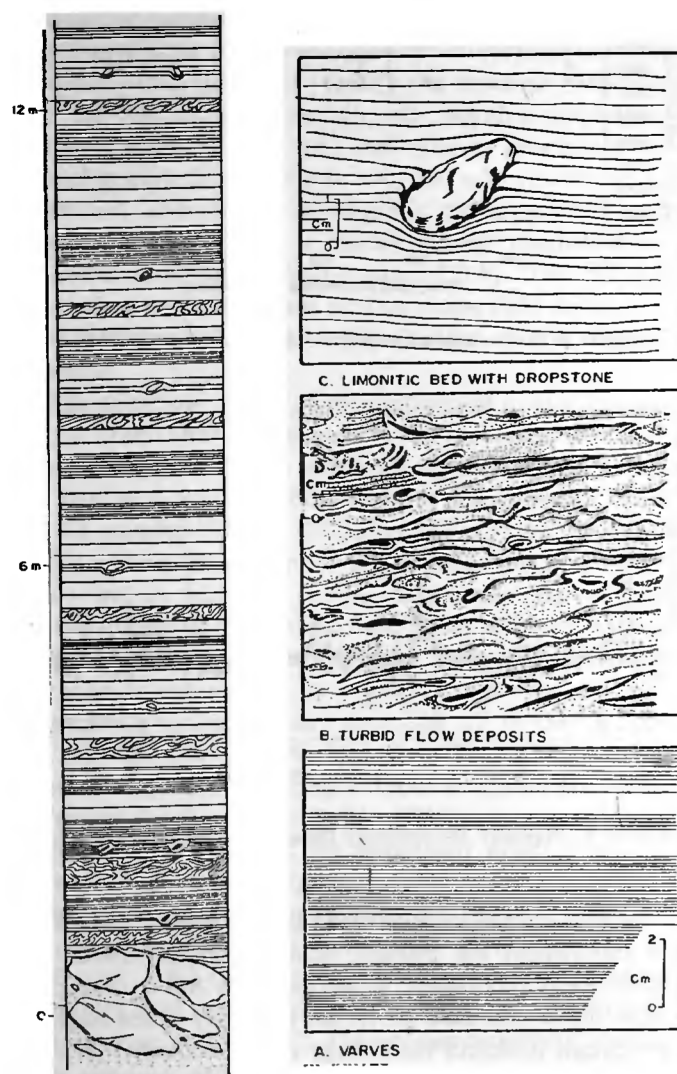


Figure 5. Schematic varve succession at Goting. A, Planar varves; B, Turbidites; C, Ice rafted dropstone within limonitic varves.

in proglacial lake environments in the study area. However, there is ample evidence from glaciated regions in Himalaya to demonstrate similar features develop in the ice-contact deposits⁴. It should be pointed out that the above mentioned features develop under cold sub-aerial environment whereas the deposits discussed here were laid under lacustrine environment. Secondly, highly contorted varves showing gravity-induced penecontemporaneous deformed horizons and such load casts as ball and pillow structures and highly flexed recumbent folded structures reported from Kleszczow graben in central Poland have been ascribed to earthquakes resulting from graben tectonic activity⁵. At Goting these do not conform to those developed by cryoturbation or tectonics.

The most prominent mechanism for the formation of such deformations lies in the very processes of sedimentation in the proglacial lake fed by sediment-laden tur-

bidity currents which is considered as the most important mechanism for varve deposition^{6,7}. A pronounced thermocline gradient within a proglacial lake produces three major types of currents, viz. heavy density turbidity currents, interflows and low density overflows. A heavy density flow occurs during glacial summers through a cold inlet stream. Suspended sediment load further contributes to the density differences. During winters, sediment deposition takes place by settling of suspended particles and it is not influenced by overflows. During glacial winters the lake freezes and the ice cover shuts off any contact with the atmosphere. Dissolved oxygen is slowly depleted and at the same time the concentration of CO₂ gradually increases. The fine particles still suspended in the water column from the previous summer's turbidity current deposits slowly as vertical fallout. The winter layer is usually dark coloured and lacks laminae. The turbidity deposits are essentially a summer deposition in the proglacial lake which have the same sedimentary structure as those of distorted varve deposits at Goting. We are, therefore, inclined to interpret these bed-form differences representing two microenvironments existing during the glacial period when the Goting proglacial lake was formed. The possibility of these convolutions being seismites is ruled out by the absence of coarser material (sand and coarse silt).

In addition to the bed-form described above, there are approximately 3 cm thick limonitic bands appearing invariably overlying the turbidity deposits at almost regular intervals. Presence of finely-powdered hydrated iron oxide in these bands impart pale yellow colouration which is characteristic of goethite, lepidocrocite, hematite, etc. The grain size of these bands that occur in rhythmic fashion is relatively coarser than the underlying ash grey layers. The coarsening of the grain size along with the iron oxide staining indicate that these were laid down in a climate that was relatively warmer compared to the varve sedimentation. Presence of the iron oxide in the lake sediments can be used as an indicator of weathering in the source area specially if the oxides are goethite, magnetite or hematite. These bands are invariably associated with dropstones either appearing at the base or on the top of the individual bands (Figure 5 c). Their association with dropstones suggests a diamictic lithology produced by the ice rafting and suspension deposition on the basin floor^{8,9}. The dropstones at Goting range in size between 1 cm and 3 cm along their longer axis and are mostly subrounded to subangular placed inclined to the bedding. At the contact point the beds show downward bending and compression of the laminae. The overlying laminae curves following the pebble surface contour and thereafter the usual planar bedding pattern is followed. The limonitic bands in association with dropstones suggest that the lake was in existence when the limonitic beds were forming. Fur-

thermore, the situation calls for breaking of ice front which would require slight rise in the surrounding temperature. Since varves do not show any compositional and structural change, it is likely that conditions remained essentially glacial but were less severe.

The important aspect of these deposits is their cyclicity. The change takes place apparently at almost regular intervals. The general succession commences with planar deposits – the varves proper, followed by limonitic bands with dropstones. However, turbidity structures are not present all through the column. These deposits underlie limonitic beds wherever present. However, it will not be possible to demonstrate whether there has been any trend towards climatic amelioration leading to the deposition of interglacial fluvial gravel occurring at the top of the Khal Kurans ridge as the top of the varve deposit is truncated.

Only 13 m out of ~20 m could be sampled for various laboratory analyses. The top part of the exposure has to be left out as it was inaccessible and highly weathered. However, the total thickness of the deposits may have exceeded 60 m considering the depth of the basin and the occurrence of topmost level of varve patches fringing the basin (Figure 3). The varves are capped by the gravels indicating a major shift in the climate representing a very high energy fluvial regime comparable with interglacial conditions. The Goting lake breached after the interglacial gravel was laid. Thereafter, two more paired fluvial terraces developed along the Dhauliganga (Figure 4). The geotectonic setting of the Goting basin makes it an ideal candidate to record the paleoseismic events. However, no such evidence has been found in the varve deposits. We thus attribute breaching of the lake to a climatogenic event rather than tectonics.

Radiocarbon technique has been used to determine the chronology (Figure 6). All samples were treated with 5% HCl to remove calcium carbonate in the sediments. Further, these were dried and the organic fractions have been dated by preparing benzene and counting in the 'Quantulus' spectrometer. The carbon content of these samples varies from 0.048% to 0.29% (wt./wt.).

Out of the six ages obtained in a section measuring 12 m, two ages have been found to deviate from the linear trend. These ages correspond to 79 and 852 cm respectively. It is difficult at this stage to ascertain these age inversions. One explanation could be the rates of change in the ^{14}C production during the past. A linear regression has been plotted along the ages in order to interpolate the ages in the profile and to calculate the average sedimentation rate. The results show that the Goting varve deposits date back to 40 ka BP and the deposition continued till 20 ka BP. The average annual estimated rate of sedimentation comes out to be around 0.7 mm.

Therefore, the remnants of the varve deposits span the last glacial stage (LGS) till the glacial maxima around 20 ka BP.

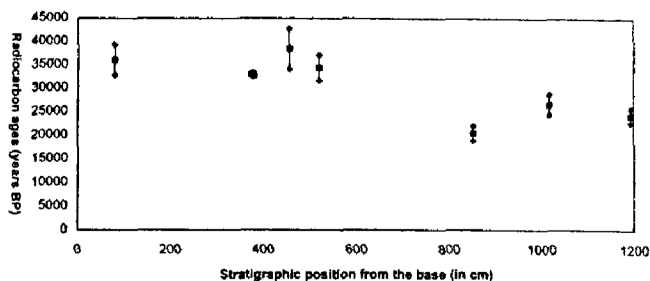


Figure 6. Radiocarbon ages of the varve succession at Goting.

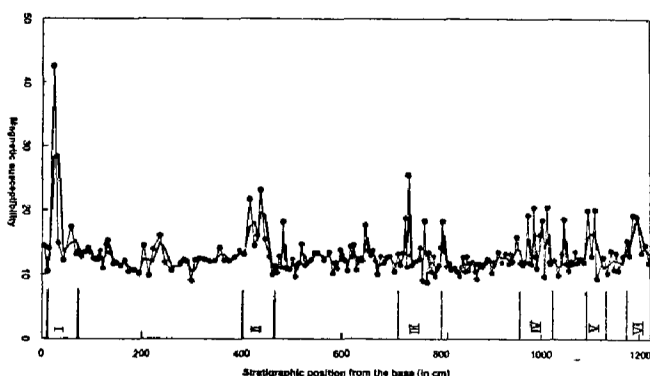


Figure 7. Magnetic susceptibility through the varve succession at Goting.

Magnetic susceptibility (MS) studies were undertaken to supplement the climatic scenario as evidenced in lithological succession. A Bartington's MS-2 susceptibility meter was used which has a sharply tuned oscillator circuit to detect the change in the frequency of AC waveform resulting after the insertion of sample into the field. The change in the AC frequency is directly proportional to the MS of sample. A peak alternating strength of 3×10^4 Tesla is applied in the discriminator oscillator circuit with a provision for low (0.465 kHz) and high (5.65 kHz) frequency. The coefficient of frequency dependence (cfd), which is sensitive to the magnetic grainsize¹⁰, was calculated for each sample. Figure 7 shows the MS through the varve column at Goting. It is noted that marked susceptibility enhancement takes place corresponding to the limonitic bands. This apparently shows that during the deposition of the limonitic bands the catchment area of the proglacial lake was witnessing relatively warmer climate conducive for the *in situ* weathering of the sediments. This is further corroborated by the presence of relatively coarse grains in the limonitic bands suggesting enhanced glacial melt. The catchment area is dominated by Tethyan sedimentaries. Thus it is likely that the antiferromagnetic haematite is getting weathered to ferromagnetic goethite during the pedogenesis which is subsequently being transported into the lake at rhythmic intervals.

Selected samples from major peaks and drops in susceptibility were further analysed for isothermal remnant magnetization (IRM) to identify the minerals responsible for the variation in MS. An impulse magnetizer (model: IM10, ASC, USA) was used to generate short duration high field pulse at 100–200 mT window up to 2500 mT. The change in magnetic moments after each step was measured on a digital spinner magnetometer (DSM-2, Schonstedt Instruments, USA). The demagnetization was carried out on alternating field demagnetizer (Molspin-AFD) up to 800 Oersted of 100 Oersted window.

The minimum values of χ_{IR} correspond to major peaks in χ_{IR} . When IRM is imparted to the representative samples, none of it ideally saturated even after application of maximum available field of 2500 mT. However, most of the samples (barring GS-53; at 436 cm from the base) show a steep gradient near 300 mT. Ferrimagnetic minerals such as magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) fully saturate in the applied field of the order of 300 mT (ref. 11). It therefore indicates that magnetite and maghemite are present in negligible quantity. A small depression further appears near 500 mT in GS-38, GS-97 and GS-140 (at 299, 672 and 871 cm respectively from the base). Interestingly, these samples correspond to major drops in the MS. The IRM was repeated over these samples to check the anisotropy effect if any. It however, showed negligible anisotropy indicating paramagnetic and diamagnetic minerals. However, samples at major peaks in susceptibility (GS-53 and GS-168; at 436 and 1012 cm respectively from the base) show identical IRM peaks with increase near 1500 mT and do not saturate at 2500 mT. The antiferromagnetic haematite (Fe_2O_3) and ferromagnetic goethite ($\alpha\text{-FeOOH}$) typically require the field in excess of 2500 mT for saturation to occur¹¹. Thus the enhancement in susceptibility is attributed to the varying proportion of haematite and goethite in the limonitic bands which in turn indicate the temporary shift in the climate.

The varve deposition in the Goting proglacial lake commenced around 40 ka B.P. and represents last glacial stage (LGS). This is further evidenced by their association with terminal moraines. The deposits show two distinct environments as indicated by the varve sequence and the limonitic bands. The inferred lithological climate suggests that the horizontal or planar varve laminations represent cold conditions typical of glacial climate. Whereas the cyclic appearance of the limonitic bands in association with the dropstones suggest mild climatic oscillations during their deposition. This inference finds support in the MS measurements through the varve succession. The limonitic bands show that the χ increases with the limonitic bands whereas the varve

laminae have been found to be poor in the ferrimagnetic minerals. It has been observed that haematite transforms to goethite under cool and humid climate¹². IRM on the selected limonitic samples confirm that the colouration to the beds has been imparted by the presence of goethite.

MS shows six major peaks appearing around 39, 33, 29, 26, 24 and 23 ka B.P. It will be noted that the first three susceptibility enhancement peaks appear at regular intervals of approximately 5000 years and the remaining three peaks at an interval of 1200 years respectively. Climatic significance of this pattern is hard to establish. However, it does suggest that climatic oscillations became frequent towards the glacial maxima with the amplitude progressively decreasing excepting that of last peak. The pattern, in general, may suggest climatic deterioration towards the last glacial maxima (LGM) with a short interlude of amelioration around 23 ka B.P. This event compares well with similar event recorded at the Tso Kar lake deposit dated to 21 ka B.P. (ref. 13) and that of Dunde ice core¹⁴ around the same time.

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