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Snow line depression over Tibet during last Ice Age

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The Tibetan plateau has received considerable attention in recent years for its role in influencing the regional and global climatic changes during the last Ice Age. However, debate persists on the thickness and areal extent of the ice cover for which estimates of the past positions of the snowline are required. Based on qualitative interpretation of geological deposits, varying estimates (200–1500 m) of the snowline depression during the last Ice Age have been proposed. We estimate this parameter to be in the range 700–850 m (maximum 1000–1170 m) from the translation of $\delta^{18}\text{O}$ data to temperature lowering on the Dunde ice cap in Tibet. Such a lowering of the regional snow line would have resulted in an extensive but marginally thick ice sheet sensitive to small regional temperature fluctuations as revealed by the isotope record of the Dunde ice cores and the palaeovegetation record of Tsokar lake in Ladakh. In this study, we have not considered the effect of possible precipitation reduction, which is likely to further reduce estimates of snow line depression.

THE Tibetan plateau, with an area of nearly $2 \times 10^6 \text{ km}^2$ at an average altitude of over 5000 m above sea level, exerts significant control on the Asian monsoon circulation pattern^{1–5}. During the last Ice Age, also known as the last glacial stage (LGS), summer monsoon circulation is supposed to have been weak or absent^{3, 6, 7} and the climate of Tibet was probably drier than today. Considerable debate persists as to whether the plateau was covered by an extensive^{8–10} or a marginal^{11–14} ice sheet. Estimates of the thickness and

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the extent of glaciation in Tibet during LGS are important because of its possible implications in palaeoclimatic modelling involving presence or absence of snow cover over Tibet as an important boundary condition.

A kilometre thick and extensive ice sheet as envisaged by Kuhle *et al.*⁸ would amount to an additional ice volume of about $3 \times 10^6 \text{ km}^3$ at the last glacial maximum (LGM), about 18 kyr ago. This would correspond to an equivalent global sea level change of approximately 7–8 m. The contribution of such an ice sheet to the $\delta^{18}\text{O}$ of the ocean water can be larger than suggested just by the hypothesized volume of this ice sheet due to introduction of nonlinearity between the $\delta^{18}\text{O}$ and the global ice volume¹⁵. This effect arises due to the fact that the ice sheet on Tibetan plateau would grow mainly by increase in the ice thickness, thus raising the altitude of precipitation. This would induce a strong change in the mean $\delta^{18}\text{O}$ of the ice during ice sheet build-up (the altitude effect). A relatively thin ice cover over Tibet would not significantly alter the estimate of global ice volume and the oceanic $\delta^{18}\text{O}$ record.

The difference between a thick versus thin ice sheet may also manifest in its response to a small warming event. In the case of a thick ($\sim 1 \text{ km}$) ice sheet over Tibet, a small warming event would not be able to lower the snowline (or the equilibrium line altitude, ELA) below the top of the ice surface and may therefore not result in significant melting of the ice mass. In contrast, small temperature-induced movements of ELA would sensitively affect the melting of a thin ($\sim 200 \text{ m}$) Tibetan ice sheet.

Kuhle has repeatedly argued^{8–10} that a large ice sheet existed on the Tibetan plateau during the late

Quaternary. His views conflict strongly with those of some glacial geologists¹¹⁻¹⁴. Kuhle's conclusions on the extent of an ice sheet on the Tibetan plateau are based mainly on his observations and interpretation of sediments, sedimentary sequences and landforms at several locations on the northern, southern, and western margins of the plateau. According to him, the ELA in the plateau region was depressed by 1100–1500 m during the last Ice Age⁸ and thus up to 600 m below the mean height (range 4000–5200 m) of the Tibetan plateau. Zheng¹², on the other hand, has suggested that the deposits regarded by Kuhle and coworkers as moraines and used to reconstruct very low palaeosnow-lines and extensive former ice cover are actually debris flow and related mass movement deposits. According to Zheng, true moraines are restricted in extent on the plateau and indicate that an extensive ice sheet did not develop there during the Late Quaternary period. Based on a study of terminal moraines in the Rongbuk valley, Mt. Everest region (elevation 5,000–5,500 m), Burbank and Cheng¹⁴ have concluded that the ELA depression was 350–450 m during the late Pleistocene. Yu *et al.*¹³ also did not find any evidence in the sedimentary record of the Qinghai lake (Tibet) for an extensive ice sheet during the last *ca.* 40 kyr.

Thompson *et al.*^{16,17} measured dust content, soluble aerosol concentration, oxygen isotopic ratio and ice crystal size on three long ice cores from the Dunde ice cap (37°06'N, 96°24'E; 5325 m elevation) in the northern part of the Tibetan plateau. The measurements provided a climatic record of more than 40 kyr. The chronological estimates of the Dunde ice cores are based on counting the annual $\delta^{18}\text{O}$ and dust peaks up to 117 m depth where the ice was deposited 4550 years ago. An empirical power law relationship between the ice-layer thickness at a given depth, the accumulation rate and the depth of the ice layer was seen to fit to the upper (0–117 m; 4550 yr) section. Below the 117 m depth, the empirical relationship was extrapolated by assigning the prominent stratigraphic transition at 129.2 m with significant increase in microparticle concentration and decrease in $\delta^{18}\text{O}$, to the LGS/Holocene transition (10,750 yr) as in the Camp Century core from northern Greenland¹⁸. The chronology so obtained can only be a rough estimate which must be kept in mind. In spite of the uncertainty in chronology, Thompson *et al.*¹⁶ have reconstructed discrete 1000-yr averages of dust concentrations, $\delta^{18}\text{O}$ depletion (temperature proxy), NO_3^- , SO_4^{2-} and Cl^- concentrations for the last 40 kyr. Since their sampling interval was 3 cm, each 1000-yr average was apparently obtained from a minimum of 2–3 samples even at the oldest part of the profile (39–40 kyr), progressively increasing to 7–8 samples in the 10–12 kyr period.

Some of the salient results of the study of Thompson *et al.*^{16,17} relevant to this discussion are:

(i) The increase in dust and decrease in $\delta^{18}\text{O}$ are inversely correlated and the average $\delta^{18}\text{O}$ of the LGS ice is 2‰ (maximum 3‰ lower than the average of the Holocene ice).

(ii) The $\delta^{18}\text{O}$ record (Figure 1a; redrawn from Figure 4 of ref. 16) reveals a short interval of warming, peaking at about 32 kyr ago, associated with reduced dust deposition and increased concentration of anions.

In addition, we also note from Figure 1a, a less pronounced warming event peaking at about 20 kyr, indicated by less negative $\delta^{18}\text{O}$. Figure 4 of Thompson *et al.*¹⁶ also shows decreased dust deposition and increased anion concentrations at about 20 kyr ago. It is interesting to note that the two warming events at 32 and 20 kyr have also been observed in the palynological record (Figure 1b; redrawn from Figure 3 of ref. 19) from the alpine Tsokar lake, (33°21'N, 78°0'E; 4572 m elevation) on the western margin of the Tibetan plateau. This study revealed continuation of the alpine steppe with periods of expansion of *Juniperus* communities during 28–30 kyr BP and 21–18 kyr BP. Another warming event inferred from the pollen profile at 10,000 yr BP is obviously related to the LGS–Holocene transition seen in the Dunde ice core at 10,750 yr BP. Similarly, another warming event reported from the pollen profile of Tsokar lake slightly before 15,800 yr BP may be related to a contemporary warming event discernible, though not very prominently, in the ice core data. The concordance between the $\delta^{18}\text{O}$ data and the

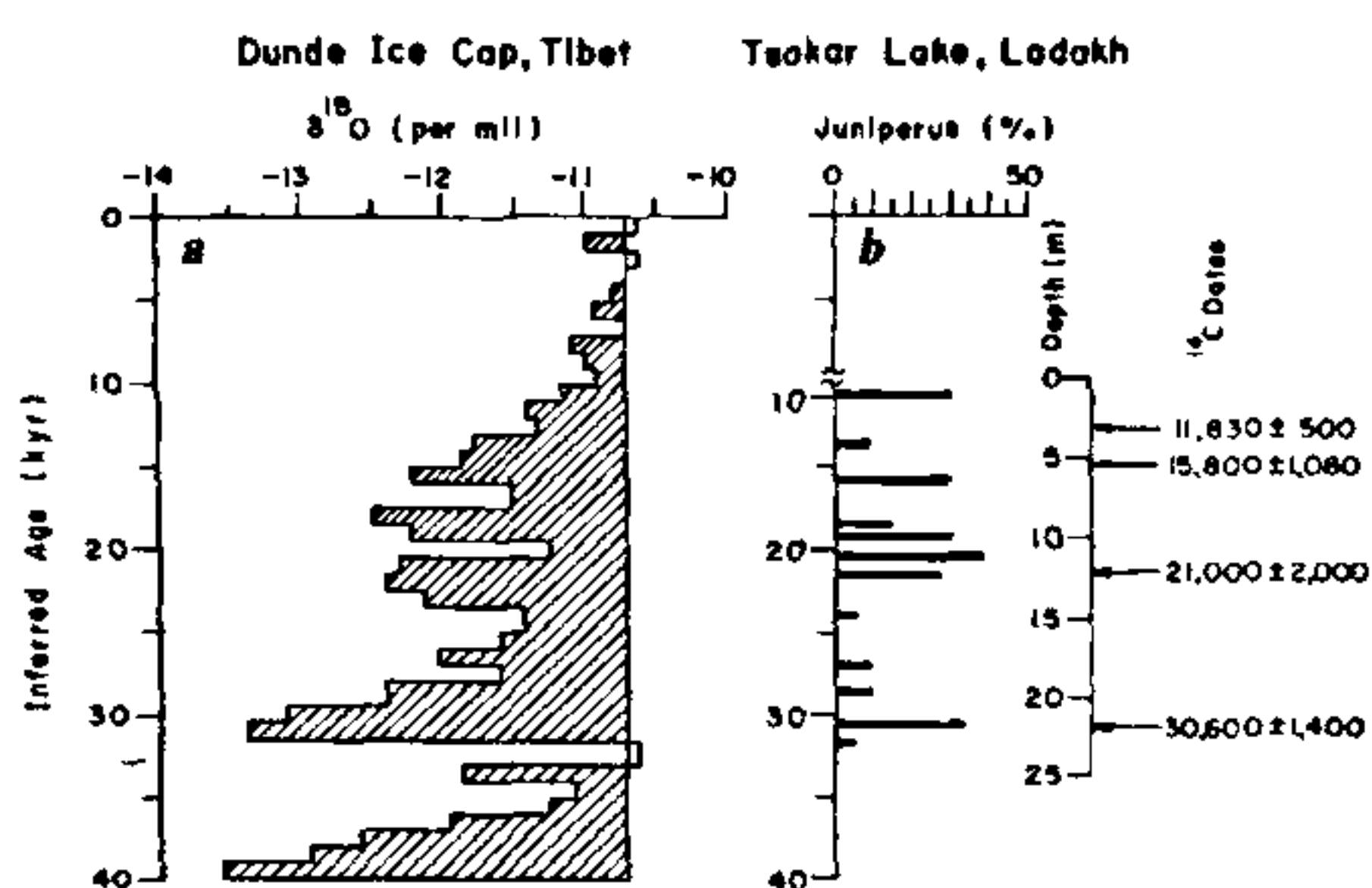


Figure 1. a, $\delta^{18}\text{O}$ profile of the Dunde ice cap of Tibet. Redrawn from Figure 4 of Thompson *et al.*¹⁶; b, *Juniperus* abundance profile from the Tsokar lake, Ladakh. Redrawn from Figure 3 of Bhattacharyya¹⁹. Note increased abundance of *Juniperus* pollen (indicative of warming) in Ladakh at 30–28, 21–18, 16–15 and at 10 kyr ago has corresponding (within limits of dating accuracy of the two profiles) increase in $\delta^{18}\text{O}$ in the Dunde ice cores. The chronological estimates of the Dunde ice cores are based on counting of annual $\delta^{18}\text{O}$ and dust peaks up to 4,550 yrs. The age of deeper ice was estimated by fitting an empirical power law relationship between ice layer thickness, depth and accumulation rate. Chronology of pollen profile from Tsokar lake is based on four radiocarbon dates marked on the Figure 1b.

palynological data from the widely separated areas of the Tibetan plateau suggests that the Dunde ice core record may be treated as representative of the entire region of Tibet.

The $\delta^{18}\text{O}$ isotope shifts observed in the Dunde ice core can be used to estimate past changes in surface air temperature. Quantitative estimation of this temperature change is, however, complicated because the isotopic composition of precipitation is governed not only by its temperature of formation but also depends on origin and history of the air masses, and on condensation processes involved. The mean $\delta^{18}\text{O}$ content of the modern precipitation has been shown²⁰ to decrease with mean annual surface air temperature (T) over a wide temperature range from -50° to $+10^\circ\text{C}$ for stations extending from the North Atlantic coast to Greenland and Antarctica in the following manner:

$$\frac{d(\delta^{18}\text{O})}{dT} \cong 0.7\text{‰}^\circ\text{C}^{-1}. \quad (1)$$

This empirical relationship does not include any station from or in the vicinity of the Tibetan plateau. We, however, derive support from the fact that even though modern Antarctic and Greenland precipitation forms under vastly different climatic conditions, $\delta^{18}\text{O}$ - T relationship has been found to be linear with slope in the range 0.67 – $0.75\text{‰}^\circ\text{C}^{-1}$ and has been used to estimate change of temperature during glacial periods both in Antarctica and Greenland^{21,22}. Further, a simple one-dimensional isotopic model²³ suggests that there is a linear relationship (gradient 1.1 – $1.2\text{‰}^\circ\text{C}^{-1}$) between the $\delta^{18}\text{O}$ of precipitation and the temperature of formation (T_F) prevailing just above the inversion layer. In the East Antarctic the $\delta^{18}\text{O}$ - T_F gradient of $1.12\text{‰}^\circ\text{C}^{-1}$ has been established from experimental data²³. Since there is a linear relationship ($dT_F/dT = 0.67$) between T_F and, the surface air temperature^{22,24} on an annual basis, a theoretical value of 0.74 – $0.80\text{‰}^\circ\text{C}^{-1}$ is thus inferred for $d\delta^{18}\text{O}/dT$.

The average 2‰ (maximum 3‰) decrease in $\delta^{18}\text{O}$ of the LGS ice (Figure 1a) must first be corrected for the increase (1.6‰) in the $\delta^{18}\text{O}$ content of oceanic waters during the LGM²⁵ to account for change in the isotopic composition of ocean. This makes the average decrease during LGS at Dunde ice cap as 3.6‰ (maximum 4.6‰). Using Equation 1, this $\delta^{18}\text{O}$ change translates to an average temperature decrease of about 5°C (max. 7°C). Now assuming the observed lapse rate of 0.6° to $0.7^\circ\text{C}/100\text{ m}$ from the sub-tropical and arid Karakoram area of Tibet¹⁰ to be valid for the Ice Age conditions as well, the 5° – 7°C decrease in the annual surface air temperature during LGS as noted above, translates to an ELA lowering in the range of 700 – 850 m (max. 1000 – 1170 m).

The above estimates do not consider the opposing

effect on ELA of the reduced precipitation due to weaker SW monsoon^{26,27} during the Ice Age raising the height of ELA. In European Alps, for example, a 300 mm/yr decrease in precipitation is accompanied by a 100 m rise in the position of ELA^{28,29}. In the relatively arid atmosphere of Tibet this effect is expected to be considerably accentuated possibly through a reduction in lapse rate becoming closer to the dry adiabatic lapse rate of $1^\circ\text{C}/100\text{ m}$. Therefore our estimate of 700 – 850 m for Ice Age ELA reduction may be an upper limit.

This lowering of ELA during the LGS is smaller than that estimated by Kuhle *et al.*⁸ but the estimated temperature reduction of 5° – 7°C is of the same order as that obtained from the average snowline depression of 900 – 950 m estimated by Rind and Peteet³⁰ for tropical and sub-tropical glaciers. In this respect, the isotopic data from the Dunde ice cap confirm the conclusion of Broecker and Denton³¹ that during the glacial period there was high mountain temperature lowering of nearly equal magnitude in both hemispheres in the lower and middle latitudes.

In summary, we note that the climatic records of the past 40 kyr from the northern (Dunde ice cap) and western (Tsokar lake, Ladakh) flanks of Tibet, even though based on different types of proxy signals, are consistent with each other. This consistency of the two proxy records suggests that the $\delta^{18}\text{O}$ record of the Dunde ice cap can be assumed to represent climatic variations over the Tibetan plateau region. The 2 – 3‰ decrease in $\delta^{18}\text{O}$ of the precipitation during LGS when adjusted for 1.6‰ increase in the ocean water $\delta^{18}\text{O}$ during glacial period indicates a 5° – 7°C decrease in the annual surface air temperature over Tibet. This combined with the prevailing atmospheric lapse rate of 0.6° – $0.7^\circ\text{C}/100\text{ m}$ suggests a possible lowering of ELA over Tibet in the range of 700 – 850 m (max. 1000 – 1170 m) during the glacial period. This would result in a fairly extensive but thin ice sheet over the plateau that would be sensitive to small, short-duration ($\sim 1000\text{ yr}$) regional temperature fluctuations. Our estimate of glacial age ELA lowering over Tibet may have to be considerably reduced if precipitation reduction and the resulting change in the lapse rate during the glacial age could be guesstimated.

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Fossil Charophyta from the Deccan intertrappean beds of Gurmatkal, Gulbarga District, Karnataka

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A taxonomically diverse charophyte assemblage (10 species, 8 genera) has been recovered from the Deccan intertrappean sequences around Gurmatkal, northern Karnataka. Most of the taxa are recorded for the first time and suggest, in conjunction with associated ostracodes, that these peripheral outcrops lying on the southeastern margin of the Deccan volcanic province were deposited close to the Cretaceous-Tertiary transition (Maastrichtian-? earliest Palaeocene). The long held Upper Eocene-Oligocene assignment for the Gurmatkal intertrappeans based on charophytes needs to be discounted.

THE intertrappean sequences exposed in parts of

Gulbarga district, northern Karnataka demarcate the southeastern margin of the Deccan basaltic province of peninsular India. Though recorded over a century ago¹, these beds were investigated in some detail only as late as 1945 (ref. 2). Over the past several years, a diverse charophytic flora has been reported (but not adequately described or illustrated) from several intertrappean localities around Gurmatkal^{3,4}. Ages as young as Oligocene have been assigned to the Gurmatkal intertrappeans and are often cited as evidence of long continued volcanic activity^{5,6}.

Fossil biotas from the Gurmatkal intertrappeans assume all the more significance in the context of recent geochronologic data^{7,8} which place the Deccan volcanic activity close to the Cretaceous-Tertiary (K-T) boundary within an age bracket of 64-69 Ma. These biotas help in establishing temporal relationships of Gurmatkal beds with other similar occurrences along the northern and eastern margin of the Deccan Traps. This in turn has a bearing on the current issue of southward age progression of the Deccan volcanics based on geochemical mapping of lava flows⁹.

A diverse charophyte assemblage was recovered in association with ostracodes, molluscs and fishes from three sections around Gurmatkal designated as GI (77°24'28"E:16°52'12"N), GII (77°27'E:16°51'42"N) and GIII (77°27'5"E:16°53'45"N) (Figure 1). Lithologically, these sections are similar and comprise a sequence of chert, cherty marl and claystone.

In terms of taxonomic diversity this charophyte assemblage is one of the largest known from the Deccan intertrappeans. It comprises 8 genera and 10 species (Table 1), most of which are being reported for the first time from Gurmatkal. Among the most abundant species are *Platychara perlata* and *Peckichara varians*. Also, apart from *Harrisichara muricata* and

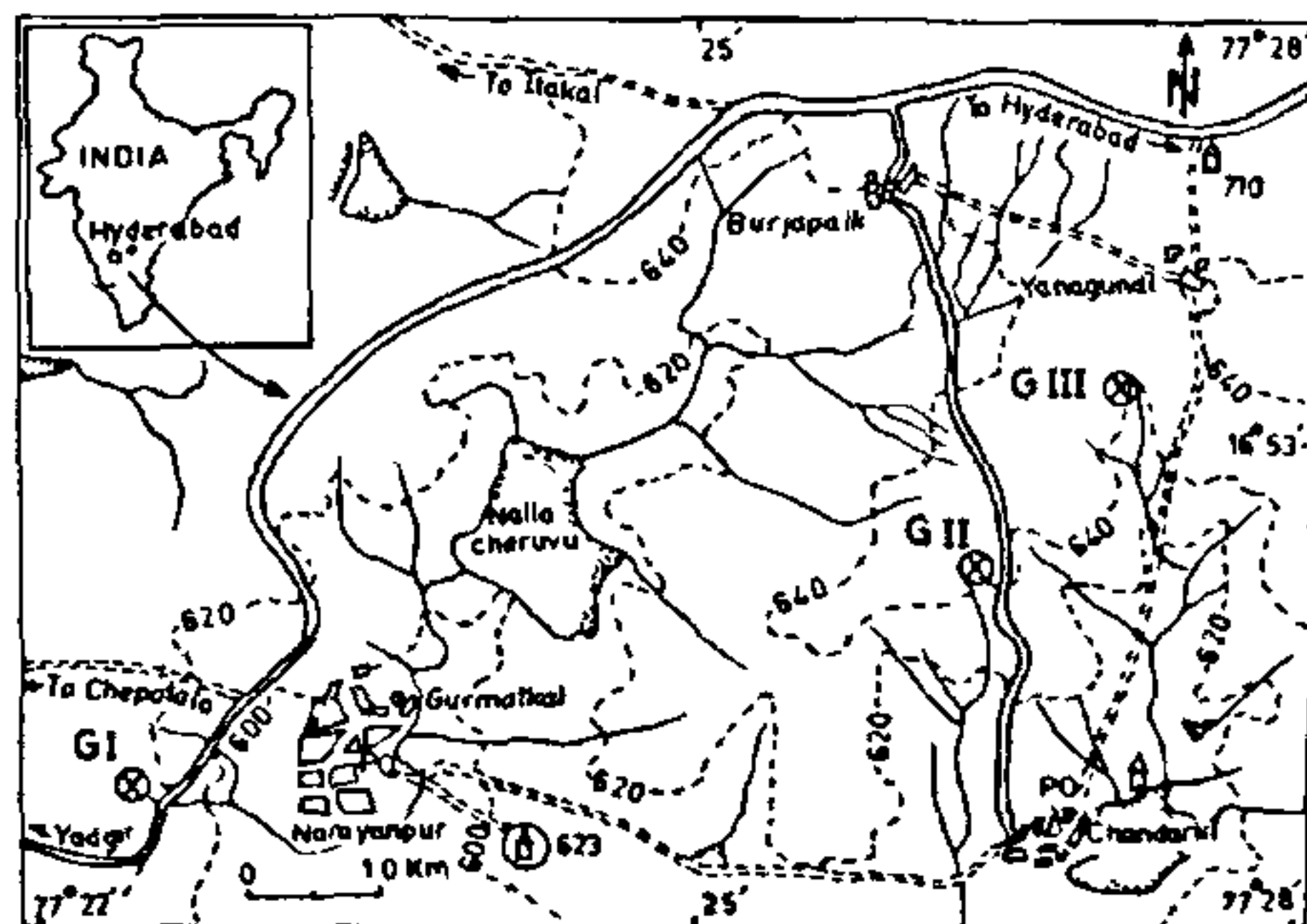


Figure 1. Map showing the location of charophyte-yielding samples (⊕).