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# The Water Tower of India in a Long-term Perspective – A Way to Reconstruct Glaciers and Climate in Himachal Pradesh during the last 13,000 Years

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**Abstract:** Here we present the first results from the project "Water Related Effects of Changes in Glacier Mass balance and River Runoff in Western Himalaya, India: Past, Present and Future" (GLACINDIA) project, aiming to reconstruct Holocene glacier variability as documented through physical sediment properties analysed on sediments from the former distal glacier-fed lake Chandra Tal (4300 m a.s.l.) combined with direct dating of marginal moraines using cosmogenic isotopes proximal to Chandra Tal and in front of the glaciers Batal and Chhota Shigri, located in Himachal Pradesh, western Himalaya, India. GLACINDIA is a multi-disciplinary project and unique, not only due to the participating institutions bringing together scientists from Norway and India, but also for the logistical challenges and the state-of-the-art science. In this particular case, we aim for detailed reconstructions of past glacier activity over the Holocene time scale (last ~11,700 years) emphasising different sediment parameters by means of statistical methods as well as integrating chronological uncertainties along with uncertainties of reconstructed glacier variability. We also aim to do oxygen isotope measurements on the pore water in addition to extracting lipids for leaf wax analysis in the sediment cores.

A multi-proxy data set of lake sediments consisting of sedimentological, physical and geochemical analyses reflects all types of processes in the lake catchment that delivers sediments to the lake. By means of principal component analysis (PCA), it is possible to extract the main process(es) driving the sediment variability in distal glacier-fed lakes. The common signal extracted from the sediment data is indicative of the main process in the catchment and is interpreted to vary in concert with the changing glacier equilibrium-line altitude over the region. Lake Chandra Tal has, based on earlier retrieved results from cosmogenic isotope dating, the potential to contain sediments deposited over the last 13,000 years, continuously deposited since the deglaciation after the glaciers retreated during the Late Glacial period. We, therefore, aim to do continuous reconstruction of climate with high temporal resolution for a better dynamical understanding of past climate. Understanding the controls of decadal, multi-decadal and century scale climate variability is crucial for many aspects of climate predictability. Climate reconstructions are important in order to validate Earth system modelling scenarios for the future; but there is at present a scarcity of consistent observational records from the Himalayas that can be used to understand and validate the existence of climate dynamics in this region.

**Keywords:** Water tower; 13,000 years climate; Himalayas; Palaeo-glaciation; High altitude lakes; Sediment core.

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## Introduction

The Himalaya is the largest mountain range of the entire Hindu-Kush Karakoram Himalayan (HKKH) region with a glacier coverage of roughly 22,800 $km^2$ (Bolch et al., 2012). It separates India along its north central and north-eastern frontier from China (Tibet) and extends between latitudes 26°20′ and 35°40′ N and longitudes 74°50′ and 95°40′ E (Ives and Messerli, 1989). The glaciers in this mountain belt are unique, as they receive significantly more solar radiation than Arctic and Antarctic glaciers, due to their position close to the Tropic of Cancer. Meltwater from the Himalayan glaciers feed numerous rivers that flow to the plains of India, Pakistan, China, Nepal and Bangladesh, thereby constituting an important water source for millions of people during the dry season, making the behaviour of these glaciers directly relevant for human societies.

There is large on-going research effort all over Himalaya in order to gain more knowledge about how this heavily glaciated region responds to global climate change, especially after the erroneous statements made by the Intergovernmental Panel on Climate Change (Parry et al., 2007) in 2007 on the future of these glaciers. The efforts include mass balance measurements (e.g., Ramanathan, 2011), frontal position measurements (e.g. Adhikari and Huybrecgtsm, 2009), and remote sensing (e.g., Scherler et al., 2011). Over the Himalayan region, high negative glacier mass balance for glaciers, especially for those directly impacted by the Indian Summer Monsoon (ISM), but less for the glaciers where accumulation is dominated by precipitation brought in through the westerlies (e.g. Harper and Humphrey, 2003). The Chhota Shigri Glacier in western Himalaya (Figure 1) is one of these glaciers that have been heavily studied over the last decade and continuous measurements of mass balance have been performed on Chhota Shigri by scientists from Jawaharlal Nehru University (JNU) over the last 12 years.

In this paper, we outline how we aim at investigating the long-term perspective of glacier variability in the western Himalaya using the instrumental time series as the base line for our reconstructions. Assessing how the glaciers in this region have varied over a Holocene time scale (last 11,700 years) can help identify their sensitivity to climate change, e.g. by using the Holocene thermal maximum and the last two millennia, including the Medieval Warm Period and the 'Little Ice Age', as target for our research and as possible analogues for the future. Further we outline how we are planning to assess the long-term behaviour of the glaciers in the Chandra Valley built on four c. 3.5-4 m-long sediment cores that were extracted during a field campaign in October 2015 from the previously glacier-fed lake Chandra

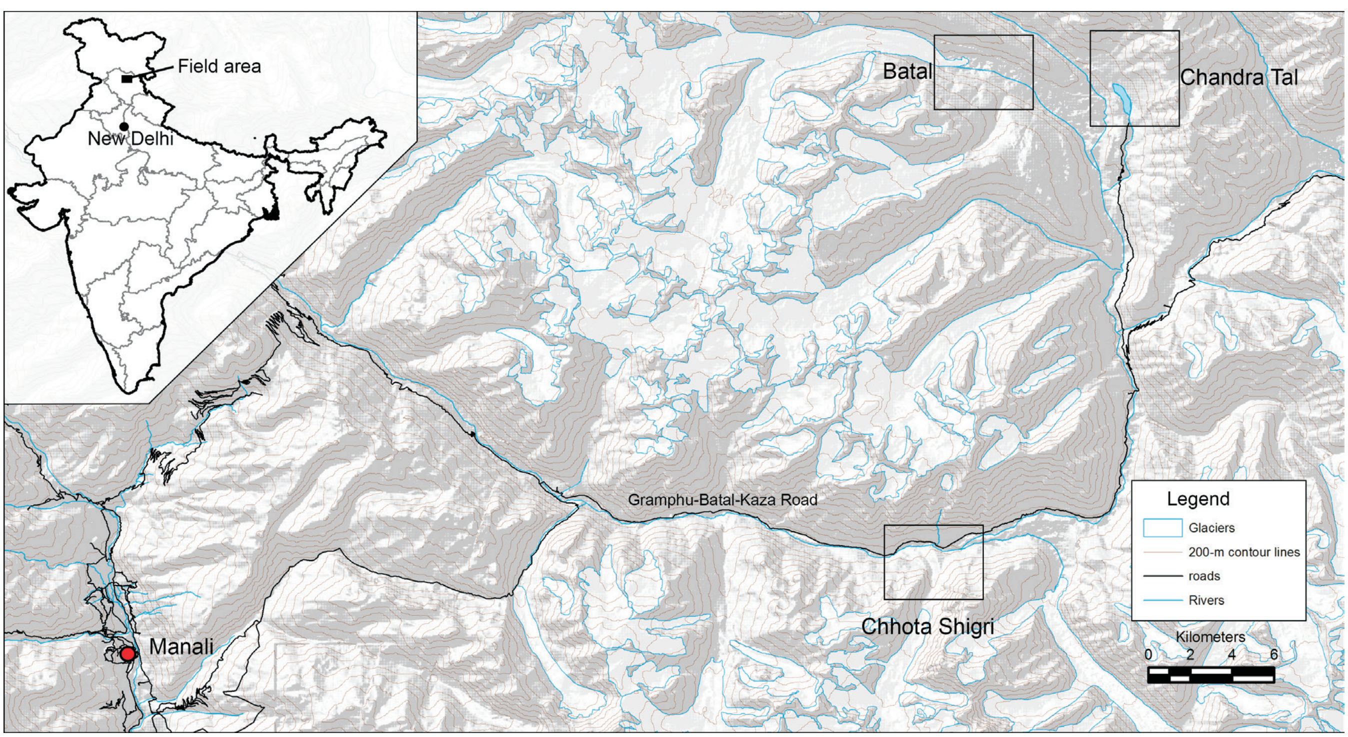


**Figure 1: (Inset) Overview map of India showing the location of our study area in the northern part of India. Map of the study areas in Himachal Pradesh; the three squares mark the different areas targeted in this project.**

Tal, located north in the Chandra Valley, in Himachal Pradesh (Figure 1). A suite of sediment analyses and numerical methods will be invoked in order to identify the glacial signal and produce a Holocene-scale glacier reconstruction.

We are using a novel methodology combining geomorphological mapping with multi-proxy studies on sediments from distal glacier fed lakes combined with independent dating of terminal moraines using cosmogenic dating techniques. The multi-proxy sedimentary datasets will be analysed by means of principal component analysis (PCA) in order to detect any common signals that might be related to glacier variability or other catchment processes. To check the validity of the Chandra Tal reconstruction in a regional context we will compare the results with independent cosmogenic dated moraines in front of the glaciers Batal and Chhota Shigri. Furthermore, the retrieved sediment cores contain an archive of past mass-movement and slope processes in the lake catchment, which can be used to reconstruct the frequency of past extreme weather events (e.g. Storen et al., 2010; Vasskog et al., 2011) and seismicity (e.g. Arnaud et al., 2002).

## Setting of the Western Himalaya

The Himalayas are classified into western, central and eastern parts based on geographical location (Bolch et al., 2012). In terms of glacier mass balance monitoring, most of the studies have been done on western Himalayan glaciers. According to Bolch et al. (2012), the total glacier volume is 415 $km^3$ with a total area of 8943 $km^2$ in the Western Himalaya. Glaciers over this region are mostly "winter accumulation type", as most of the snowfall (precipitation) occurs during the winter months (November to April/May) (Sakai et al., 2015). Chhota Shigri (Ramanathan, 2011) and Hamtah Glacier (GSI, 2011) are the most studied glaciers in this region. There is evidence of glacier retreat in the Eastern and Central Himalayas whereas glaciers in the Western Himalayas appear to be more stable, and may even be advancing (NAS, 2012).

The meltwater produced by these glaciers are fed into the Indus River, which is the largest river in the Western Himalaya. The river originates from the Tibetan plateau in the vicinity of Lake Mansarovar in the Tibet Autonomous Region of China and flows first to the northwest, turns southwest at Gilgit in Pakistan, and then flows south and southwest through the Indian subcontinent. The river has a total basin area of 1,116,086 $km^2$, of which 555,450 $km^2$ lies within the HKKH region and has an estimated annual flow of around 207 $km^3$, the twenty first highest in the world (Bajracharya et al., 2011). So, any change in glacier mass in the Western Himalaya has the potential to influence the seasonal runoff along the Indus River system.

The study area for the GLACINDIA project is located in the Chandra valley, focusing on the Chandra Tal Lake and Chhota Shigri Glacier. This area is in the rain-shadow zone immediately north of the east-west oriented Rohtang Pass, which partly restrains the entry of humid air masses from the ISM. The bedrock consists of crystalline beds comprised mostly of meso-to-ketazonal metamorphites, migmatites and gneisses (Kumar and Dobhal, 1997). In a few places, granitic rocks of different composition and younger age indicate rejuvenation. In some places of the upper Chandra Valley, older Palaeozoic granitic rocks are exposed. The Haimanta formation overlies these with a tectonic break, where black slates, phyllites and fine-grained biotite-schists are exposed (Rawat and Purohit, 1987). The slates and phyllites show a well-developed thrust tectonic contact, which forms the crest of the northern ridge. Box type folds with decollement are quite prominent in the Haimanta formation. The brown biotite, with a fine-grained texture, shows intense heating effect, which indicates periodic re-heating of the granite rocks below (Rawat and Purohit, 1987).

The climate of Chandra Tal Lake and Chhota Shigri Glacier and its adjoining area is dry and cool. Two distinct precipitation regimes (Bookhagen and Burbank, 2010) are prevalent in this glacier basin. Most of the precipitation falls in winter (November-February/March) due to the mid-latitude westerlies (MLW) and there is also some amount of precipitation falls in summer (July-September) due to the ISM. So far, limited meteorological studies have been carried out over this region. Azam et al. (2014) delineated four seasons i.e. summer-monsoon (JJAS), winter season (DJFM), pre-monsoon (AM) and post-monsoon (ON) based on Automatic Weather Station (4863 m a.s.l.) data running on Chhota Shigri Glacier since 2009. The mean annual air temperature was found to be –5.8 °C while it varies in winter (–9.4 °C) and summer (2.4 °C) (Ramanathan, 2011; Azam et al., 2016). ISM contributed only 21% to the annual precipitation (976 mm) at Chhota Shigri Glacier for the 2012/2013 hydrological year, with the remaining being supplied by the MLW, as revealed by the precipitation gauge (Geonor T-200B) at Chhota Shigri Glacier base camp (3850 m a.s.l.). At Bhuntar meteorological station (1092 m a.s.l.) the average annual precipitation is 916 mm $yr^{-1}$ (1969-2013), some 50 km (aerial distance) from Chhota Shigri Glacier (Ramanathan et al., 2011, Azam et al., 2014).

## Glacier-Climate Interactions

Chhota Shigri Glacier contains the longest series of continuous mass balance data available over the entire HKKH region, and has been measured since 2002 (12 years) (Azam et al., 2016), whereas in Hamtah Glacier mass balance data are available from 2001 to 2009 (GSI, 2011). Chhota Shigri Glacier lost mass between 2002 and 2014 with a cumulative glaciological mass balance of –6.75 m water equivalents (w.e.) corresponding to a mean annual glacier-wide mass balance of –0.56 m w.e. $yr^{-1}$ (Azam et al., 2016) while the average annual mass balance of Hamtah Glacier is estimated –1.59 m w.e. $yr^{-1}$ during 2001 to 2009 (GSI, 2011) using the glaciological method. The Lahaul and Spiti region in Himachal Pradesh is one of the largest glaciated areas in Western Himalaya, Gardelle et al. (2013) estimated a mass loss of –0.41±0.11 w.e. over this region during 1999-2011.

The goal of our investigations of geomorphology, dating of landforms and lake sediments is to reconstruct the equilibrium-line altitude (ELA), i.e. the average elevation of the zone where accumulation equals ablation over a one-year-period, backwards in time. Year-to-year differences in net balance of a glacier will thus move the ELA up and down; however, as the ELA can rarely be observed as a line at the same elevation across the entire width of the glacier due to local topographic and climatic variations in accumulation and ablation. Quantifying the ELA backwards in time is valuable as its altitude is closely related to the local climate, particularly winter precipitation and summer air temperature. The accumulation on a glacier includes all materials that add mass to the glacier, such as snow, refrozen slush, hail, rain, condensation/re-sublimation and avalanched snow and ice. The ablation includes direct ice melt, iceberg calving, wind erosion/deflation, and sublimation.

In western Himalaya accumulation is dominant in the winter months, whereas ablation mainly occurs during summer. Commonly, accumulation exceeds ablation on the upper part of a glacier, whereas ablation is larger than the accumulation in the lower parts. For a 'regular' glacier fed by snowfall in its accumulation area and that loses mass by melting of 'clean' ice in its ablation area, altitudinal mass-balance gradients are approximately linear, with ablation gradients tending to be steeper than accumulation gradients (Furbish and Andrews, 1984b; Schytt, 1967). For reconstructed variations in past ELA, it can sometimes be difficult to resolve the individual above-mentioned components affecting the ELA through time. However, the ELA is a better measure for climate than changes in frontal positions, especially when glacier snouts are debris covered, as is the case for many glaciers in the Himalayas (Scherler et al., 2011).

## Field Work—Lake Coring

Alpine glaciers are commonly located in remote and high-altitude regions of the world, areas only rarely covered by instrumental records. Glacier reconstructions have therefore proven useful for understanding past climate dynamics on both shorter and longer time-scales. Few, if any, other proxies have responded in a more unambiguous way to global warming than glaciers, which now are receding in a hitherto unrecognized pattern (Solomon, 2007). One major drawback with glacier reconstructions based solely on moraine chronologies—by far the most common method—is that due to selective preservation of moraine ridges such records do not exclude the possibility of multiple Holocene glacier advances (Balco, 2009). This problem is true regardless of whether cosmogenic isotopes or lichenometry have been used to date the moraines, or also radiocarbon dating of mega-fossils buried in till or underneath the moraines themselves. To overcome this problem Karlén (1976) initially suggested that glacial erosion and the associated production of rock-flour deposited in downstream lakes could provide a continuous record of glacial fluctuations, hence overcoming the problem of incomplete reconstructions.

Changes in average sediment evacuation from alpine glaciers are mainly governed by glacier size and the mass turnover gradient, determining the deformation rate at any given time. Several sources of error or noise have been identified when quantifying former glacier activity based on lake sediments. Reading the glacial signal, as preserved in the lake sediments, now includes the application of various methods such as measuring the amount of minerogenic versus biologic matter (typically inferred from loss-on-ignition (LOI)), grain size analysis (GSA), magnetic properties (MP), geochemical elements (GE), Rare-Earth Elements (REE), bulk sediment density (BSD), but also other techniques (e.g. Bakke et al., 2005a; Bakke et al.,

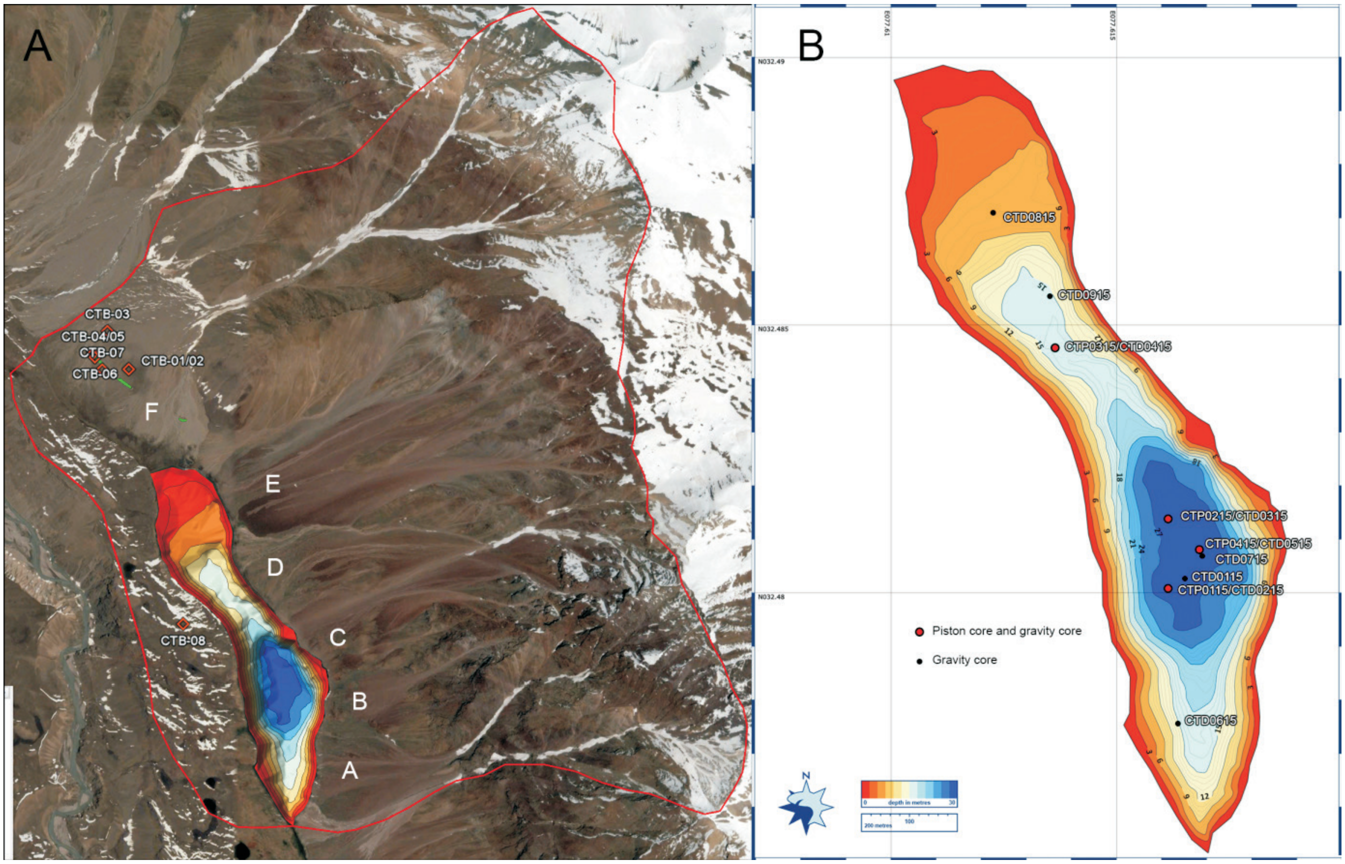


**Figure 2: A: Aerial photo of Lake Chandra Tal where the red line indicates the catchment boundary for the lake. The letters A-E mark different fans that are commented further in the text. B: Bathymetric map of Lake Chandra Tal with red dots showing the different coring locations within the basin. All the cores named CTD are short gravity cores (less than 2 metres) whereas the locations marked with CTP are longer piston cores (upto four metres length).**

**Figure 3: Lake Chandra Tal view towards S/SE. The sediment is mainly delivered to the lake from the western slopes from active slope processes that are enhanced when there is cirque glaciation in the upper part of the fans.**

**Figure 4: Returning to shore at lake Chandra Tal after retrieving one of the long piston cores. The raft is mounted on top of two light weight rubber boats with a small outboard engine in the back.**

2005b; Bakke et al., 2009; Bakke et al., 2005c; Dahl and Nesje, 1996; Guyard et al., 2007; Karlén, 1976; Leeman and Niessen, 1994; Leonard and Reasoner, 1999; Lie et al., 2004; Matthews and Karlén, 1992; Nesje et al., 2000; Nesje et al., 1991; Nesje et al., 2001; Paasche et al., 2007; Souch, 1994).

Based on the above methods we organised a field campaign to Chandra Valley in the fall of 2015 with the aim of combining several novel techniques in order to reconstruct past glacier activity. Our project team travelled to Lake Chandra Tal via Manali (Figure 1) with the goal of: (1) mapping the surficial geology of the catchment around the lake and in the glacier forelands of Batal and Chhota Shigri glaciers, (2) collecting modern vegetation and soil samples to identify the sources and biogeochemical signatures of sediments in the lake, (3) collecting additional sediment samples to properly assess the nature of organic and inorganic sediment deposition in the lake basin, (4) survey the lake with echo sounder for optimising the understanding of the lake bathymetry and infill, and finally (5) sample the lake sediments using a piston corer and a gravity corer with the goal of extracting a undisturbed Holocene sediment package deposited in the lake.

Chandra Tal is one of very few lakes in the mountainous part of Himachal Pradesh in northern India (Figures 1, 2 and 3). Situated at an elevation of 4300 m a.s.l., this 0.46 km$^2$ lake drains a currently unglaciated catchment area of 7.6 km$^2$. The catchment can be divided into two distinctly different areas: the steep slopes east of the lake and the low, hilly areas west of the lake. The low hills in the western part rise less than 100 m above the lake and feature a mostly sparse cover of unconsolidated material, mainly weathering products, and exposed bedrock can be seen in many places. At one site glacial scouring was evident on a bedrock outcrop, indicating glacial movement towards the southwest (202-213°). Glacial erratics are relatively abundant, and previous exposure dating from this area indicates deglaciation around 13000 ka BP (Owen et al., 2001). East and north of Lake Chandra Tal, steep slopes rise more than 1200 metres from the lake surface, to a maximum altitude of more than 5500 m a.s.l. for the highest summit directly to the north. A layer of light-coloured bedrock is found between 5000 and 5200 m a.s.l. in the eastern slopes and this is overlain again by a distinct red-coloured rock layer.

Several types of active slope processes are evident in the highly distinct fan deposits bordering the eastern shore of the lake. Based on field mapping, the fans and lobe-shaped landforms found along the eastern lake shore have been named from A-F, moving counter-clockwise from the outlet (Figure 2). The A, D, E, and F fans are all relatively complex forms showing evidence of several different depositional processes (Figures 2 and 3), and channels with levees formed by recent debris-flows can be seen on the surface of all these fans. Scattered, very large boulders, sometimes stacked on top of each other, were observed on the D fan, with infilled finer material in between, which might indicate that snow-avalanches have played an important role in formation of this fan. The E fan on the other hand shows a grading in boulder size downslope, with the largest boulders in front, evidently coming from the uppermost (red) bedrock layer. This sorting indicates that rock fall could be the dominant process in forming the E fan. The B and C lobe forms both have distinctly flat tops (4-5°) and steep frontal walls (>30°), leading us to believe that they are (possibly active) rock glaciers.

Prior to lake coring, Lake Chandra Tal was surveyed with an Ecosounder (LowranceElite 5×) that images the bottom of the lake, and combined with the integrated GPS, stores the position of the individual depth measurements. After collection of the data, they were transferred to a computer and post-processed in the software Reefmaster interpolating between the different transects measured (Figure 2). Results show that the lake has a maximum water depth of 29 m in the main southern basin, which also features a relatively large flat area well-suited for coring, whereas a shallower sub-basin (15-17 m) makes up the northern part of the lake. The lake coring was done using a piston corer from a raft (Figure 4). With the coring system it is possible to take sediment cores with a length of upto 6 m down to water depths of ~100 m. In addition, we used a gravity corer (type UWATIECH) allowing sampling of upto 2 m of undisturbed sediments where the sediment-water interface is preserved (Figure 2). This is important for precise $^{210}$Pb dating and estimates of sedimentation rates.

During mapping of surficial sediments around the lake we collected 35 catchment samples representative for the various soils found in the catchment, like moraine deposits, debris flow deposit, flood deposits and avalanche deposits. They will be sieved and analysed with the same suite of methods as used on the lake sediment cores in the laboratory with the goal of fingerprinting the different sediment sources deposited in the lake. In addition we collected numerous water samples that will be used to validate the isotopic composition of the pore water that was extracted from the cores. In the Chandra Tal catchment two terminal moraines were mapped and sampled for cosmogenic dating (Figures 5 and 6). In front of the Batal and Chhota Shigri glaciers several terminal moraines were mapped and sampled for cosmogenic dating (Figures 5 and 6).

**Figure 5: Bedrock sampling for cosmogenic exposure dating using hammer and chisel of a boulder deposited in a terminal moraine in front of Chhota Shigri glacier. The metamorphic bedrock contains a lot of quartz and is well suited for dating.**

Preliminary examination of the sediment cores from Lake Chandra Tal indicates fine laminated sediments that have significantly different geochemical properties throughout the core (Figure 7). The many laminas are expected to be caused by stratification in the water column through the year with a monomict mixing, and no mixing during the winter when the lake is covered with lake ice. Especially the calcium concentration shows variability indicating that there is significant changes in environment through time. In Figure 8, we examine the lamina using a CT-scanner from ProCon to study closer the nature of the lamina. Further we intent

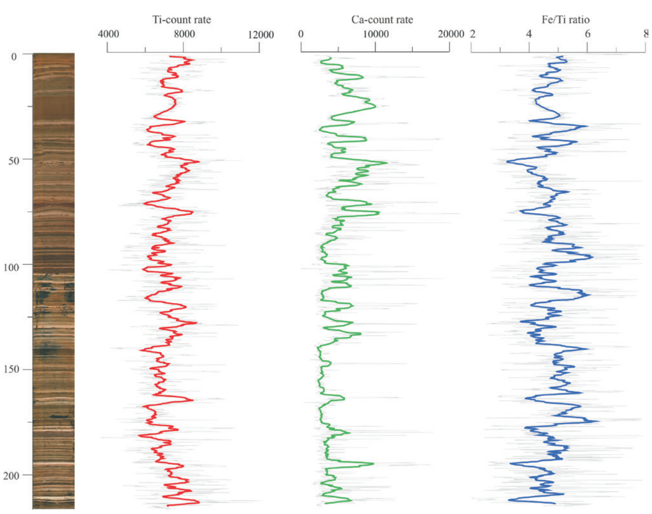


**Figure 7: Picture of the lithology and some major XRF parameters measured on an ITRAX-XRF scanner on core CTP-0415 plotted according to depth (cm) in core. The core is laminate throughout the whole length indicating that the boundary conditions for the lake has remained more or less the same throughout the time span that the sediment covers.**

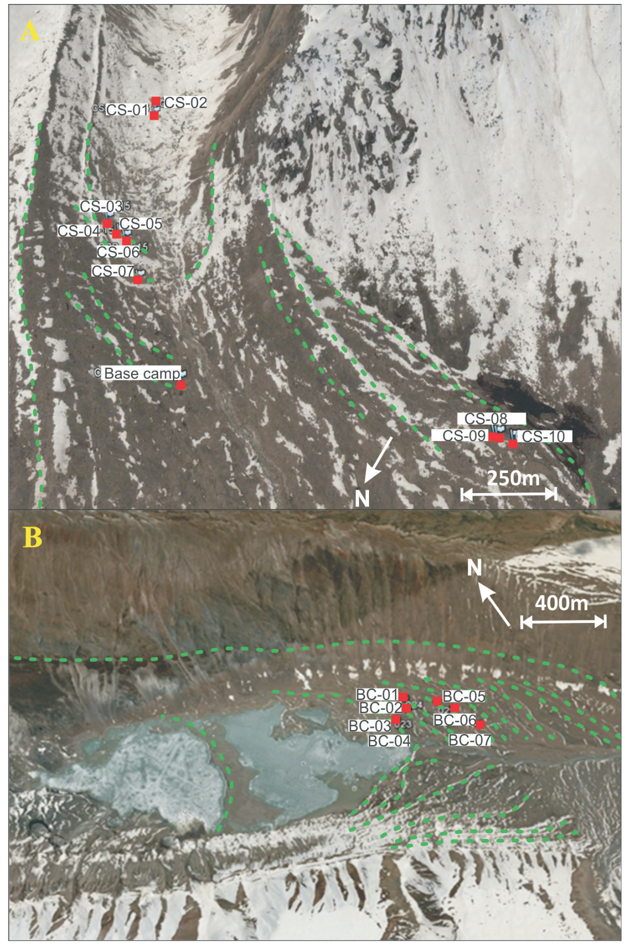


**Figure 6: A: Location for samples collected for cosmogenic dating in front of Chhota Shigri glacier. The green dotted lines are major terminal moraines mapped in the glacier foreland. Our sampling strategy was to date as many of these moraines as possible. B: Location of samples collected for cosmogenic dating in front of Batal glacier. Here we focused on dating two of the moraines in order to constrain the retreat after the "Little Ice Age". The green dotted lines indicate continuous terminal moraines mapped in the glacier foreland.**

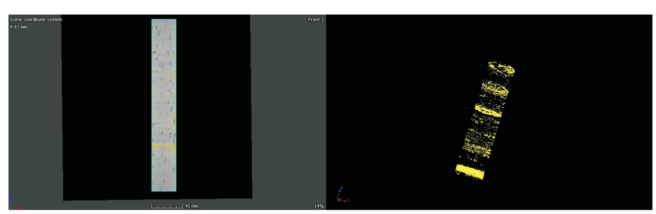

**Figure 8: Computer Tomography (CT) scan of a section in core CTP-0415 from Lake Chandra Tal. Denser minerogenic layers are shown in yellow. The CT images allow a resolution down to 2 micron and it is possible to examine in high detail the boundaries in lower and upper parts of the cores.**

to analyse the CT-images in the visualisation software Avizo and quantify the lamina, drop stones, erosional boundaries and sorting of individual layers.

## Palaeoclimatic Reconstructions Based on Sediment Cores from Distal Glacier-fed Lakes

When sediment records have been validated (i.e., establishment of a master stratigraphy following intra-basin comparison), the next step involves connecting the continuous sediment record to shifts in the equilibrium-line-altitude (ELA) of the glacier in question. The ELAs (present and past) of dated glacier advances can be reconstructed with established methods such as the accumulation-area ratio (AAR) (Porter, 1975). Because the potential effect of glacier hypsometry is not taken into account by the AAR method, Furbish and Andrews (1984a) developed an ablation-accumulation balance ratio method which also considers the glacier hypsometry. In a recent paper, Pellitero et al. (2015) outline an automatic tool for calculation of ELA using GIS, taking into account the Accumulation Area Ratio and the Area-Altitude Balance Ratio methods. This toolbox provides a fast method to calculate ELA for both single glaciers and more complex ice fields of glaciers with more than one flow line.

In earlier studies dry bulk density (DBD) or SIRM have been used for such quantification (Bakke et al., 2010; Bakke et al., 2005c). The first step in this approach is to integrate an independently dated moraine chronology with an independently dated sedimentary record. By doing so, it is possible to establish a statistical relationship between the ELAs belonging to the dated moraines and the corresponding sedimentary values. The second step is to use (if available) $^{210}$Pb dated sections in the sedimentary records to correlate sedimentary values to historical documented glacier-front positions recalculated to ELA. Taken together, this allows for the construction of a continuous record of ELA variations, validated by independently dated archives.

## The Road Ahead: Multi Proxy Approach and Palaeoclimatic Implications

In total, we collected 27 metres of sediment cores, 23 samples for cosmogenic dating and 35 sediment catchment samples. The palaeoclimatic outcome of this investigation will allow in-depth studies of the palaeoclimatic sensitivity of glaciers in the Western Himalaya. GLACINDIA will provide a new avenue for understanding how Himalayan climate has varied during the Holocene through the application of new methods aimed to reconstruct primary features of atmospheric circulation and variability. The rationale for this research effort can be summarised as follows:

- Understanding the controls of decadal, multidecadal and century scale climate variability is crucial for many aspects of climate predictability. In climate model simulations the amplitude, mean state and phasing of the variability are based on instrumental time series. Climate reconstructions are important, but there is at present a scarcity of consistent observational records from the Himalayas that can be used to understand and validate the existence of such dynamics in this region.
- In the palaeoscience community many papers have used a number of proxies and model runs to reconstruct and understand Holocene climate variability. However, the scarcity of data relating to atmospheric circulation variability on longer timescales from the Himalayan region hampers our understanding of the climate modes and to what extent changes in external forcing (e.g. mid-latitude sea-surface temperature anomalies, solar variability) impact climate dynamics.
- It is shown from previous work that distal glacier-fed lakes are excellent archives of past glacier activity, providing a pristine signal because there is practically no post-depositional alteration of the lake sediment. In order to link downstream lake sediments to glacier activity a novel approach needs to be developed and calibrated, integrating several different sedimentary parameters used in combination with novel dating techniques.
- By reconstructing glaciers located in dynamically sensitive areas at mid-latitudes, it is possible to examine changes in atmospheric variability in a pre-industrial frame, providing unique palaeoclimatic data that will enhance our knowledge about natural climate variability.

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