3.1. Description and geology of cave sites

Considering the vast expansion of limestone host rock throughout the Himalaya, we studied six caves in the different sectors (Figure 12) under varying precipitation regimes. These are, Kalakot Cave (33°13'19" N: 74°25'33"E; altitude, 826m) from Jammu and Kashmir; Borar Cave (30°38'18"N: 77°39'09"E; altitude, 1,622m) and Tityana Cave (30°38'30.7" N: 77° 39'07.4" E; altitude, 1,470m) from Himachal Pradesh; Dharamjali Cave (29°31'27.8"N: 80°12'40.3"E; altitude, 2,200m), Sainji Cave (30°16'07"N: 79°18'14"E; altitude, 1,478m) and Chulerasim Cave (29°53'08"N: 79°21'06" E; altitude, 1,254m) from Uttarakhand.

Figure 12. Caves studied in the present work. 1, Kalakot (Jammu and Kashmir); 2, Borar and 3, Tityana (Himachal Pradesh); 4, Chulerasim, 5, Sainji and 6, Dharamjali (Uttarakhand).
Kalakot Cave is about 5 m long (entrance 1.8 m x 1.5 m, Figure 13a) and is almost horizontal. The thickness of host rock (Sirban Limestone) above the cave is 50 m (Figure 13b). The vegetation above the cave is dominated by broad leaved elements followed by pine trees. We observed 6 stalagmites of varying heights and a 19.6 cm long stalagmite (Figures 13c-d) was collected. It was the longest inactive stalagmite and was collected at a distance of about 2.2 m from the main entrance. The composition of stalagmite is calcite with very well developed growth rings showing no discontinuity (Figure 13e). The inside temperature and humidity at the time of collection of the sample was 10.6°C and 79% respectively.

In the Kalakot region, the Sirban limestone (Figure 14) is underlain by Jangli Formation (Subathu Group) and an unconformity lies between these (Mathur and Juyal, 2000). In the study area, the Sirban limestone is exposed as occupying the crestal part of anticlinal features (Siddaiah and Shukla, 2012). The presence of stromatolites suggests a Neoproterozoic age for the Sirban limestone (Raha and Sastry, 1982).
Sainji Cave is located in the Almora District, Ranikhet Tehsil in the Kumaun Himalaya. This is a 32 m long cave with an entrance of 1.5 m² (Figure 15a). The entrance of the cave is sub vertical (Figure 15b), middle part almost vertical and then horizontal till the end. At the time of collection of specimen, the mean annual temperature around the cave site was ~13.5 °C and the inside humidity was measured as 70%. The host rock above the cave is 50 m thick Deoban limestone. Several structures like stalactites, stalagmites and flow stones were observed inside the cave. The surrounded area is dominated by the Pinus roxburghii with small shrubs, grasses and scattered Quercus. The cave is situated in subtropical climate with wetter and warmer summers and cooler and drier winters. The selected specimen, 26 cm in length
(Figures 15c-d) was collected from the last narrowest chamber (0.8 x 0.7 m), about 31.5 m from the entrance.

Figure 15. (a) Entrance of the Sainji Cave; (b) Entrance becomes narrower in the middle part of the cave; (c) Collected specimen inside the cave; (d) Stalagmite in the laboratory after collection; (e) Sliced parts of the stalagmite.

Figure 16. (a) Entrance of the Chulerasim Cave; (b) Host rock above the cave; (c) Collected specimen (11.5 cm long) from the cave; (d) Sliced parts of the sample.
Chulerasim Cave is situated near Chulerasim village, Chaukhtia (District Almora) in the Kumaun Lesser Himalaya. This is a 5m long cave with main entrance as ~ 3m x 3 m (Figure 16a) and very narrow end. The 11.5 cm long active stalagmite (Figures 16c-d) was collected at a distance of 4.9 m from the entrance. The vegetation around the cave area is dominated by Quercus incana, Pinus roxburghii and small shrubs. The yearly weather is sub-tropical wet/moist with warmer summers and cooler winters. The humidity outside the cave varies between 60 to 70% during the ISM period and 30-40% during the WDs months. The drip rate inside the cave was 1 drop/min, when specimen was collected.

Figure 17. Geological map around Sainji and Chulerasim Caves (after Valdiya, 1980).
The Sainji and Chulerasim Caves are situated in the Tejam group of rocks (Deoban and Mandhali formation) (Valdiya, 1980). The caves are formed mainly in the rocks of the Deoban formation (Figure 17). This formation is marked by stromatolite bearing cherty dolomite and dolomite limestone bands. The limestone and slate occur as intercalation and overlies with Rautgara Formation (Valdiya, 1962, 1980) as a conformable contact. The age of Deoban limestone is Riphean (1,400-800 Ma) (Srivastava and Kumar, 1997).

**Figure 18.** (a) Entrance of the Dharamjali Cave; (b) Structures like stalactites, stalagmites, flow stones etc.; (c) Stalagmite inside the cave; (d) Sliced part of the stalagmite.

**Dharamjali Cave** is located 7 km southwest of Pithoragarh. The sub-vertical cave is 35 m long with an entrance of 4.5 x 2 m (Figure 18a) from where the cave dips 60° NW at an angle of 40-45°. The cave is very narrow in the last chamber (ca 0.8 x 0.9 m). It has structures like stalagmites, stalactites, pillars and flowstones (Figure 18b). We collected five stalagmites of various heights. In the present study, we used a 41 cm long stalagmite (Figures 18c-d) which was collected at a distance of about 34 m from the entrance. The thickness of the host rock above the cave is about 50 m with a 1-2 m thick brownish black soil. The vegetation is dominated by *Quercus* and *Rhododendron* with occasional occurrences of *Pinus roxburghii*, as well as small shrubs, grasses, ferns and herbs. The cave is wet throughout the year with highest dripping rate during the monsoon season and minimum water supply occurs during winter.

Dharamjali Cave is situated in the Mandhli (Sor and Thalkedar) Formation (e.g., Nautiyal, 1990). This formation consists mainly of greyish green and black carbonaceous pyritic phylites-slates, interbeded limestone with paraconglomerate. The Mandhali Formation occurs in the core of Gangolihat Dolomite Formation. The
sedimentary rocks have been designated as Sor slates and Thalkedar limestone (Figure 19). The age of this Formation is Riphean to Vendian (1,600 Ma -540 Ma) (Valdiya, 1980, 1989).

Figure 19. Geology around Dharamjali Cave area (after Valdiya, 1980).

Tityana Cave is 13 m and long sub vertical with a small entrance (3 m x 1 m, Figure 20a). The host rock thickness is 2m. Two stalagmites were collected at distance of about 12.1 m and 12.9 m respectively from the main entrance. The cave is dry and has
flow stones, stalactites and unbroken stalagmites. In the present study, we selected a 13 cm long stalagmite (Figures 20c-d). Structures like stalactites, stalagmites and flowstones are present inside the cave. The surrounding vegetation is dominated by *Pinus* trees along with shrubs. This cave has three chambers, two chambers have a slant of 60° to 70° from main entrance and the last chamber is sub-horizontal.

**Figure 21.** (a) Entrance of the Borar Cave; (b) Different cave structures inside the cave; (c) 23.6 cm long stalagmite inside the cave; (d) Stalagmite sample outside the cave; (e) sliced part of the sample.

**Borar Cave** is a 5.5 m long and is sub horizontal to sub vertical with a ceiling height of 2m. The cave has very small entrance of 2m x 1m (Figure 21a). The host rock thickness is about 20 m. While collecting the sample, the temperature and humidity inside the cave were 16.1°C and 78% respectively. The surrounding vegetation is dominated by broad leaved sub-tropical forests and a lot of ferns. Stalagmites, stalactites and flowstones are present in the cave (Figure 21b). Four stalagmites were collected at a
distance of 2m from the main entrance. We used a 23.6 cm long stalagmite in the present study (Figures 21c-d). The sliced part of the sample shows dark rings (Figure 21e). The drip rate inside the cave was 9 drops/min at the time of sample collection.

The Tityana and Borar Caves are located in the Deoban limestone (Figure 22) of Precambrian age (Shali-Deoban Formation). This Deoban sequence begins with a red quartzite-limestone in the basal part, followed by a shale/slate series and grey dolomite in middle and upper parts (Bhargava, 1976). Based on the characteristic stromatolites, the Deoban Formation has been assigned a Mesoproterozoic age (Valdiya, 1969; Thakur and Rawat, 1992).

3.2. Meteorological data around cave sites

We examined the precipitation data of six meteorological stations (1900-2000, http://www.indiawaterportal.org/met_data/), which are near by the studied caves. The data of all stations for ISM and WDs, display a variation in the minimum and maximum
values of annual mean precipitation (Figure 23). The maximum annual precipitation of all stations is about three times larger than minimum annual precipitation. The mean annual precipitation amount suggests that the ISM has a major role in different sectors of the Himalaya from Uttarakhand to Jammu and Kashmir. The meteorological data suggest that the ISM intensity decreases from east (Uttarakhand, ~2090 mm) to Northwest (Jammu and Kashmir, ~1352 mm) in the Himalayan region. However the WDs play a very significant role in total annual precipitation in Jammu and Kashmir.

Figure 23. Meteorological data from different districts around studied caves (data from http://www.indiawaterportal.org/metdata), (a) Rajouri District (J&K); (b) Almora (UK); (c) Pithoragarh (UK); (d) Nainital (UK); (e) Sirmour District (HP) and (f) Simla (HP).
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Table 2. Precipitation data between 1900-2000 from the different meteorological stations (http://www.indiawaterportal.org/met_data).

3.3. Methodology adopted in the present study

3.3.1. U/Th dating

Selected stalagmites were sliced into two halves, for dating, isotopic study and mineralogical analyses. For U/Th dating, the samples were drilled with sample size smaller than 5 mm. All samples were analysed by Thermal Ionisation Mass Spectrometry (TIMS) at Heidelberg Academy of Sciences, Germany and University of Queensland, Australia. Methods used for sample preparation and mass spectrometric analysis are explained in detail by Frank et al. (2000), Burns et al. (2002), Holzkämper et al. (2005) and Kotlia et al. (2012). Samples were dissolved in 7N HNO₃ and equilibrated with a mixed spike containing $^{229}\text{Th}$, $^{233}\text{U}$, and $^{236}\text{U}$. The U and Th were separated using two stages of HNO₃–HCl cation exchange chemistry followed by reaction with HNO₃ and HClO₄ to remove any residual organic material. The Ages were calculated using Isoplot (Ludwig, 2003) and the decay constants of Jaffey et al. (1971). The StalAge (age-depth) model was performed following Scholz and Hoffmann (2011). Age uncertainties are at 2-σ level and do not include half-life uncertainties.
3.3.2. AMS dating

In some stalagmites, the U/Th method was unsuccessful due to multiple source of non-authigenic $^{232}$Th and low uranium concentration (< 10 ppb). Thus, the AMS chronology was introduced for such stalagmites. Only one stalagmite from Tityana Cave was dated by AMS method. All samples were drilled at different depths using dental drill for $^{14}$C AMS chronology and were analyzed at Poznań Radiocarbon Laboratory, Poland. The AMS measurements are dedicated to the $^{14}$C because the Carbon-14 is a naturally occurring radioactive isotope of carbon. For AMS dating, the sample size is very less as 1-2 mg and in few cases as small as 50-100 micrograms. This technique determines the isotopic composition of a sample by first generating a negatively-charged ion beam, which is then subjected to a series of selective filtering procedures in order to get $^{14}$C. This method is based on $^{14}$C/$^{12}$C ratios in the range of $10^{-12}$ to $10^{-15}$. Thus, the AMS method has successfully been applied to build chronologies for young speleothems (Goslar et al., 2000; Mattey et al., 2008; Laskar et al., 2013; Zhao et al., 2015). All obtained AMS ages were calibrated using online Cal Pal program to convert the conventional radiocarbon dates into calendar ages. The Age/depth model was constructed by linear interpolation between the calibrated ages.

3.3.3. $\delta^{18}$O and $\delta^{13}$C isotopes

For isotopic analysis, the sub samples were drilled at every 0.8 mm along the growth axis (Figure 24) by using a triaxial drill machine at National Geophysical Research Institute (NGRI) Hyderabad.

![Figure 24. (a) Triaxial drilling machine for isotopic analysis; (b-c) Isotope Ratio Mass Spectrometer (IRMS) coupled with a Kiel-IV automatic carbonate device at NGRI Hyderabad.]
The Hendy test was performed on selected layers (from centre to right of the growth axis) at various depths to understand whether the deposition of the stalagmite carbonates was in isotopic equilibrium with precipitating waters (Hendy, 1971). All the isotopic measurements were carried out using a Delta plus Isotope Ratio Mass Spectrometer (IRMS) coupled with Kiel-IV automatic carbonate device (Figure 24). The obtained isotopic values are reported in δ notation as permil deviation from PDB standard (Spötl and Mattey, 2006). The Analytical precision was better than 0.10‰ for δ¹⁸O and 0.05‰ for δ¹³C. The calibration standard was achieved by repeated measurements of international reference standards NBS19 and NBS18 (Ahmad et al., 2008). The standard used is V-PDB supplied by IAEA (International Atomic Energy Agency, Vienna).

**3.3.4. Petrography and SEM**

For laminae analysis, the polished surfaces of stalagmites were scanned using a precalibrated high resolution scanner at RGB/3200 dpi. The X-Ray Diffraction (XRD) method was involved in identification of the mineralogical composition of the sample. The Scanning Electron Microscope (SEM) was used for determining the structure and composition of the stalagmite by coating the fresh broken surface of the sub-sample by carbon to provide electrical conductivity to the surface. Mineralogy, surface morphology and crystal composition of the stalagmites were determined by using petrographic microscope as well as Scanning Electron Microscope (SEM). The analysis was performed at Jawaharlal Nehru Centre for Advance scientific Research (JNCASR), Bangalore, India.

**3.3.5. Abbreviations of studied cave stalagmites**

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</table>

Table 3. Abbreviations used for studied stalagmites.