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A 2500 years deglacial record of paleo-vegetation over a cave of southern India as inferred from carbon isotopes of stalagmite

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Carbon isotopes of stalagmites are influenced by various factors operating in a cave, like evaporation, vegetation, drip rate and changes in partial pressure of carbon-di-oxide (pCO_2) inside and around a cave system. Consequently, interpretation of δ^{13}C record becomes a bit complicated. However, the vegetation changes at a given cave location are generally considered as the dominating factor influencing δ^{13}C values of a stalagmite. The δ^{13}C records can provide useful information regarding changes in the class of vegetation over a cave due to dissimilar pathways of photosynthesis linking C_3 and C_4 vegetation. Here we present a high-resolution δ^{13}C record from a 180 mm long VSPM1 stalagmite collected from the Valmiki cave in Kurnool district of southern India. This study is mainly based on high-resolution δ^{13}C measurements of 263 subsamples. The data has been used to infer vegetation and climatic variations for the last deglacial period starting from 15,607 to 13,161 years BP. The StalAge modelling was employed on eight U–Th dates to reconstruct the age model of the stalagmite sample. The stalagmite grew at the rate of 0.07 mm per year with varying growth rate from around 0.03 to 0.8 mm per year. X-ray diffraction analysis reveals absolute aragonite mineralogy of the sample. The record exhibits a weak positive relationship between δ^{13}C and δ^{18}O values. The main factors influencing δ^{13}C values were associated with local hydroclimate. The δ^{13}C record suggests vital evidence of rapid alterations in vegetation changes from $\sim$15,607 to 13,161 yr BP. A major shift in vegetation activity occurred from 15,607 to 15,105 yr BP with an episode of highly poor vegetation cover around 15,460 yr BP, followed by a gradual decline in vegetation conditions between 15,105 and 14,722 yr BP.

Keywords. Carbon isotope; stalagmite; Valmiki cave; hydroclimate; paleoenvironment.

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1. Introduction

Stalagmites have enormous prospective for documenting the information of paleoclimatic conditions. The moist and warm climatic conditions are ideal for the growth of a stalagmite (Ayliffe and Veeh 1989). Moreover, high growth rates of stalagmite are observed throughout the interglacial periods (Harmon *et al.* 1975). The stable C and O isotopic compositions in stalagmites have been valuable proxies to reconstruct the climatic changes occurred in the past. A range of studies have been accomplished on δ^{18}O of speleothems which establishes that the δ^{18}O in conjunction with

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radiometric dating of speleothems provides very important information of past climate (Harmon *et al.* 1975; Ayliffe and Veeh 1989; Dorale *et al.* 1992; Kotlia *et al.* 2012, 2016; Lone *et al.* 2014; Joshi *et al.* 2017; Raza *et al.* 2017), but carbon isotope ratios of speleothems have acquired less attention as compared with oxygen isotope; however, quite a few studies have been established the utility of δ^{13}C of speleothems (Hendy 1971; Quade *et al.* 1989; Brook *et al.* 1990; Dorale *et al.* 1992, 1998; Baskaran and Krishnamurthy 1993; Genty *et al.* 1998, 2003; Frappier *et al.* 2002; McDermott 2004; Fairchild *et al.* 2006; Cosford *et al.* 2009; de Cisneros and Caballero 2011). In their study, Quade *et al.* (1989) exhibit an evident link between carbon isotope ratios and vegetation changes. Moreover, Dorale *et al.* (1992) have also demonstrated that the vegetation type over the cave can be inferred by using the δ^{13}C of speleothems. Furthermore, Baskaran and Krishnamurthy (1993) established that the δ^{13}C values in speleothems can be employed to interpret the isotopic ratios of atmospheric CO_2. Cosford *et al.* (2009) describe the utilization of δ^{13}C of speleothems to obtain the records of paleo-environmental changes. However, several other studies have also suggested that the changes in concentration of atmospheric CO_2, surface temperature, land cover and cave environment (Baldini *et al.* 2006; Breitenbach *et al.* 2015) all can influence speleothem δ^{13}C. Therefore, stalagmite δ^{13}C is more complex than δ^{18}O because of various controlling factors. However, studies have revealed that stalagmite δ^{13}C largely represents the local vegetation change (Tieszen *et al.* 1979a; Ku and Li 1998; Kuo *et al.* 2011; Zhao *et al.* 2015 and references therein). de Cisneros and Caballero (2011) also establishes the ability of carbon isotope values as paleoclimate indicator in their study on stalagmites from Nerja Cave, South Spain. They stated that the carbon isotope variations are associated with the terrestrial carbon cycle and thus provide information about the vegetation. In particular, it has been primarily employed to interpret C_3 *vs.* C_4 vegetation changes (Drysdale *et al.* 2004; Genty *et al.* 2006; Fleitmann *et al.* 2009; Rudzka *et al.* 2011) with lower δ^{13}C value reflecting better vegetation cover because of dissolving more biogenic CO_2 into the seepage water during the periods of better precipitation, whereas the enriched or higher δ^{13}C values reflect less vegetation coverage due to a reduced amount of vegetative input of biogenic CO_2 during the periods of arid climates (Dorale *et al.* 1998; Kotlia *et al.* 2016; Joshi *et al.* 2017). The temperature and precipitation mainly alter the properties of vegetation above the cave. In general, the vegetation cover increases during periods of better precipitation. Raza *et al.* (2017) established that the VSPM1 δ^{18}O record on annual to centennial scales reflects Indian summer monsoon (ISM) or southwest monsoon precipitation changes with lower δ^{18}O corresponding to wet climates. As mentioned earlier, usually vegetation development is better under wet climates. Therefore, a wet climate will show the depletion in both δ^{13}C and δ^{18}O with occasionally a time delay in δ^{13}C because of delayed response of vegetation change.

2. Geological settings

Valmiki cave is situated in Kurnool district of southern India (Raza *et al.* 2017) (figure 1). The local climate is dominated by hot/moist conditions during the summer months and cold/arid during the winters (October–January). The mean annual rainfall and temperature are around 670 mm and 28°C, respectively. From a geological perspective, the Valmiki cave is situated in the

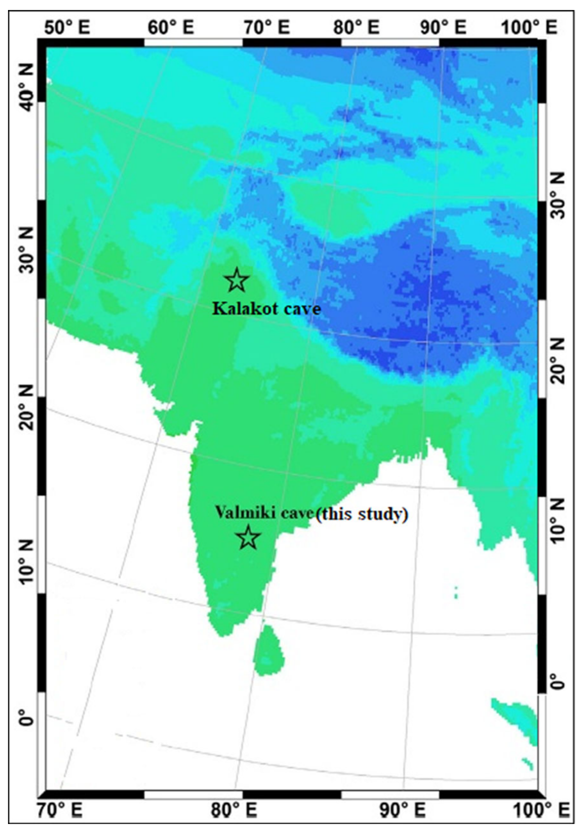

Figure 1. The location of Valmiki (this study) and Kalakot caves discussed in this study are indicated here.

Paleoproterozoic Vempalle Formation of stromatolitic dolomite as mentioned by Raza *et al.* (2017). This cave is an exceptional site of prehistoric significance and provides paleoenvironment record of the last deglacial period. The Valmiki cave comprises several hallways and the revelation of internal chambers with the outside atmosphere is restricted to a very narrow creep-in passage. The other details of the Valmiki cave have been described in Raza *et al.* (2017).

3. Materials and methods

The VSPM1 stalagmite sample was cut vertically to uncover the growth bands and also to inspect the secondary adaptation. Further, a vertical section of the sample was sliced and polished (figure 2). Later, the sample was cleaned to remove the solid particles adhere to the sample. The slicing and cleaning of the sample were performed at CSIR-National Geophysical Research Institute, Hyderabad by a diamond cutter and an ultrasonic bath respectively. With an approximate length of 180 mm, the VSPM1 stalagmite sample has a maximum diameter of ∼120 mm at the bottom. Consistent laminae with the shift of skinny and thick layers are clearly visible. The apparent light and dark bands show alterations in the formation. Hendy test was carried out to ensure whether or not the VSPM1 stalagmite was grown under isotopic equilibrium. This test establishes the suitability of the stalagmite sample for the paleoclimate studies. For this purpose, three different layers were selected at different depths on regular interval (figure 2). Afterward, six subsamples were drilled from these three layers and analyzed for isotopic compositions of carbon and oxygen (δ^{13}C and δ^{18}O) (figure 3).

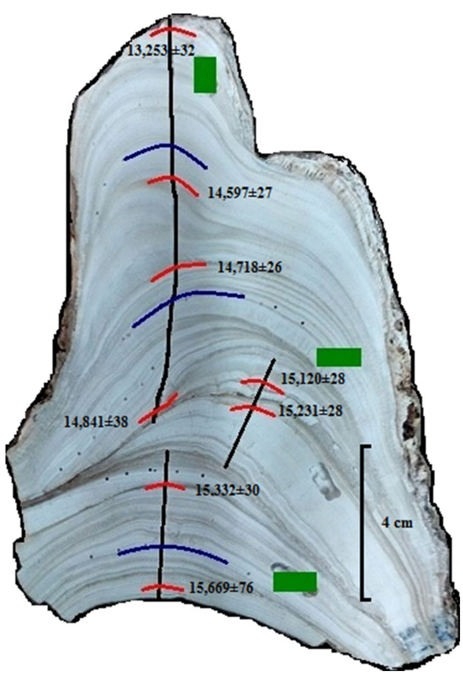

Figure 2. VSPM1 stalagmite. Black lines represent the drilling points for δ^{18}O measurements. Red lines represent eight ^{230}Th dating samples. Blue lines show layers of Hendy test and green boxes mark XRD analysis points (modified after Raza *et al.* 2017).

To assess the mineralogical composition of VSPM1 stalagmite and also to inspect any change subsequent to its deposit, the X-ray diffraction (XRD) analysis was carried out on three subsamples (∼1 gm each) by using a Philips X-ray diffractometer using nickel filtered Cu Kα radiation at the CSIR-National Institute of Oceanography (NIO), Goa, India (Kessarkar *et al.* 2010). Three subsamples used for detailed mineralogical investigation were drilled at ∼20, 100 and 170 mm depths from top of the sample using Manix-180 drilling device. X-ray diffraction measurements revealed that the sample is made up of aragonite mineral with uniform composition throughout the sample from top to bottom. Moreover, no indication of any change in mineralogy from aragonite to calcite was noticed.

The VSPM1 stalagmite was formed between 15,610 and 13,160 yr BP (Raza *et al.* 2017) as determined by U–Th dating of eight sub-samples (table 1) taken from different selected layers (figure 2). U–Th dating was performed on a Thermo Fisher NEPTUNE Multi-collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, following the methods developed by Shen *et al.* (2002, 2012). The age modelling was carried out by utilizing both linear and StalAge modelling program (figure 4). The StalAge model based on Monte-Carlo simulation is described in Scholz and Hoffmann (2011). The purpose of linear modelling was to correlate it with the StalAge model.

Continuous sub-sampling was carried out along the growth profile of VSPM1 stalagmite for high resolution measurement of carbon isotope ratios (δ^{13}C). A total number of 263 sub-samples were analyzed for isotopic ratios. The sub-samples were reacted with saturated H_3PO_4 at 70°C in a vacuum system and evolved CO_2 was analyzed for the

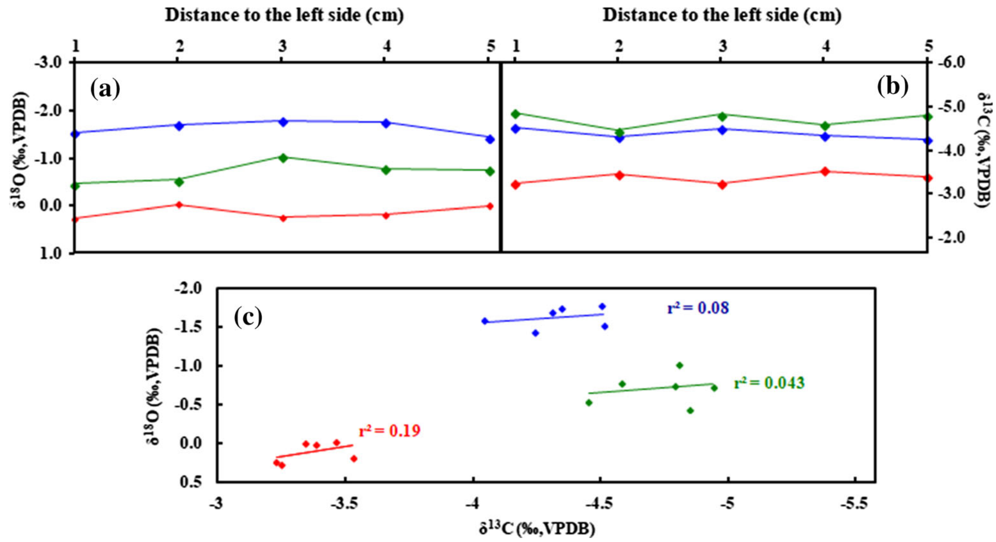

Figure 3. Hendy test results. Red, blue and green lines represent three dissimilar test layers. **(a)** δ^{18}O values, **(b)** δ^{13}C values, and **(c)** shows the correlation between δ^{18}O and δ^{13}C. r^2 in (c) represents that the sample formed under equilibrium conditions (modified after Raza *et al.* 2017).

measurement of δ^{13}C according to the procedure described by Ahmad *et al.* (2008, 2012). The δ^{13}C analyses of all the sub-samples were performed at CSIR-National Geophysical Research Institute, Hyderabad, India using MAT-253 Isotope Ratio Mass Spectrometer (IRMS) attached to a Kiel IV automatic carbonate device. The internationally recognized carbonate reference materials, NBS-18 and NBS-19 were analyzed after every eight samples to ascertain the reproducibility of the instruments. The measured δ^{13}C values are articulated against VPDB (Vienna Pee Dee Belemnite) and the precision of the instruments was calculated to be $\leq\pm0.06$‰ for δ^{13}C. The detailed procedures regarding the Hendy test, mineralogical investigation by XRD, U–Th dating and isotopic measurements of VSPM1 stalagmite sample are described in Raza *et al.* (2017).

4. Results and discussion

Prior to the discussion of the carbon isotope signatures of VSPM1 stalagmite, we need to confirm about the efficacy of this sample. The foremost requirement for any stalagmite sample for paleoclimate reconstruction studies is to ensure its formation under isotopic equilibrium condition. The stalagmite grown under isotopic equilibrium should exhibit almost similar δ^{18}O values of each growth layer (Hendy 1971). The VSPM1 stalagmite was grown under isotopic equilibrium as evident by Hendy test results (figure 3). The details of Hendy test results have been provided in Raza *et al.* (2017). The assessment of carbon and oxygen isotopic records along with the changing growth rates of VSPM1 stalagmite reveals a wide range of δ^{13}C and δ^{18}O values indicating absence of any relationship.

Figure 5 shows δ^{13}C variations of VSPM1 stalagmite sample during last deglaciation compared with its δ^{18}O record (Raza *et al.* 2017). Previously published δ^{18}O record of VSPM1 stalagmite has shown rainfall variations, with depleted and enriched δ^{18}O values corresponding to wet and dry episodes respectively (Raza *et al.* 2017). The δ^{13}C values of VSPM1 range from −2.42‰ to −6.02‰ with an average value of −4.54‰ (*vs.* VPDB) (figure 5). Earlier studies have demonstrated approximately 2–3‰ higher δ^{13}C values in aragonitic stalagmites than calcitic samples (Morse and Mackenzie 1990; McMillan *et al.* 2005). A higher difference of 5–7‰ in δ^{13}C values between calcite and aragonite samples has been reported by Zhang *et al.* (2004). Since the δ^{13}C values of speleothems depend on soil CO_2, fractionation process and the degree of interchange between drip water and source rock, the lower δ^{13}C values suggest warm or wet climate (Dorale *et al.* 1992; Fairchild *et al.* 2006; Baldini *et al.* 2008; Kotlia *et al.* 2016). The large variations in δ^{13}C values of stalagmites are perceived on different timescales (Frappier *et al.* 2002). Moreover, the source rock plays an important role in δ^{13}C values of stalagmite due to its mineralogical and chemical composition. In addition, evaporation can also influence δ^{13}C values of a

Table 1. *^{230}Th ages of VSPM1 stalagmite sample (India) by MC-ICPMS, Thermo Electron Neptune, at NTU (Raza et al. 2017).*

Sample (ID)	Weight (g)	^{238}U ppb[a]	^{232}Th ppt	d^{234}U measured[a]	[^{230}Th/^{238}U] activity[c]	[^{230}Th/^{232}Th] ppm[d]	Age (yr BP) uncorrected	Age (yr BP) corrected[c,e]	d^{234}U$_{initial}$ corrected[b]
Va1_01	0.0656	8352.1 ± 7.9	3672.6 ± 8.9	827.4 ± 1.9	0.21198 ± 0.00043	7948 ± 24	13,259 ± 32	13,253 ± 32	859.1 ± 2.0
Va1_02	0.1170	10100 ± 10	815.1 ± 9.8	822.8 ± 1.9	0.23148 ± 0.00031	47289 ± 572	14,598 ± 27	14,597 ± 27	857.5 ± 1.9
Va1_03	0.0974	6594.5 ± 6.1	786.5 ± 4.9	909.0 ± 1.9	0.24445 ± 0.00033	33792 ± 213	14,720 ± 26	14,718 ± 26	947.7 ± 1.9
Va1_04	0.1031	7911.5 ± 8.1	2490.7 ± 6.0	913.8 ± 2.4	0.24702 ± 0.00050	12937 ± 39	14,845 ± 38	14,841 ± 38	953.0 ± 2.5
Va1_05	0.0909	10260.0 ± 9.5	649.3 ± 5.2	935.5 ± 1.8	0.25421 ± 0.00037	66230 ± 538	15,121 ± 28	15,120 ± 28	976.4 ± 1.9
Va1_06	0.1046	13236 ± 13	671.0 ± 4.6	894.5 ± 2.0	0.25048 ± 0.00034	81475 ± 561	15,232 ± 28	15,231 ± 28	934.0 ± 2.0
Va1_07	0.1569	8527.9 ± 7.8	708.1 ± 3.2	879.5 ± 1.7	0.25002 ± 0.00040	49649 ± 234	15,333 ± 30	15,332 ± 30	918.6 ± 1.7
Va1_08	0.1441	12616 ± 40	386.9 ± 3.4	915.2 ± 5.3	0.26006 ± 0.00094	139799 ± 1258	15,669 ± 76	15,669 ± 76	956.8 ± 5.5

Chemistry was performed on 3rd Dec., 2015 (Shen *et al.* 2002), and instrumental analysis on MC-ICP-MS (Shen *et al.* 2012).

Analytical errors are 2σ of the mean.

[a] $[^{238}U] = [^{235}U] \times 137.818$ (±0.65‰) (Hiess *et al.* 2012); $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$.

[b] $\delta^{234}U_{initial}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{-\lambda_{234} * T}$, and T is corrected age.

[c] $[^{230}Th/^{238}U]_{activity} = 1 - e^{-\lambda_{230} T} + (\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda_{230}-\lambda_{234})T})$, where T is the age.

Decay constants are 9.1705×10^{-6} yr^{-1} for ^{230}Th, 2.8221×10^{-6} yr^{-1} for ^{234}U (Cheng *et al.* 2013), and 1.55125×10^{-10} yr^{-1} for ^{238}U (Jaffey *et al.* 1971).

[d] The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio.

[e] Age (yr BP, before 1950 AD) corrections for samples were calculated using an estimated initial atomic ^{230}Th/^{232}Th ratio of 4 ± 2 ppm.

Those are the values for a material at secular equilibrium, with the crustal ^{232}Th/^{238}U value of 3.8. The errors are arbitrarily assumed to be 50%.

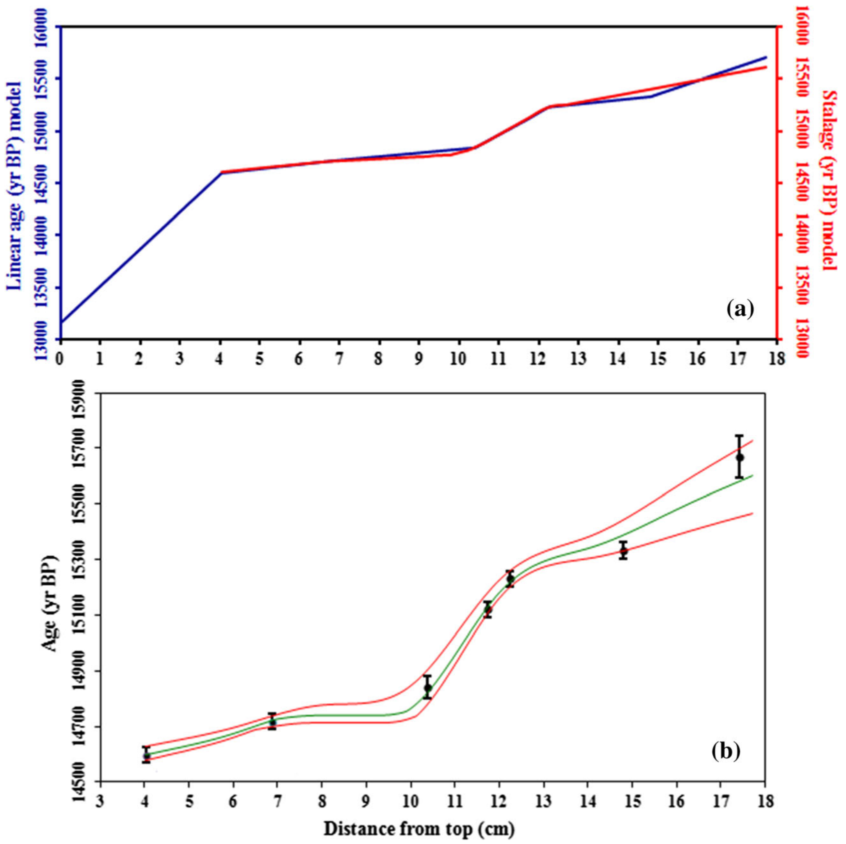

Figure 4. **(a)** Comparing linear and StalAge models for the ages between 13,161 and 15,607 yr BP and **(b)** the StalAge model. Green line represents modelled ages and red lines showing the 95% confidence limits. The black dots with vertical error bars represent eight ^{230}Th samples with standard error (modified after Raza *et al.* 2017).

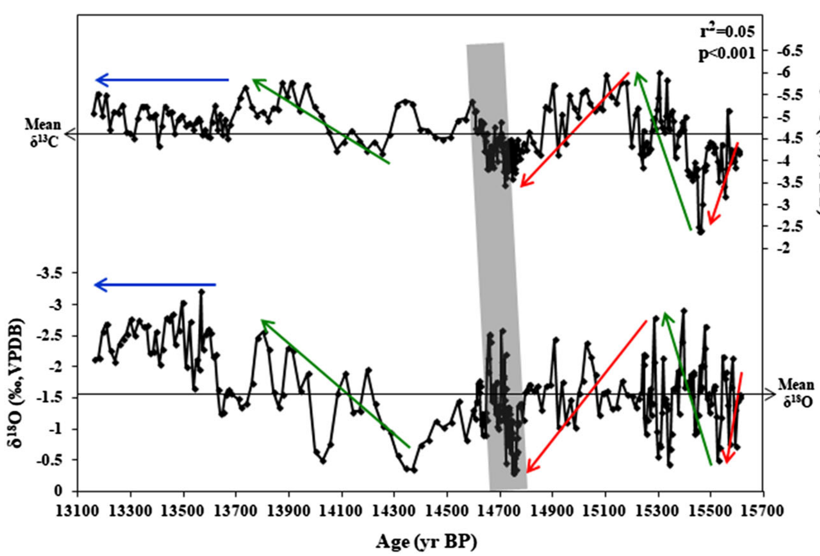

Figure 5. The variations in δ^{13}C (this study) and δ^{18}O (Raza *et al.* 2017) values of VSPM1 stalagmite is presented in this graph.

stalagmite due to the loss of water from the solution layer and the related increase of Ca^{2+} ion concentrations. This may lead to elevated precipitation rates and larger isotope fractionation. A change in pCO_2 due to ventilation effect can also influence stalagmite δ^{13}C values because of the effect of pCO_2 on the equilibrium concentrations of the CO_2–H_2O–$CaCO_3$-system.

The deployment of δ^{13}C for reconstruction of past climate is based on comprehensively diverging ratio of carbon isotopes ($^{13}C/^{12}C$) of C_3 and C_4 plants categorized on the basis of their photosynthesis pathways of carbon fixation. The δ^{13}C value of C_3 and C_4 plants ranges from −26 to −28‰ and −11 to −14‰ respectively (Smith and Epstein 1971). In addition, the δ^{13}C values of C_3 and C_4 plants are −24 to −33‰ and −10 to −16‰, respectively as reported by O'Leary (1988). Moreover, the δ^{13}C values of C_4 plants are ∼17‰ higher than C_3 plants and the majority of C_4 plants are grasses. Therefore, environmental shift from forest to grassland can cause an increase in δ^{13}C (Dorale *et al.* 1998). It can be observed from all above mention studies that the δ^{13}C values of C_3 plants are supposed to be far lower than C_4 plants. The C_3 plants dominate in the areas of elevated soil moisture whereas the C_4 plants dominate in arid, semi-arid climates and regions of low soil moisture (Tieszen *et al.* 1979b). Consequently, when the C_3 plants grow well under relatively warmer environment, the δ^{13}C is influenced by decomposition and deprivation of C_3 plants results in lesser δ^{13}C values of stalagmites (Zhang *et al.* 2004; Fairchild *et al.* 2006).

As shown in figure 5, a long-term trend is observed between δ^{13}C and δ^{18}O records of VSPM1 stalagmite on different time periods, despite some time lag. This time lag between these two tracers may be due to the time delay in δ^{13}C (carbon isotopes incorporation into the system) because of delayed response of vegetation change. Laskar *et al.* (2011) suggest that a short-term correlation between δ^{13}C and δ^{18}O records is somewhat problematic because of the presence of old carbon in deeper soil horizons. The absence of a strong relationship between δ^{13}C and δ^{18}O values of VSPM1 stalagmite could be attributed to some contribution arising from the old soil carbon with a different isotopic composition. It appears that the hydroclimate may have influenced both oxygen and carbon isotopes. It may be noted that the vegetation cover over the Valmiki cave was probably influenced by the climatic activity as reflected in VSPM1 stalagmite δ^{13}C record. An increase in summer temperature and rainfall can lead to enhancement in vegetation density and production of soil CO_2, resulting in lower δ^{13}C values. Also, the increase in drip rate and reduction in degassing time due to improved rainfall results in decreasing and vice-versa. Although, δ^{13}C values of a stalagmite are influenced by various factors as discussed above, the vegetation changes are generally considered as the dominating factor that controls δ^{13}C of a stalagmite. The enrichment trend from 15,568–15,460 and 15,105–14,722 yr BP is clearly seen in VSPM1 δ^{13}C record. The δ^{13}C increases steadily with small fluctuations during these periods. The δ^{13}C increase of ∼2.75‰ from 15,568 to 15,460 yr BP suggests a decline in vegetation cover during this period with poorest vegetation environment around 15,473 yr BP manifested by the most enriched δ^{13}C value. This severe drop in vegetation coverage shown by the most enriched δ^{13}C at ∼15,473 yr BP may have caused by some local vegetation change at this time. A gradual shift from 15,460 to 15,105 yr BP, marked by 3.55‰ δ^{13}C decrease due to change in vegetation density has been attributed to strengthened ISM activity (Raza *et al.* 2017). A gradual increase in δ^{13}C is observed from 15,105 to 14,722 yr BP followed by decrease in δ^{13}C from 14,722 to 14,597 yr BP showing reduction in vegetation density from 15,105 to 14,722 yr BP followed by enhanced vegetation coverage from 14,722 to 14,597 yr BP. Moreover, the shaded bar in figure 5 represents the coincident variability in δ^{13}C (this study) and δ^{18}O (Raza *et al.* 2017) values of VSPM1 stalagmite at around ∼14,722 and 14,750 yr BP, respectively, during Termination 1a (i.e., the onset of late-glacial interstadial around 14,800 yr BP). This simultaneous reduction and enhancement in vegetation density are also demonstrated by a decline in ISM activity followed by strengthening of ISM precipitation based on δ^{18}O values during these periods (Raza *et al.* 2017). The δ^{13}C values are relatively depleted than the average δ^{13}C value between 14,597 and 13,161 yr BP, indicating a good vegetative cover during this period. Raza *et al.* (2017) also reported an enhancement in ISM activity during this period, except from 14,656 to 14,369 yr BP. The VSPM1 δ^{13}C record shows that δ^{13}C values are mostly lighter than the average between 14,597–13,161 yr BP and 15,404–4,872 yr BP, whereas heavier between 14,872–14,597 yr BP and 15,607–15,404 yr BP indicating vegetation density was relatively better from 14,597 and 13,161 yr BP and 15,404 and 14,872 yr BP, while there was deprived vegetation environment from 14,872–14,597 yr BP to 15,607–15,404 yr BP. The better vegetation coverage during 14,597–13,161 yr BP is also evident by intensified ISM activity marked by gradual decrease in δ^{18}O during this period except from 14,656 to 14,369 yr BP.

Therefore, based on our findings, the climatic patterns can be categorized in three major phases: relatively wet period with better vegetative coverage from 15,607 to 15,105 yr BP revealed by VSPM1 δ^{13}C values fluctuating above the average value of δ^{13}C, a dry period with low vegetation cover between 15,105 and 14,722 yr BP followed by gradually strengthened vegetation activity between 14,722 and 14,597 shown by increase and decrease in δ^{13}C values respectively and lastly a moderately wet period with good vegetation cover from 14,597 to 13,161 yr BP represented by decreasing trend in δ^{13}C values of VSPM1 stalagmite (figure 5). These changes in vegetation cover and density based on δ^{13}C values of VSPM1 stalagmite (this study) from $\sim$15,607 to 13,161 yr BP is also verified by the variations in Indian summer monsoon (ISM) activity based on stable oxygen isotope record of the same sample (Raza *et al.* 2017). An almost synchronous variability appears between δ^{13}C and δ^{18}O records of VSPM1 stalagmite (figure 5).

5. Comparison of VSPM1 δ^{13}C record with another stalagmite record

We have compared δ^{13}C variations of VSPM1 stalagmite with another published δ^{13}C record of a stalagmite sample KL-3 in figure 6 from the northern India (Kotlia *et al.* 2016). The locations of VSPM1 (15°09′N: 77°49′E) and KL-3 (33°13′19″N: 74°25′ 33″E) stalagmites lies at an elevation (altitude) of 420 and 826 m above sea level respectively. The objective was to understand the response of hydroclimate and vegetational changes for the studied time interval. The δ^{13}C values of VSPM1 stalagmite show greater δ^{13}C values (ranging from −2.42 to −6.02‰ with an average value of −4.54‰), whereas δ^{13}C of KL-3 stalagmite show significantly lower values (ranging from −8.03‰ to −10.40‰ with an average value of −9.24‰) (figure 6). Although, the comparison between δ^{13}C records of VSPM1 and KL-3 stalagmites does not show a strong one-to-one relationship, broad synchronous variations appear in both records on multidecadal to centennial time scales within age uncertainties (figure 6). Moreover, the amplitude variations in δ^{13}C values for the two records (VSPM1 and KL-3) after around 13,700 yr BP is almost similar ($\sim$1.5‰). A gradual δ^{13}C depletion in both these records from around 14,300 to 13,700 yr BP is clearly evident in figure 6. The amplitude difference of $\sim$1.23‰ in δ^{13}C records of VSPM1 and KL-3 stalagmites may be due to the difference in vegetation changes in both these regions. The average δ^{13}C value of KL-3 is $\sim$4.7‰ lower than the average δ^{13}C value of VSPM1 stalagmite. There are many factors that may be responsible for this large difference in δ^{13}C values, such as the hydroclimatic conditions, dissimilar mineralogy of source rocks, vegetation type (C_3 and C_4 plants), etc. It may be noted that the host carbonate rock composition plays a vital role in δ^{13}C values of stalagmites. The host rock for KL-3 stalagmite is limestone, whereas VSPM1 stalagmite was accumulated by overlying dolomite. In addition, the contribution of C_3 and C_4 plants might have played a role in δ^{13}C values of these two stalagmites. Moreover, the amount of organic and inorganic carbon contribution in both the samples cannot be

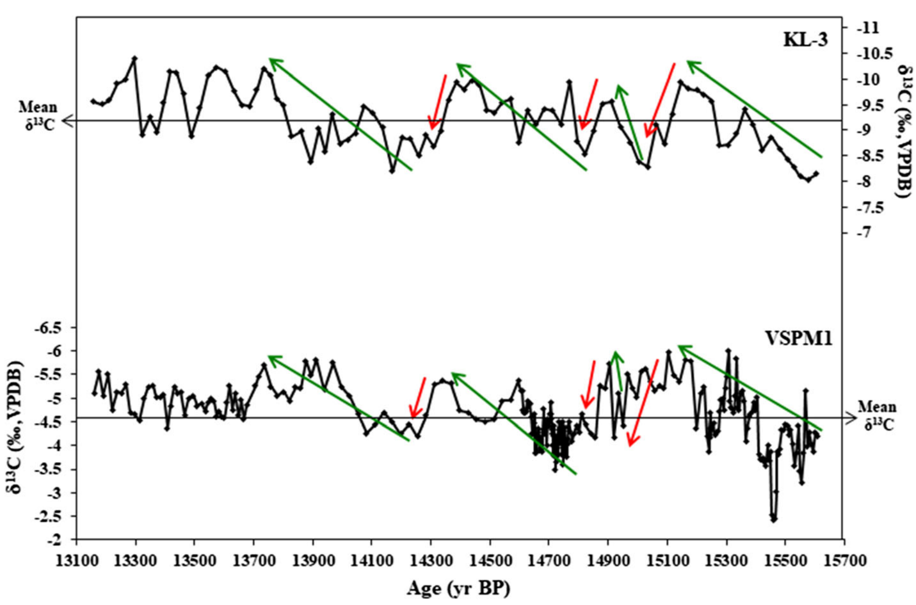

Figure 6. Graph shows the synchronous variability between δ^{13}C values of VSPM1 (this study) and KL-3 (Kotlia *et al.* 2016) stalagmites.

ruled out which could have an effect on the $\delta^{13}C$ values of stalagmites. Usually in higher altitudes, the erosion is relatively more responsible for any change in environmental system than chemical weathering. It seems that there could be more inorganic carbon content in VSPM1 stalagmite because of somewhat more chemical weathering of host rock in southern India due to higher rainfall as compared with KL-3 stalagmite from the north Indian region. The $\delta^{13}C$ values of KL-3 stalagmite are more negative relative to VSPM1 $\delta^{13}C$ values due to more organic carbon contribution. This could be because of more organic carbon supply to cave overlying soil from fallen leaves and relatively less inorganic carbon contribution from the host rock.

6. Conclusions

This study demonstrates the importance of stable carbon isotopes in understanding hydroclimate and paleo-vegetation changes during the last deglaciation based on variations in $\delta^{13}C$ values of VSPM1 stalagmite from southern India. The $\delta^{13}C$ fluctuations suggest rapid changes in vegetation controlled by ISM activity between 15,607 and 13,161 yr BP. Three major phases were noticed during the time window of this study, first a wet period of good vegetative coverage from 15,607 to 15,105 yr BP, followed by a dry period with low vegetation cover between 15,105 and 14,722 yr BP and finally another wet event from 14,722 to 13,161 yr BP. These changes in vegetation cover, based on $\delta^{13}C$ record of VSPM1 stalagmite was controlled by local hydroclimate as evident by its $\delta^{18}O$ record. This study establishes the utility of stable carbon isotopes in stalagmites as an important tracer of paleo-vegetation activity.

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Author statement

Waseem Raza: Carried out the field work, isotopic analysis, interpretation of data and initial draft preparation. Syed Masood Ahmad: Designed the study, guided the analytical work, contributed in the write-up of final version of the manuscript and overall supervision of the work. D Srinivasa Sarma: Contributed in field study, data interpretation and write-up of initial and final version. E V S S K Babu: Contributed in data collection.

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