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Mid–late Holocene palaeoclimate and biogeochemical evolution of Wular Lake, Kashmir Valley, India

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ABSTRACT: Continuous multiproxy data were generated to understand the mid–late Holocene palaeoenvironmental history of the Kashmir Valley and the biogeochemistry of Wular Lake, India. For this purpose, geochemical and stable isotopic analyses were carried out on sediment samples retrieved from a 160 cm long trench excavated on the eastern bank of Wular Lake located in the Union Territory of Jammu and Kashmir, India. The chronology of the sediment strata developed using ^{14}C dating by accelerator mass spectrometry covered the last ~5600 yr BP. Our results indicated the occurrence of an extended dry climate phase from 4600 to 3800 yr BP, which coincided with the widely recognised Meghalayan Stage, when major civilisations like the Harappa and the Akkadian were known to collapse. The lake biogeochemistry revealed dominance of the emergent macrophytes during this stage. Another dry phase was observed between 3100 and 2200 yr BP. This dry phase peaked at around 2900 yr BP, coinciding with Bond Event 2. Wular Lake faced nutrient limitation due to low runoff around 2500 yr BP caused by the persistent dry and cold climate. Geochemical signatures revealed that anthropogenic activities during the last two millennia might have significantly influenced erosion in the catchment area. © 2023 John Wiley & Sons, Ltd.

KEYWORDS: Carbon and nitrogen isotopes; geochemistry; Holocene palaeoenvironment; limnology; Wular Lake

Introduction

The Holocene interglacial warm climate was punctuated by a number of dry climate events, termed 'Bond events', which are known to have resulted from ice rafting in the North Atlantic (Bond et al., 1997, 2001). These major dry climate events influenced humans and resulted in numerous behavioural changes, which have been observed in various archaeological records (Weninger et al., 2006; Akkermans et al., 2006; Berger and Guilaine, 2009; Nishiaki, 2010; Van der Plicht et al., 2011; Nisiaki, Darabi, 2018). Some of these dry events of a global nature, due to their direct impact on agricultural yields, resulted in worldwide societal collapse or forced humans to alter their agricultural practices (Kerr, 1998; Sengupta et al., 2019), particularly during the late Holocene. The intense aridity period around ~4200 yr BP is known to have resulted in the collapse of the Indus Valley civilisation in Asia (Jarrige and Meadow, 1980; Archer and Fowler, 2004; Sengupta et al., 2019). Arid conditions in the Mesopotamia region during this period also resulted in the collapse of the Akkadian empire (Weiss et al., 1993; Kerr, 1998).

Studies related to the above-mentioned dry event and its impact on civilisation are limited for the Indian sub-continent. Given the prominence in the human pastoral, agricultural practices and migration history, such studies in the Kashmir Himalayas, particularly the Kashmir Valley, are of extreme importance. The Kashmir Valley is 140 km long by 40 km wide and lies in the subtropical region of the western Himalayas, where the present climate is dominantly influenced by the westerly derived moisture sources (Ali and Juyal 2013; Dixit and Tandon 2016; Lone et al., 2020a). Thus the influence of several Bond Events (4 (~5900 yr BP), 5 (~8200 yr BP), 7 (~10 300 yr BP) and 0 (~500 yr BP)) has been observed and reported by earlier studies (Shah et al., 2020a; Shah et al., 2021). Of the many remnant lakes (Manasbal, Anchar and Dal) located in the Kashmir Valley, continuous and high sedimentation rates have been observed in Wular Lake (Shah et al., 2017; Shah et al., 2021). An earlier study from the lake revealed strong precipitation during the Holocene Climate Optimum and a strong influence of Bond Events 4 (~5900 yr BP), 5 (~8200 yr BP) and 7 (~10 300 yr BP) during the early Holocene (Shah et al., 2020a), whereas Bond Event 0 (~500 yr BP) had a strong influence during the late Holocene (Shah et al., 2021). The carbon isotopic composition of black carbon from Wular Lake, revealed a drier climate phase during the period 3752 to ~1500 yr BP, along with an extreme dry event at 2500 yr BP, and a wet climate phase from 1500 yr BP to recent (Verma et al., 2023). A late Holocene palaeoenvironmental study carried out in Manasbal Lake suggested the influence of the Indian Summer Monsoon (ISM), westerlies and the local katabatic winds (Babeesh et al., 2019). Further, Lone et al. (2020b) suggested the prevalence of westerly dominated precipitation in the Kashmir Valley during the late Holocene. However, high-resolution palaeoclimate data for the mid–late Holocene period from Wular Lake is yet to be reported. Given the limited numbers and lack of high-resolution data from the mid to late Holocene period from the Kashmir Valley, this study aims to bridge this gap. High-resolution chronological (^{14}C AMS) and multiproxy data obtained through analysing an ~160 cm deep sediment trench covering the last ~5600 yr BP have been provided in this study. The main objective of the present study was to understand and reconstruct the mid–late Holocene palaeoenvironmental record of the Kashmir Valley. Along with climate changes during the last 5600 yr BP, this study also attempted to decipher the source of organic matter and associated biogeochemical changes in the lake.

Material and methods

Study area

Wular Lake (34°16′–34°20′N and 74°33′–74°44′E) is located in the Bandipora district (Kashmir Valley) of the Union

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Territory of Jammu and Kashmir, India. The Kashmir Valley is a graben-shaped landscape of ~140 km length and ~60 km width, at an average elevation of ~1800 m above mean sea level. The valley is enclosed between the greater Himalayan mountain range to the northeast and the Pir-Panjal mountain range to the southwest. Wular Lake lies in the course of the Jhelum River that drains water and sediments from south and central Kashmir to the lake. The lake water is largely neutral in pH and oxic (Ganai et al., 2010; Shah et al., 2020b). It hosts a variety of phytoplankton, zooplankton and macrophytes (Ganai et al., 2010; Ganai and Parveen, 2014). The anthropogenic influence has resulted in a moderate level of metal pollution in the lake sediments (Shah et al., 2020c). The geology in the higher regions of the catchment area is dominated by basaltic and andesitic rocks of Panjal volcanic series dating from the upper Carboniferous to lower Permian (De Terra, Paterson, 1939), whereas the central part of the valley is dominated by the Plio-Pleistocene Karewa Formation of fluvial, glacial and aeolian origin (De Terra, Paterson, 1939).

Sampling and measurements

A sediment trench of 160 cm depth was dug on the eastern bank of Wular Lake near Banyari village (34°21′23″N–74°39′37″E) located at the confluence of the Jhelum River and the lake (Figure 1). The sediment sampling was carried out at 2 cm intervals from the top to the bottom of the trench. Samples of ~1 cm vertical thickness were taken from six depths for radiocarbon dating. All the samples were dried in a hot air oven at 70°C.

The chronology of the sediment sequence was determined by dating bulk organic matter using an accelerator mass spectrometer at the Physical Research Laboratory, Ahmedabad, India. Sediment samples were first treated with 1 M HCl to eliminate carbonates and then with 0.1 N NaOH solution to remove the humic acid, followed by rinsing with ultrapure water to bring it to a neutral pH. Treated samples were then dried to remove the water. Next, the samples were combusted in a vacuum glass line at ~1000°C to extract CO_2 gas. This extracted gas was passed through silver wool to remove halides and later cleaned in multiple steps by freezing and thawing in a vacuum glass line using liquid nitrogen. While the CO_2 was frozen, all other gases generated, if any, were pumped out. The extracted CO_2 was reduced to graphite by heating at ~550°C in the presence of catalyst iron powder and Zn at ~450°C to utilise oxygen and form ZnO. The ^{14}C ages were calibrated using IntCal 13 atmospheric calibration data (Reimer et al., 2013) in OxCal v 4.3.2 (Bronk Ramsey, 2017). The age–depth model was also generated using the same software.

The isotopic composition of organic carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) along with total organic carbon (TOC) and nitrogen (N) content in the samples were analysed using EA-IRMS (Delta V plus Isotope Ratio Mass Spectrometer interface with Flash 2000 Elemental Analyzer). For organic carbon content and isotopic compositions, the dried and powdered samples were treated with 1 M HCl at 80°C to eliminate sediment carbonates (Verardo et al., 1990). The treated samples were washed with ultrapure water and dried at 60°C in a lab oven. The dried samples were packed into a tin capsule for mass spectrometer analysis. For nitrogen content and its isotopic compositions, bulk sediment samples were used without any chemical pretreatment. Cellulose (IAEA-CH-3; $\delta^{13}C = -24.74 \pm 0.04$‰; C content ~44.4%) and ammonium sulphate (IAEA-N-2; $\delta^{15}N = 20.3 \pm 0.08$‰; N content ~21.2%) were used as laboratory standards for the C and N analyses, respectively. The reproducibility for C and N isotopic compositions for repeat measurements of standards were better than 0.1 and 0.3‰, respectively. The analytical uncertainty for C and N content for repeat samples was <10%.

The elemental concentrations of the sediment samples were measured using VP-320 X-ray fluorescence (XRF) spectrometry. Dried and powdered samples were treated with 1 M HCl at 80°C to eliminate sediment carbonates (Verardo et al., 1990) and H_2O_2 to remove organic matter

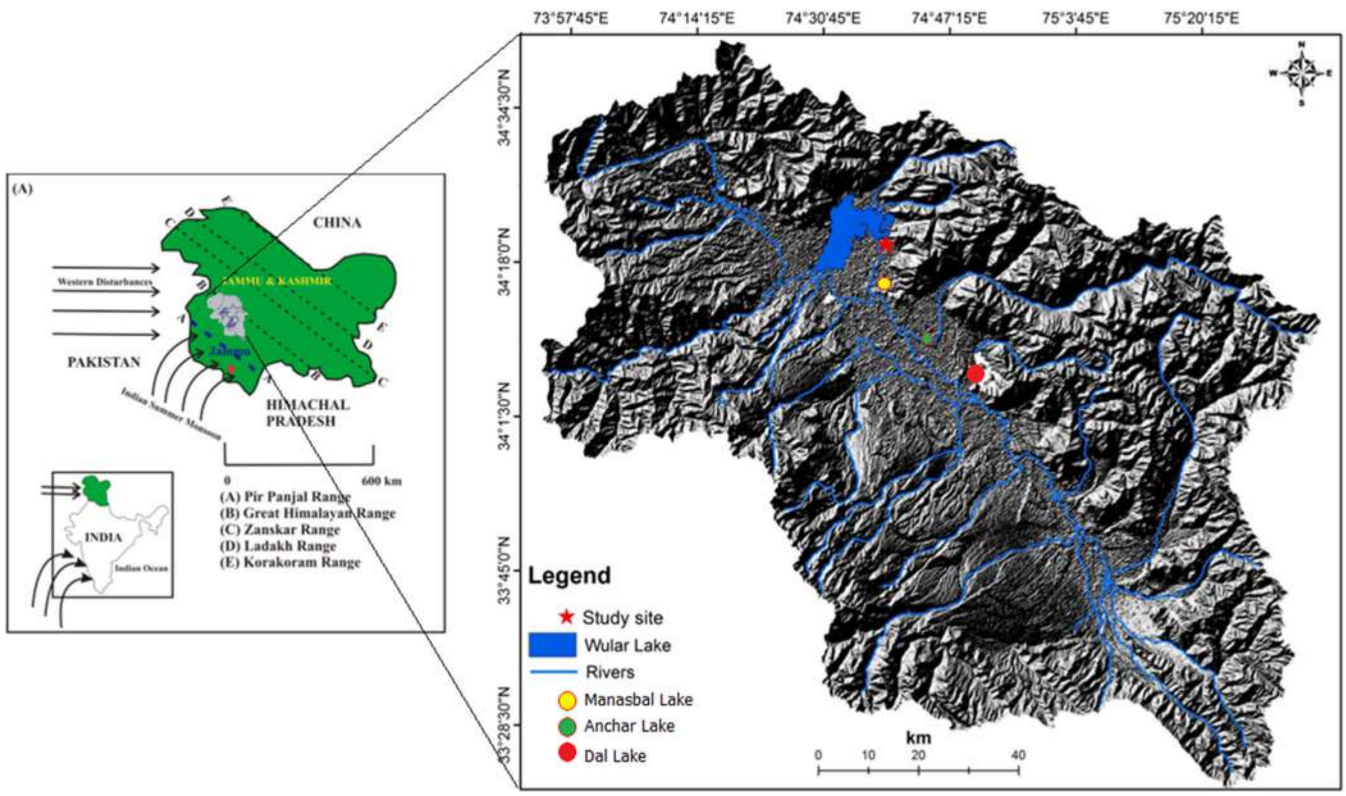

Figure 1. Study area map showing trench site on the eastern margin of Wular Lake. [Color figure can be viewed at wileyonlinelibrary.com]

(Ingram, 1970). Pressed powdered pellets were prepared by homogeneously mixing the sample and binder in a 4:1 ratio. The accuracy of the analytical method was established using an internationally recognised standard reference material (SDO – 1). The analytical error for major oxides was <5%. The chemical index of alteration (CIA) was calculated based on the abundance of mobile and immobile elements using the formula proposed by Nesbitt and Young (1982) as:

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \times 100 \quad (1)$$

Here the CaO* represents the amount of CaO only incorporated as silicates.

The chemical index of weathering (CIW) was calculated using the following formula proposed by Harnois (1988).

$$CIW = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O} \times 100 \quad (2)$$

Results

Sediment sequence

The sediment sequence in the trench was characterised by a vertical arrangement of various sediment types with predominantly fine-grained sediments (Figure 2). The upper portion of the sequence, extending up to 62 cm and dating back less than 1700 years BP, exhibited diverse sediment texture, with sediment strata gradually transitioning into one another.

The top 10 cm of this section consisted of dark grey sandy clay (2.5 Y 5/1). Below this layer, there was a 4 cm thick horizon of reddish yellow clay (7.5 YR 6/8) followed by a 6 cm thick layer of grey sand (2.5 Y 5/1) between depths of 15 and 20 cm. At 21–24 cm depth, there was a 4 cm thick horizon of oxidised silty clay with an olive-yellow colour (2.5 Y 6/8), followed by a 4 cm thick layer of dark grey sandy silt (2.5 Y 5/1) from 25–28 cm depth. Continuing downward, there was an 8 cm thick horizon of reddish yellow clay (7.5 YR 6/8) from 29–36 cm depth and a 4 cm thick grey sand (2.5 Y 5/1) layer from 37–40 cm depth. The sequence continued with a 9 cm thick horizon of oxidised silty clay in an olive-yellow colour (2.5 Y 6/8) from 41–49 cm depth, followed by a thin 2 cm layer of reddish yellow clay (7.5 YR 6/8) from 50–51 cm. From 52–58 cm depth, there was a 7 cm thick horizon of oxidised silty clay in an olive-yellow colour (2.5 Y 6/8) and a 4 cm thick layer of grey sand (2.5 Y 5/1) from 59–62 cm depth (Figure 2).

Below the upper 62 cm, there was a consistent 88 cm thick horizon of uniform light brown clayey silt (7.5 YR 6/3) from depths of 63–150 cm. This horizon displayed minimal variation but showed significant differences in the proxy data records. Subsequently, a grey-coloured coarse sand horizon (2.5 Y 5/1) was observed with a sharp contact between the sediment strata above and below it. This sand horizon was not sampled for analysis because of the disturbance due to the water saturation of this highly permeable horizon, and sampling was limited up to 150 cm depth (Figure 2).

Chronology

Chronology of the sediment sequence generated using ^{14}C dating methods and calibrated using OxCal software showed that the ages of the sequence ranged from 5750 to 42 cal. yr BP (Table 1). The calculated sedimentation rates showed a significant variation with slower sedimentation towards the lower end of the section and increase in sedimentation rate during the last two millennia (Figure 2). The age–depth model suggested sedimentation rates of 25.42 cm kyr^{-1} from 145 to 141 cm (~5750–5590 cal. yr BP), 18.11 cm kyr^{-1} from 141 to 101 cm (5590–3381 cal. yr BP) and 15.03 cm kyr^{-1} from 101 to 85 cm (3381–2316 cal. yr BP). Subsequently, the sedimentation rate increased to 34.74 cm kyr^{-1} from 85 to 65 cm (2316 to 1741 cal. yr BP), 46.4 cm kyr^{-1} from 65 to 51 cm (1741–1439 cal. yr BP), 52.69 cm kyr^{-1} from 50 to 21 cm (1439–869 cal. yr BP) and 25.39 cm kyr^{-1} from 21 to 1 cm (869–42 cal. yr BP). In general, relatively higher sedimentation rates were observed during the last two millennia.

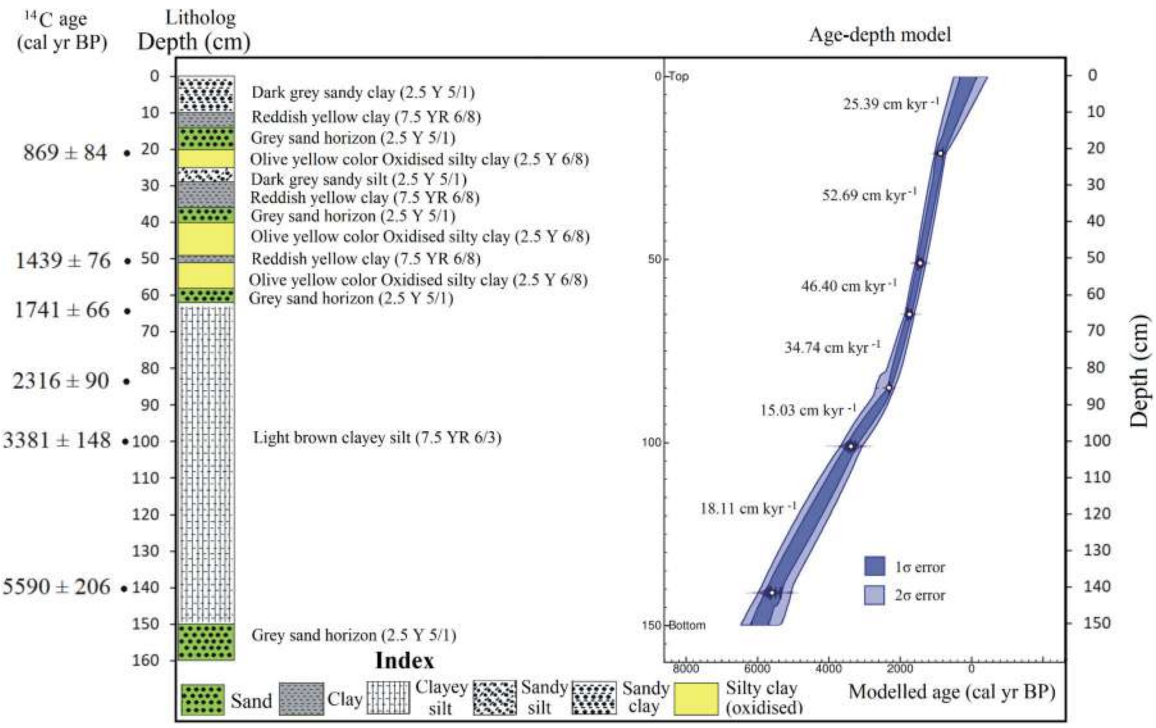

Figure 2. Litholog and calibrated age versus depth model of the studied trench sediment sequence. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. AMS ^{14}C ages of the analysed sediment samples.

S. No.	Sample ID	Depth (cm)	Radiocarbon age (yr bp)	Calibrated age (cal. yr BP) From	To	Age (cal. yr bp)
1	PRL3518	21	1190 ± 90	1034	731	869 ± 84
2	PRL3519	51	1400 ± 130	1571	1284	1439 ± 76
3	PRL3645	65	1730 ± 70	1869	1612	1741 ± 66
4	PRL3646	85	2190 ± 70	2682	2168	2316 ± 90
5	PRL3520	101	3260 ± 150	3678	3075	3381 ± 148
6	PRL3521	141	5090 ± 160	5987	5056	5590 ± 206

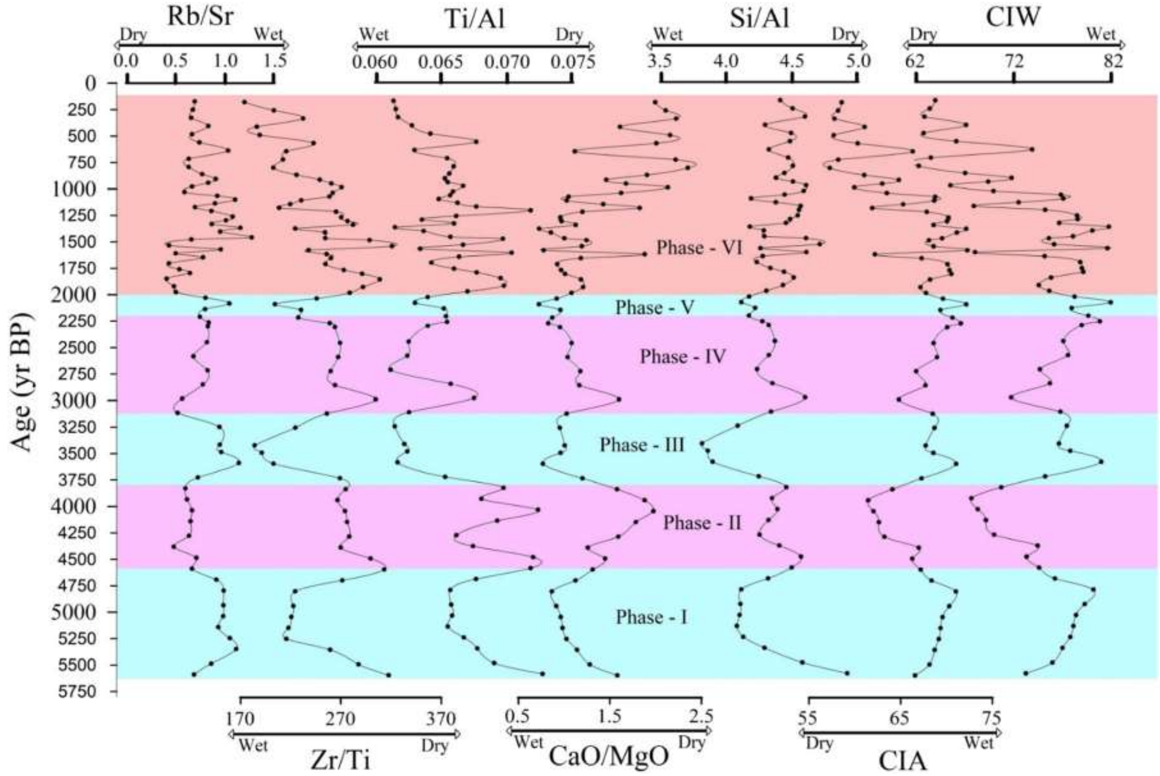

Figure 3. Temporal variations in geochemical proxies (blue: warm climate phase; pink: cold/dry climate phase; red: anthropogenic-influenced phase). [Color figure can be viewed at wileyonlinelibrary.com]

Geochemistry and stable isotopes

The sediment deposition rate during 5600–4600 cal. yr BP was ~18.11 cm kyr^{-1}. This segment revealed comparatively high values for CIA and CIW. A comparatively high Rb/Sr ratio and low value of weathering proxies CaO/MgO, Zr/Al, Ti/Al and Si/Al were also observed in this segment (Figure 3). A relatively high N percentage was also observed during this phase (Figure 4). A significant lowering of CIA, CIW and Rb/Sr ratio was noticed from 4600 to 3800 cal. yr BP. Decreases in TOC and N content and weathering proxies CaO/MgO, Zr/Al, Ti/Al and Si/Al were also observed. The sedimentation rate during 3800–3100 cal. yr BP was nearly equal to the earlier two phases. However, this segment revealed sediment deposition with high CIA, CIW, Rb/Sr ratio, TOC and N content, whereas CaO/MgO, Zr/Al, Ti/Al and Si/Al were relatively low. From 3100 to 2200 cal. yr BP, sedimentation showed lower CIA, CIW and Rb/Sr ratios (Figure 3). A decrease in TOC and N content were also observed. CaO/MgO, Zr/Al, Ti/Al and Si/Al revealed a substantial increase compared with the earlier phase (Figure 3). From 2200 to 2000 cal. yr BP, the down-trench profile of the proxy records showed a significant increase in the sedimentation rate (Figure 2), whereas the CIA, CIW, Rb/Sr ratio, TOC and N content along with δ^{15}N again showed increasing values. For this duration, CaO/MgO, Zr/Al, Ti/Al and Si/Al showed relatively low values. The average sedimentation rate from 2000 to 0 cal. yr BP was very high (~50 cm kyr^{-1}) with a significant increase in δ^{15}N to as high as 6.9‰. Other geochemical proxies did not reflect a clear trend for this time segment as was observed in the earlier phases. Instead, signals appeared to be noisy with peaks and dips (Figures 3 and 4). Three phases of high values for δ^{13}C were observed (−16 to −14‰) corresponding to 976 cal. yr BP, 714 cal. yr BP, and for the surface sample.

Discussion

In general, the palaeoenvironmental evolution during the Holocene in the Kashmir Valley has been linked to the western disturbances (Shah et al., 2020a). However, mid–late Holocene palaeoenvironmental records are meagrely reported from the area. This study has bridged that gap along with an improved understanding of the biogeochemical evolution of Wular Lake. The present study reveals significant intervals of

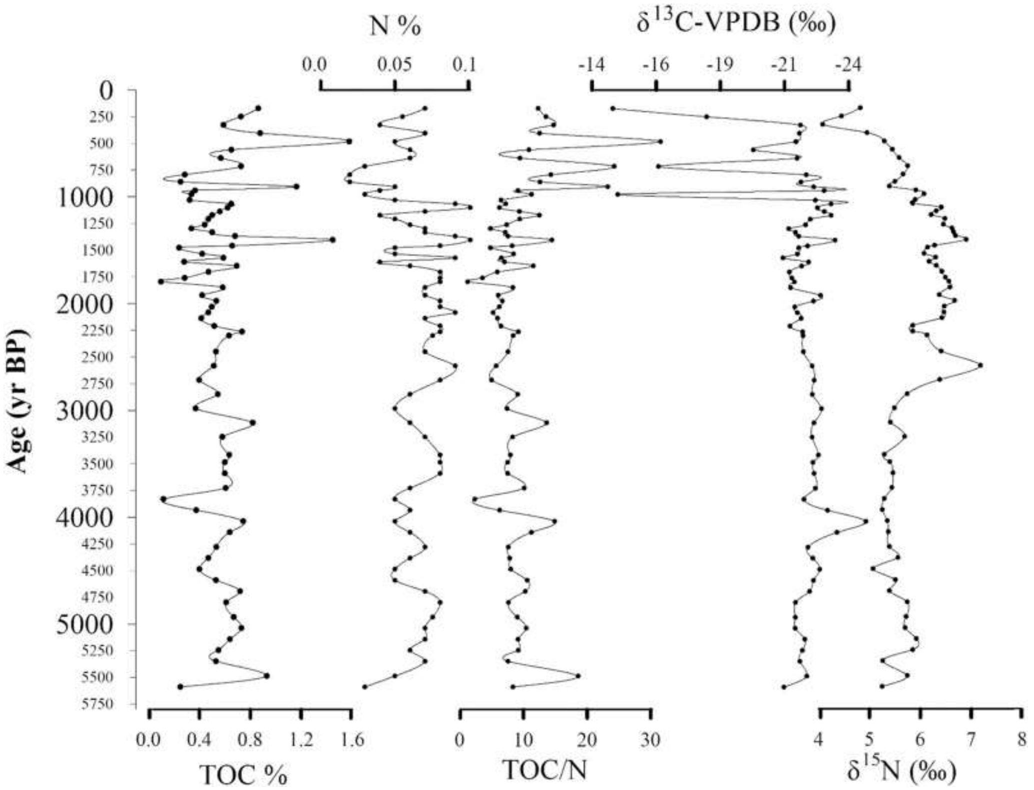

Figure 4. Temporal variations in organic carbon and nitrogen content and their isotopic compositions.

hydroclimatic shifts that controlled the physical and chemical alteration of the sediments around Wular Lake during the late Holocene and caused strong dry climate phases at 4600–3800 yr BP and 2900 yr BP. The upper 62 cm of the sediment sequence indicated multiple environmental changes during sedimentation, characterised by turbulent phases with coarser sediment deposition and a higher sedimentation rate. In contrast, the lower 88 cm revealed a consistent fine sediment grain size, suggesting sediment deposition in a relatively deeper water column under calm water conditions. Different phases characterised with prominent climatic shifts in the region are discussed below.

Characteristic climate phases

Phase I (5600–4600 yr BP): This time range was characterised by high weathering indices (CIA and CIW; Figure 3) indicating the occurrence of a strong wet climate as is globally reflected during the Holocene Climate Optimum. This is also supported by high Rb/Sr ratio along with low CaO/MgO, Zr/Al, Ti/Al and Si/Al values. Concentration of N in sediments increased from 0.03% (5590 yr BP) to 0.08% (4796 yr BP) and subsequently decreased to 0.05% (4589 yr BP) by the end of this phase. TOC/N during this phase was mostly ~10 that suggested largely *in situ* production (Figure 4). The strong wet climate would have resulted in enhanced precipitation resulting in impoundment of water in the lake basin and creating a thicker water column during this phase. The occurrence of the thicker water column would have also caused the expansion of the lake margins and resulted in the submergence of the present-day dried margins. The Neolithic culture reportedly developed in the Kashmir Valley possibly during this phase, with agricultural evidence of wheat and barley production by 4.5 ka (Spate et al., 2017). The excavation work from Burzohama, Kanispura, Gufkral and Qasim Bagh collectively shows evidence of the development of Neolithic culture in the Kashmir Valley during this phase (Possehl 2002; Mani 2000; Sharma 2013; Spate et al., 2022b).

Phase II (4600–3800 yr BP): This phase signified a strong period of dry climate which coincided with the Meghalayan Stage (Walker et al., 2018) and Bond Event 3 (Bond et al., 2001). Occurrence of a dry climate during this phase is supported by significantly low values of CIA, CIW and Rb/Sr ratio (Figure 3) and substantial increase in the values of weathering proxies CaO/MgO, Zr/Al, Ti/Al and Si/Al compared with phase I. The detrital geochemistry and weathering indices (Figure 3) signified low precipitation in the catchment area that resulted in weak alteration of the sediments. This is further supported by the reports of West Asian wheat, barley, lentils and East Asian broomcorn millet production in the Kashmir Valley as early as 4.4 ka, suggesting dry agriculture practices in the region (Spate et al., 2017; Yatoo et al., 2020; Spate et al., 2022b). The dry climate during this phase would have resulted in low precipitation in the catchment area resulting in extreme lowering of water levels and desiccation of lake margins. The occurrence of a dry climate event at ~4250 cal. yr BP is widely reported on the Indian subcontinent and is related to a weak ISM (Staubwasser et al., 2002; Gupta et al., 2003; Giosan et al., 2012; Ponton et al., 2012; Dixit et al., 2014; Prasad et al., 2014; Dutt et al., 2018). This dry climatic event at 4.2 ka had resulted in severe effects on the human civilisations *viz*., the Indus Valley civilisation, the Akkadian empire, etc. (Witzel, 1987; 1999; Wright, 2010; Giosan et al., 2012; Sarkar et al., 2015; Kathayat et al., 2017; Petrie et al., 2017; Kathayat et al., 2018). The Meghalayan dry/cold climate stage was terminated by a relatively wetter phase ~3800–3100 yr BP (Kathayat et al., 2018). Similar variability is seen in our reconstructed record.

Phase III (3800–3100 yr BP): Following the strong dry climate that terminated at ~3800 cal. yr BP, a climatic improvement was inferred during 3800–3100 cal. yr BP. This phase was characterised by high CIA, CIW and Rb/Sr ratio, while CaO/MgO, Zr/Al, Ti/Al and Si/Al show relatively low values (Figure 3), suggesting ameliorating climate conditions. The TOC/N ratio of ~10 suggests *in situ* lake productivity. Climatic improvement during this time would have resulted in enhanced precipitation leading to impoundment of a thicker water column in the lake basin and expansion of the lake margins.

Phase IV (~3100–2200 yr BP): Following a relatively wet phase ~3800–3100 cal. yr BP, another dry/cold climate event from ~3100–2200 cal. yr BP appeared to have prevailed. This event is revealed in proxy data by a substantial increase in CaO/MgO, Zr/Al, Ti/Al and Si/Al, while the weathering indices CIA, CIW and Rb/Sr ratio have decreased (Figure 3). This dry phase peaked at around 2900 yr BP, coinciding with Bond Event 2. This dry event was comparatively less intense than phase II, but this phase would have also resulted in low precipitation, lowering of water levels and desiccation of the lake margins.

Phase V (~2200–2000 yr BP): The proxy data suggested the occurrence of another brief warm climate phase from ~2200 to 2000 cal. yr BP due to enhanced chemical weathering as revealed by CIA, CIW and the Rb/Sr ratio. CaO/MgO, Zr/Al, Ti/Al and Si/Al showed relatively low values (Figure 3). A significant increase in sedimentation rate suggested a possible surge in runoff and precipitation. Lake margins would have again expanded during this phase due to the accumulation of the thicker water column by the enhanced precipitation.

Phase VI (2000–0 yr BP): An unexpectedly high rate of sedimentation (~50 cm kyr^{-1}) and the geochemical proxy records did not reflect a clear trend; rather, these showed noisy data. Contrary to other phases, the geochemical data revealed a mixture of low and high values of CIA and CIW with an increased sedimentation rate. This points towards the conclusion that anthropogenic-aided physical weathering in human-occupied regions and normal chemical weathering in undisturbed areas was occurring simultaneously, which pointed towards potential human habitation and land use and land cover transformation during the last two millennia. The high sedimentation rate also indicated acceleration in sediment erosion in the catchment area possibly due to enhanced transformation of pastures and forest land into agricultural fields as observed elsewhere (Bradshaw et al., 2005).

Biogeochemical changes in Wular Lake

The sample collection site for this study, chosen at the confluence of the Jhelum River and the lake, provided an excellent opportunity to understand the impact of riverine inputs on the lake's biogeochemistry. Furthermore, as the sampling site is currently a desiccated bank of the lake, it could be used to infer changes in biology (submerged or emergent plants) caused by changes in lake levels using stable isotope systematics (Figure 5). It has been reported that Wular Lake experienced extreme water level changes that led to consecutive deep and shallow water conditions due to changes in the Jhelum River discharge in wet and dry periods, respectively (Shah et al., 2020a). Along with primary productivity and terrestrial input, macrophytes are also one of the dominant organic matter sources in the littoral zone of Wular Lake. Various types of macrophyte have been reported in Wular Lake, such as submerged macrophytes (*Potamogeton crispus* and *Ceratophyllum demersum*), emergent macrophytes (*Phragmites australis* and *Polygonum hydropiper*), rooted-floating and free-floating (*Nymphaea mexicana*) (Dar et al., 2013). It has been observed that the $\delta^{13}C$ of submerged plants is higher than that of emergent plants (Table 2) (Gong et al., 2021).

During the initial phase between 5600 and 4600 yr BP, relatively high TOC and TN have been observed compared with the succeeding phase, which suggested higher productivity in the lake (Figure 3). The $\delta^{13}C$ of organic matter revealed relatively high values (~-21‰), which might be due to the contribution of submerged macrophytes to the organic matter pool at the core location. It indicated that the lake level was

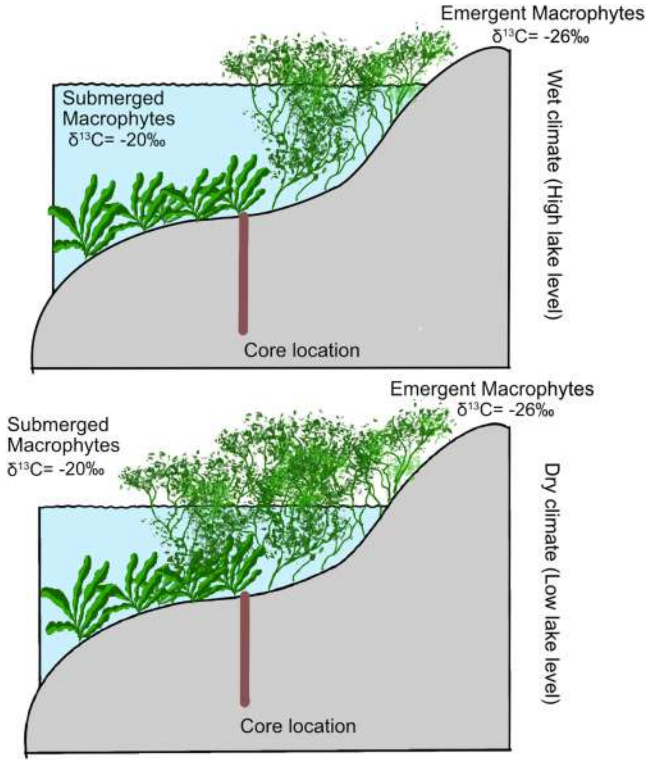

Figure 5. Schematic diagram of potential macrophyte growth at the trench location near the bank of Wular Lake (Banyari) along with the carbon isotopic compositions in wet (high lake level) and dry (low lake level) climates during the studied period. [Color figure can be viewed at wileyonlinelibrary.com]

relatively high due to high river runoff, which has also been shown using geochemical proxies (Figure 3). As the climate shifted from wetter to drier during 4600–3800 yr BP, TOC and TN content in the sediment showed a slight decline, indicating a decrease in productivity in the lake. During the same time period, a drop in $\delta^{13}C$ was also observed (Figure 4), which might be due to the lowering of the lake level and appearance of the emergent macrophytes at the study location (Table 2). The $\delta^{13}C$ again shifted to ~-21‰ after 3800 yr BP (Figure 4), which continued with no significant change up to 2250 yr BP. It indicated that the lake level had risen and the study location was potentially dominated by submerged plants during 3800–2250 yr BP. Within the same time period, variations in TOC and TN indicated higher and lower productivity during 3800–3100 and 3100–2250 yr BP, respectively. During this climate shift, the lake level did not appear to change significantly enough to affect the biology at the core site. The $\delta^{13}C$ values showed very high fluctuations with an increasing TOC/TN ratio (TOC/TN > 10) after 2250 yr BP (Figure 4). This indicated significant disturbance in the watershed leading to non-systematic inputs of terrestrial organic matter to the lake, possibly due to human influence in the region. It has been observed that human settlement and development dominated in the valley after 2000 yr BP (Spate et al., 2022a). Within the time period from 2000 yr BP to present, there were three peaks of $\delta^{13}C$, which indicated potential contributions from C_4 plants at the core site. This might have been due to a decrease in the lake level that exposed the surface for C_4 grass growth.

The $\delta^{15}N$ of organic matter is a potential proxy for the lake nutrient cycle (Rahman et al., 2020; Rahman et al., 2021). Wular Lake's nutrient dynamics are largely controlled by discharge from the Jhelum River, which transports N, P and other nutrients to the lake and supports the lake's biology, including macrophytes. Previous studies have shown that both

Table 2. Carbon isotopic compositions of the submerged and emergent macrophytes.

Type	Macrophytes	$\delta^{13}C$	References
Submerged		-20.31 ± 5.03^a	Gong et al. (2021)
	*Potamogeton crispus**	−9.08	LaZerte and Szalados (1982)
	*Ceratophyllum demersum**	−19.16	Yu et al. (2015)
Emergent		-26.75 ± 1.84^b	Gong et al. (2021)
	*Phragmites australis**	−25.8‰	Chen et al. (2015)
	*Polygonum hydropipe**		

[a]Average $\delta^{13}C$ of all submerged plants reported in Gong et al. (2021).
[b]Average $\delta^{13}C$ of all emergent plants reported in Gong et al. (2021).
*Identified macrophytes in Wular Lake (Dar et al., 2013).

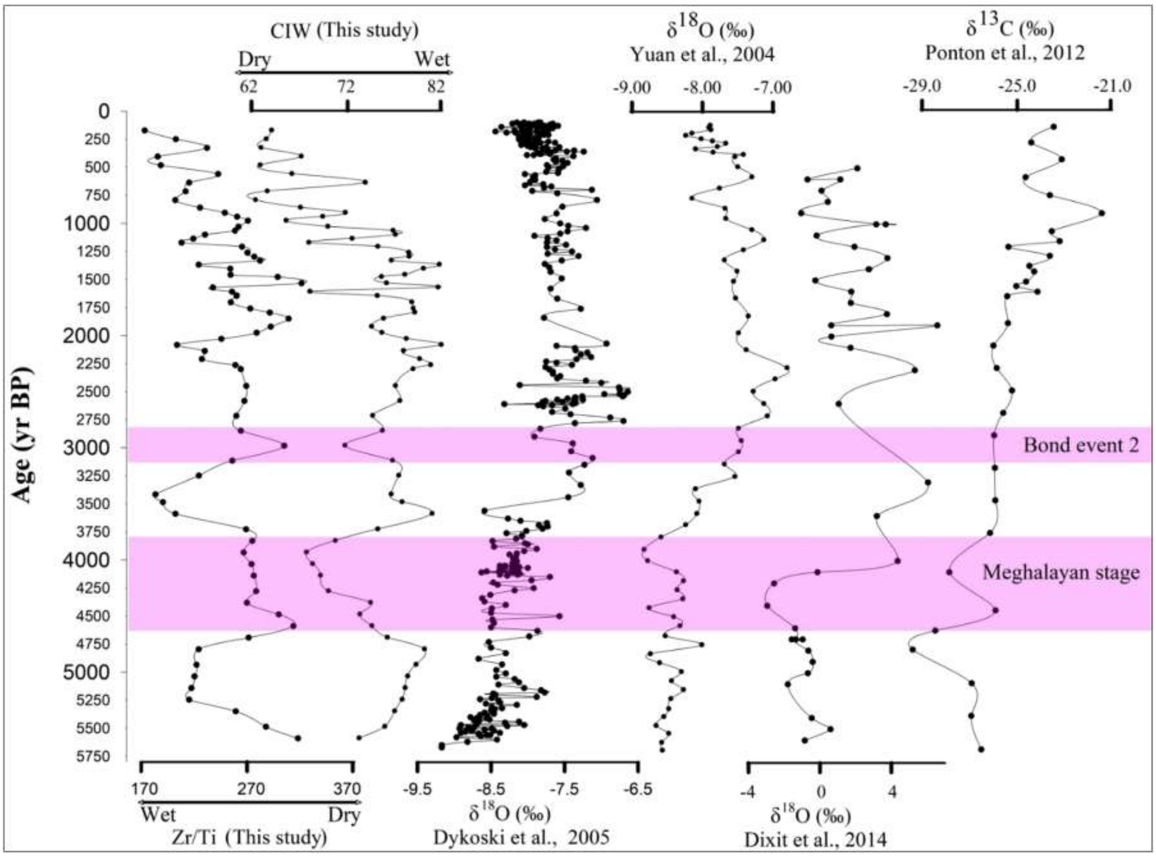

Figure 6. A plot showing comparisons of climate proxies from the present and other studies. [Color figure can be viewed at wileyonlinelibrary.com]

emergent and submerged macrophytes support denitrifying bacteria in the sediment and water column (Weisner et al., 1994; Eriksson et al., 1999). It has also been suggested that submerged macrophytes have more epiphytes and a large attachment area in the water column for denitrification bacteria (Weisner et al., 1994). Although the $\delta^{13}C$ of organic matter showed relative increase and decrease from 5600–2500 yr BP, indicating a change in climatic conditions along with the relative dominance of emergent and submerged macrophytes, respectively, $\delta^{15}N$ did not fluctuate significantly during this period (Figure 4). Nor did it show evidence of submerged macrophyte-associated denitrification in the water column. At 2500 yr BP, a sudden increase in $\delta^{15}N$ (>7‰) was noticed in the lake sediments (Figure 4), which suggested potential nutrient limitation in the lake due to low runoff. At 2500 yr BP, a dry and cold climate has previously been noticed, including in this study, which supported low runoff in the catchment of Wular Lake. Low supply along with continuous consumption of available nutrients (NO_3^-) might have enhanced the $\delta^{15}N$ of NO_3^- in the water column, leading to an increase in $\delta^{15}N$ of organic matter sustained on this isotopically enriched NO_3^-. Afterwards, a gradual decrease in $\delta^{15}N$ was observed from 2000 yr BP to the present, which suggested inputs of terrestrial organic matter such as litter and soil organic matter to the lake. It might be possible that deforestation because of human intervention might have increased the soil erosion in the catchment leading to an increased contribution of terrestrial organic matter to the lake.

Comparison with the regional studies

The Holocene palaeoclimate studies on the Indian subcontinent and Himalayan region have been carried out robustly during the last decade to reconstruct changes in the palaeomonsoon and western disturbances (Mishra et al., 2015; Rawat et al., 2015; Bhushan et al., 2017; Srivastava et al., 2017;

Khan et al., 2018; Babeesh et al., 2019; Ali et al., 2020; Lone et al., 2020b; Amir et al., 2020; Dash et al., 2020; Phartiyal et al., 2020a, 2020b; Shah et al., 2020a). To compare the effects of the palaeoclimate variability in the Kashmir Valley during the late Holocene, temporal variability in the proxy records from this study has been compared with the other well-dated spatially distributed palaeorecords from the ISM-dominated Indian region (Ponton et al., 2012; Dixit et al., 2014) and speleothem records from China (Yuan et al., 2004; Dykoski et al., 2005; Figure 6). While the Kashmir Valley experienced a warm/wet climate with enhanced precipitation during the early Holocene (Shah et al., 2020a), the commencement of the mega-drought during the Meghalayan Stage (~4200 yr BP) resulted in an adverse impact on various human civilisations worldwide, especially the Indus Valley civilisation (Lawler, 2008; Ponton et al., 2012; Pokharia et al., 2017). The proxy records from this study revealed a longer and intense effect of the dry Meghalayan Stage that started around 4600 yr BP and continued up to 3700 yr BP, with a distinct peak of dryness at ~4000 yr BP as observed in studied proxies (Figure 4). Similar observations were made earlier by Dixit et al. (2014), revealing a distinct aridity peak at 4100 yr BP in western India, and by Ponton et al. (2012) in eastern India. This prominent arid climate event at 4000 cal. yr BP has also been reported from the Himalayas (Kotlia et al., 1997; Phadtare, 2000; Kotlia et al., 2015) and from South Asia (Madella and Fuller, 2006; Willis and MacDonald, 2011).

The post-Meghalayan Stage has been followed by multiple cold and warm climate events, such as 2900–3300 yr BP (Van Geel et al., 1996; Mauquoy et al., 2004), 1600–2300 yr BP (Roman Warm Period; Campbell et al., 1998), 800–1200 yr BP (Medieval Climate Anomaly; Mann et al., 2009) and 400–600 yr BP (Little Ice Age; Mann et al., 2009). In this study, the Meghalayan Stage was followed by a wetter phase, after which another dry/cold climate event was observed that peaked around ~3100–2800 cal. yr BP and was comparable to Bond Event 2, which has been reported to be due to ocean surface cooling that resulted from a substantial change in the North Atlantic's surface circulation (Bond, Showers, Cheseby, Lotti, Almasi & Demenocal, 1997). It has also been proposed that the cause of widespread climatic deteriorations at ~2800 yr BP occurred due to reduced solar activity (e.g. Van Geel et al., 1996; Van Geel et al., 1998; Speranza et al., 2000, 2002; Blaauw et al., 2004; Mauquoy et al., 2004).

Conclusions

Multiproxy analyses coupled with radiocarbon dating on a 160 cm deep trench dug near the confluence of Wular Lake and the Jhelum River was carried out to reconstruct the late Holocene palaeoclimate history and lake biogeochemistry. The study revealed the occurrence of an extended phase of dry/cold climate conditions from ~4600 to 3800 yr BP with peak aridity at ~4000 yr BP known as the Meghalayan Stage. A less dry climate than the ~4600–3800 yr BP phase was observed between ~3100 and 2200 yr BP. Phases with the dry climate would have experienced lower water levels and desiccation of the lake margins. The study has revealed the occurrence of relatively warm/wet climate phases during ~5600–4600 yr BP, ~3800–3100 yr BP and ~2200–2000 yr BP. A thicker water column would have prevailed during the warmer/wetter climate phase and it would have also resulted in the submergence of the present-day dried margins. The lake biogeochemistry revealed a significant contribution from the emergent macrophytes during this stage. Wular Lake faced nutrient limitations due to low runoff around 2500 yr BP caused by the persistent dry and cold climate conditions. The geochemical signatures of the sediments revealed extensive erosion in the catchment area during the last two millennia, possibly due to anthropogenic activities.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Abbreviations. Al, aluminium; AMS, accelerator mass spectrometry; C, Carbon; cal yr BP, calibrated years before present; CaO, calcium oxide; CIA, chemical index of alteration; CIW, chemical index of weathering; Cm, centimetre; CO2, carbon dioxide; HCl, hydrochloric acid; IAEA, International atomic energy agency cellulose; ISM, Indian Summer monsoon; kyr-1, per kilo(thousand)years; M, mole; MgO, magnesium oxide; N, nitrogen; NaOH, sodium hydroxide; pH, potential of hydrogen; SDO, sample devonian ohio shale; Si, silicon; Ti, titanium; XRF, xray fluorescence; yr BP, years before present; Zr, zirconium; Zn, zinc; ZnO, zinc oxide.

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