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Palaeoenvironmental Reconstruction Through Granulometric Analysis of a Palaeolake Deposit at Bhikiyasain, Kumaun Lesser Himalaya

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Abstract: Grain size analysis is an essential tool for classifying sedimentary environments. The main aim of the current research is to use granulometric analysis of the Bhikiysain palaeolake sequence along the Ramganga river to describe changes in the depositional environment within the lake during the late Quaternary. The granulometric analysis was conducted using a laser particle size analyser on 32 samples, collected at 10 cm intervals in a vertical palaeolake profile, at Bhikiyasain (Ramganga Basin). The results of the grain-size analysis indicate that the size distribution of the sediment is unimodal. The unimodal size distribution of the sediment suggests that the sediment was supplied via fluvial action. The Bhikiyasain Basin (29°43.106’ N; 79°15.682’ E) underwent tectonic activity around 44 ka, resulting in the ponding of the Ramganga river and the formation of palaeolake deposit. Based on grain size analysis, variation in the colour and lithofacies, the entire profile has been divided into 6 different zones (zones 1 to 6). The silt has the highest concentration in all the zones except for zones 1 and 3. Zones with high silt concentration are inferred to represent low energy depositional environments during the time of deposition. The higher amount of sand concentration in zones 1 and 3 represent higher energy depositional environment. For the whole profile, the sorting of the samples varies between 1.1 and 2.0, indicating poor sorting of the samples. The poorly sorted sediment in all six zones represents limited transportation of sediment from the catchment and also suggests that the sediment was deposited in a low energy environment. The ternary plots also signify the dominance of silt followed by sand and clay. The skewness values range from 0.1 to 0.5 which indicates that the samples are symmetrical to very finely skewed. Variability in the skewness values may be due to changes in the intensity of wind and hydrodynamic conditions of the lake. The kurtosis value ranges from 0.9-1.4, indicating the samples are platykurtic, leptokurtic and mesokurtic in nature. Variability in the kurtosis may be due to changes in the flow characteristics of the depositional medium.

Keywords: Ramganga river; Bhikiyasain palaeolake; Granulometric analysis; Hydroclimate; Himalaya.

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Introduction

The Himalayas, formed as a result of the continental collision between the Eurasian and Indian plates around 55-54 million years ago, is divided into different litho tectonic units by intracrustal boundary thrusts e.g., Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), South Tibetan Detachment (STD) and Indus Tsangpo Suture Zone (ITSZ) from south to north. During the late Quaternary period, a number of palaeolakes were formed due to upliftment along these intracrustal boundary thrusts or subsidiary thrusts/faults in the Indian Himalaya (Kotlia, 1985, 1992; Kotlia et al., 1997a,b, 1998a,b, 2000; Valdiya et al.,1996, Valdiya and Kotlia, 2001; Joshi and Kotlia, 2015). Reactivation of thrusts/faults in the Kumaun Himalayan sector particularly resulted in similar upliftment which blocked the drainage and caused the formation of palaeolakes with intercalated lacustrine and fluvial deposits (Kotlia and Rawat, 2004; Kotlia et al., 1997a, 1998b).

In the Himalayas, climate and tectonics play a vital role in influencing the terrain and associated processes. In the past, the Himalayan region has been impacted by the Indian Summer Monsoon (ISM) and Indian Winter Monsoon (IWM) with varying intensities, mainly responsible for the changing climate regime in that region. Heavy rains, glacial lake outbursts and rapid snowmelt cause flooding in the Himalayan rivers, affecting drainage systems in the high mountainous regions as well as in the downstream regions. Tectonism, as an alternate mechanism, also leads to gradual changes in drainage patterns and landform design (Sanwal et al., 2019). As a result of these processes, Himalayan rivers become obstructed, allowing ponds and lakes to grow in numerous parts of the region. In addition, the vegetation cover on the steep slopes is exhausted due to long dry and cold spells, leading to the formation of loose soil on its surface. During wet periods, the loose unconsolidated soil and debris cover moves down to the slope, causing landslides that impede the streams and create landslide-dammed lakes. The damming of rivers, which is caused by tectonism and/or climatic processes, also results in the formation of depositional niches where sedimentary records of past climatic events are likely to be preserved (Sanwal et al., 2019).

Lakes are active dynamic systems that integrate climatic and tectonic forcing in continuous, high-resolution archives of local as well as regional-scale environmental changes (Gierlowski-Kordesch and Kelts, 2000). Because sedimentation in Himalayan lakes is generally ongoing, the study of these lakes allows a better understanding of the climatic fluctuations in the past. These lakes not only provide information about past climatic variability but also give information about the mechanism of climate forcing and its global connection (Srivastava et al., 2013). In the lake deposit, the uninterrupted sequence of sediments is extremely sensitive to climate change and has great potential to provide records of different climatic events which occurred in the past (Pietras and Carroll, 2006; Phartiyal et al., 2009). Particle size is one of the most basic physical properties of sediments. In the sediment records, variation between the particle sizes indicates the fluctuation of lake levels, change in transport energy and palaeoenvironmental conditions (Conroy et al., 2008). Transportation and deposition of sediment from the catchment to a depositional basin are mainly controlled by hydraulic conditions (Sly, 1978; Hankson and Jansson, 1983). The grain size distribution analysis is generally conducted to characterize palaeoclimatic conditions because it is sensitive to changing climatic conditions and is generally unaffected by biological processes (Chen et al., 2004). The distribution of grain size reflects the energy environment that affects the texture and size of the particle during transportation and depositional process. Thus, analysis of grain-size has long been used as a powerful and reliable tool to describe the sedimentary processes, depositional setting, environmental conditions and regional climate (Middleton, 1976; Ghosh and Mazumder, 1981; Tucker, 1991).

In the Kumaun Himalaya, a number of ancient and modern lake sediments have been studied to obtain records of high-resolution climate variability (Bhattacharya, 1989; Chauhan et al., 1997; Kotlia et al., 1997a,b, 2000, 2008, 2010; Kotlia and Joshi, 2013; Kotlia and Bisht, 2020; Ghosh et al., 2003; Basavaiah et al., 2004; Juyal et al., 2004, 2009; Pant et al., 2006; Bhattacharya et al., 2006; Trivedi et al., 2009; Wunnemann et al., 2010; Sanwal et al., 2019; Joshi et al., 2019). We investigated the granulometric parameters of the palaeolake profile of Bhikiyasain, District Almora. This study presents insight into the granulometric analysis of a sediment profile which provides us useful information about transport energy, lake level fluctuation and palaeoenvironmental condition during the late Quaternary.

Study Area

The study area is located at an elevation of 798 m m.s.l in Bhikiyasain, district Almora of Uttarakhand state. It falls in Survey of India toposheet no. 53O/2 and 53O/6 and lies at 29°44.581N-9°38.200N and 79°11.982'E-79°18.262'E in the Kumaun Lesser Himalaya. Geologically, the area falls between the South Almora Thrust (SAT) and Ramgarh Thrust (RT) (Figure 1). About 6m thick lacustrine deposit is exposed along the roadside on the left bank of Ramganga River and our current work focuses on the exposed part of the palaeolake adjacent to the Ranikhet-Chaukhutia motor road.

Regional Geology

The Bhikiyasain area is situated between the RT in the south and SAT in the North (Figure 1). It comprises the rocks of two different tectonic units – Almora Group and Ramgarh Group (Valdiya, 1976). Apart from important structural boundaries such as the North Almora Thrust (NAT), SAT, RT, MBT and HFT, the Ramganga River cuts a few transverse faults, especially the Chaukhutiya (CF) and Binau-Bhikiyasain-Naurar faults (BBNF), where a dramatic shift in landform is evident (Valdiya,

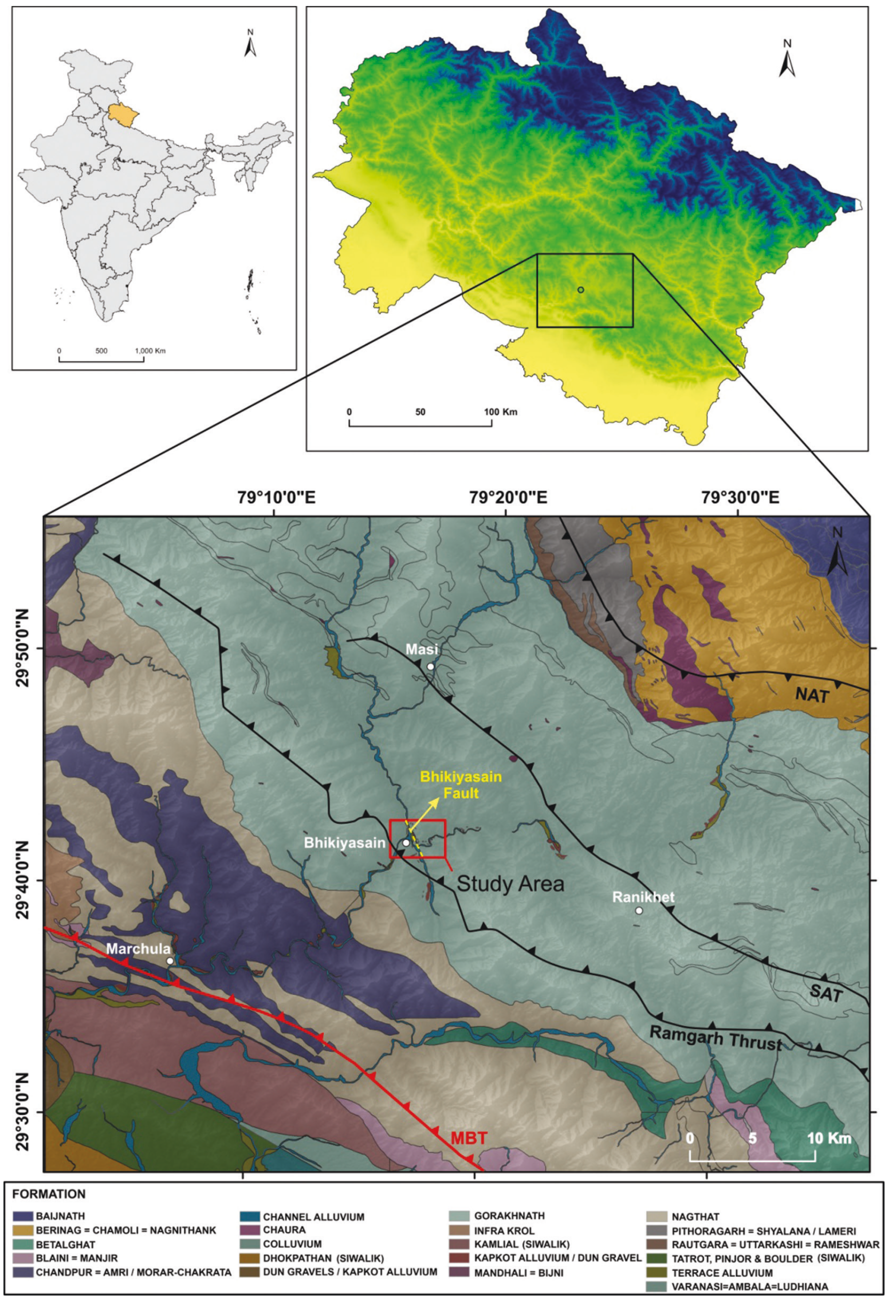

Figure 1: Site location and geological map of study area (Https://bhukosh.gsi.gov.in/Bhulosh/Public).

1976; Chaudhary et al., 2017). Continued motions along the NAT and SAT as well as other transverse faults, such as BBNF and CF, have an impact on landform evolution (Chaudhary et al., 2017).

Lithostratigraphy

The Bhikiyasain palaeolake probably came into existence at 44.6±3.0 ka (see Table 1) because of blocking the Ramganga river due to upliftment along the Bhikiyasain fault (see Figure 1). Sedimentation took place in the lake until it was drained as a consequence of the movement of faults that exist in this area as the subsidiary thrust of the RT (see Figure 1). A sequence of about 6 m of muds, unconsolidated sands, silty clays and cm scale gravels is exposed. The basal portion is composed of mottled mud which is poorly sorted. The sequence starts from 0-60 cm at the bottommost part which is mottled mud inferred to reflect an interval characterised by low energy deposition. From 60-100 cm, the profile contains reddish laminated layers of clay representing moderate energy conditions. Upward from 100-200 cm, fine laminated sand with red clay and sand lenses are observed that reveal comparatively moderate energy conditions at the time of deposition. The profile from 200-340 cm consists of a sand unit with parallel red clay layers. A sand horizon from 340-360 cm contains small mud balls. The palaeolake sequence from 360-415 cm comprises angular clasts of quartzite, gneiss and schist which are poorly sorted within a matrix of sand and clay which indicates comparatively high energy conditions. The sand unit with parallel red clay layers are observed from 415-550 cm whereas, mottled mud is noticed from 550-600 cm and this deposit may represent low energy conditions. The lithology is shown in Figure 2.

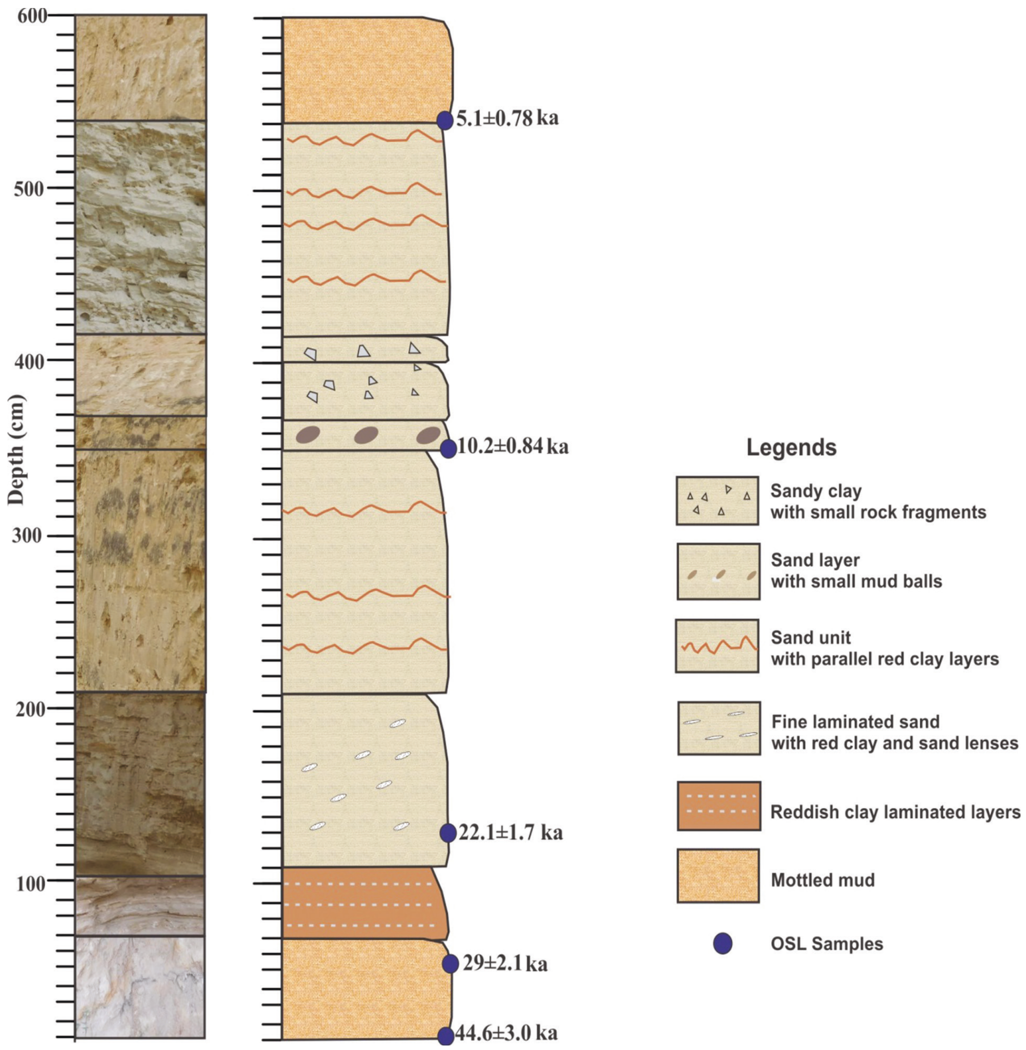

Figure 2: Litholog of Bhikiyasain palaeolake profile.

Table 1: OSL dates from Bhikiyasain lacustrine profile

S.No.	*Sample code (OSL)*	*Height from base (cm)*	*OSL dates*
1	RG OSL-04	0	44.6±3.0
2	RG OSL-05	45	29±2.1
3	RG OSL-06	130	22.1±1.7
4	RG OSL-07	350	10.2±0.84
5	RG OSL-08	540	5.1±0.78

Methodology

Field measurements

Field work was carried out in the Bhikiyasain area along the Ramganga river. After a detailed field survey, we identified a 6 m long exposed section consisting of several sedimentary facies. The exposed section was scraped to gain access to a fresh surface and systematic sampling at an interval of 10 cm was done for detailed sedimentological studies. A total of 60 samples were collected with extreme care to avoid contamination. The samples were packed in ziplock plastic bags labelled and brought to the laboratory for further analysis.

Optical Chronology

Five samples of medium to fine-grained sand were dated for Optically Stimulated Luminescence (OSL) dating (see Table 1). The dating was performed at the Institute of Seismological Research, Gandhinagar (Gujarat). Estimation of ages was undertaken after the separation of quartz from the sand on the basis of a single aliquot regeneration protocol with a preheat of 240°C for 60 s and cut the heat of 200°C, initially proposed by Murray and Wintle (2003). Automated Ris0 TL-OSL reader (TL/OSL-DA-20) was used to perform the luminescence measurements. A blue diode (470 ± 20 nm) was used to stimulate the samples. An EMI 9835QA photomultiplier tube coupled to a 7.5 mm Hoya U-340 filter (emission 330 ± 35 nm) was used for the estimation of detection optics. The samples were irradiated using a beta irradiation source on plate 90Sr/90Y beta with a dose rate of 0.131 Gy/s. Infrared-stimulated luminescence was measured at 50°C for 100 s to remove any contribution from feldspar, and the optical luminescence was measured at 125°C for 40 s prior to every OSL measurement (see Kothyari et al., 2020). Construction of dose versus growth curves was carried out using five regeneration dose points including one point to estimate the recuperation and another point to estimate the reliability of sensitivity correction (recycling ratio). Only those aliquots were considered for age estimation whose recycling ratios were within 10% of unity, recuperations being <1% of the natural signal. The minimum age model was employed (Arnold and Roberts, 2011) for the samples where the over-dispersion (OD) value was >40%. For samples having <40% OD, the centralized age model (Bailey and Arnold, 2006) was used. Five luminescence ages were obtained from discrete sand horizons of the section to construct the chronological framework. The ages in chronological order are as 44.6 ± 3.0 ka (at the bottom), 29.1 ± 2.1 ka (45 cm), 22.1±1.7 ka (130 cm), 10.2±0.84 ka (350 cm) and 5.1±0.78 ka (540 cm).

Granulometric Analysis

A total of 32 samples were dried in an oven at a temperature of 50°C. Grain size analysis was carried out to understand various sedimentary characteristics. The grain size analysis was chemically treated by the Pipette method or Hydrometer (Jackson, 1956). For this, 2 gm of samples were put in a centrifuge tube and added 10 ml Sodium Acetate, was then heated for 1 hour and the same centrifuge process was repeated 2 times. After centrifuging, 2 ml H_2O_2 was added to the sample and boiled for one hour and kept in a tube for overnight. Following day, the samples were centrifuged and descended 2 times then add sodium bicarbonate (10 ml) + sodium citrate (0.2 ml) + sodium dithynide (0.2 gm) in the sample and put the sample boiling for one hour then centrifuge it 3 times and descended. Finally, the analysis of chemically treated samples was carried out in Laser Particle Size Analyser (LPSA). The data

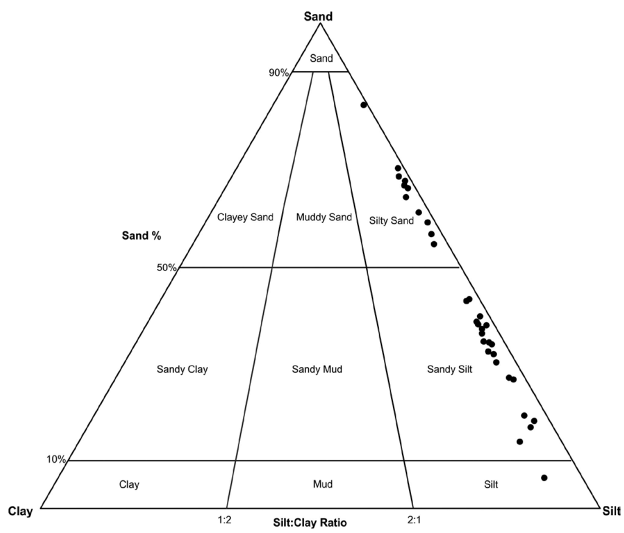

Figure 3: Ternary plot showing distribution of sand, silt and clay percentage (e.g., Flok and Wartd, 1957).

generated by LPSA was processed in Gradistat software (Blott and Pye, 2001) for further granulometric analysis.

Results and Discussion

Grain Size Statistics

Lake sediments often exhibit polymodal distribution and reflect a mixture of sedimentary mechanisms. The size and texture of lake sediments provide history and hydrodynamic processes influencing a lake over time (Mason and Folk, 1958; Friedman, 1961a,b; Sahu, 1964; Visher, 1969; Hakanson and Jansson, 1983; Xiao, 2013; Runge, 2017). Grain size analysis is a reliable proxy to characterize the mechanism of sediment supply, changes in the lake level and evolution of the depositional environment (Digerfeldt, 1986; Dearing, 1997; Boyle, 2001). In the present study, detailed lithology and the stratigraphic description of sedimentary layers were carried out using various energy conditions, mainly reflected in the distribution of grain size. A higher concentration of coarse particles is generally considered an indicator of a warm and dry climate, whereas a high content of fine particles usually indicates a cool and wet climate (Wang et al., 2001; Xiao et al., 2009). The ternary plot diagram (e.g., Folk and Ward, 1957) of Bhikiyasain paleolake sediments show a dominance of silt, followed by sand and clay. The silt content has an average value of 53.6% (85.9-14.2%), sand of 43.7% (14.8-85.1%) and clay of 2.8% (0.6-7.5%) (Figures 3 and 4). The high content of silt particles indicates that the study region has experienced a cool and wet climate whereas, the percentage of sand concentration indicates the existence of warm and dry climate in the study area. Based on the grain size analysis, variation in colour of sediment and lithofacies the 6 m thick Bhikiyasain palaeolake profile has been divided into 6 different zones (Zone-1 to Zone-6) (Figures 4-5).

Zone-1 (0-85 cm; 44.6±3.0-29±2.1 ka). The grain size varies between 1.8 and 4.9 $ (average 3.9$) showing very coarse silt and very fine sand as most dominant in this zone. Sand (54.7%), silt (43.2%) and clay

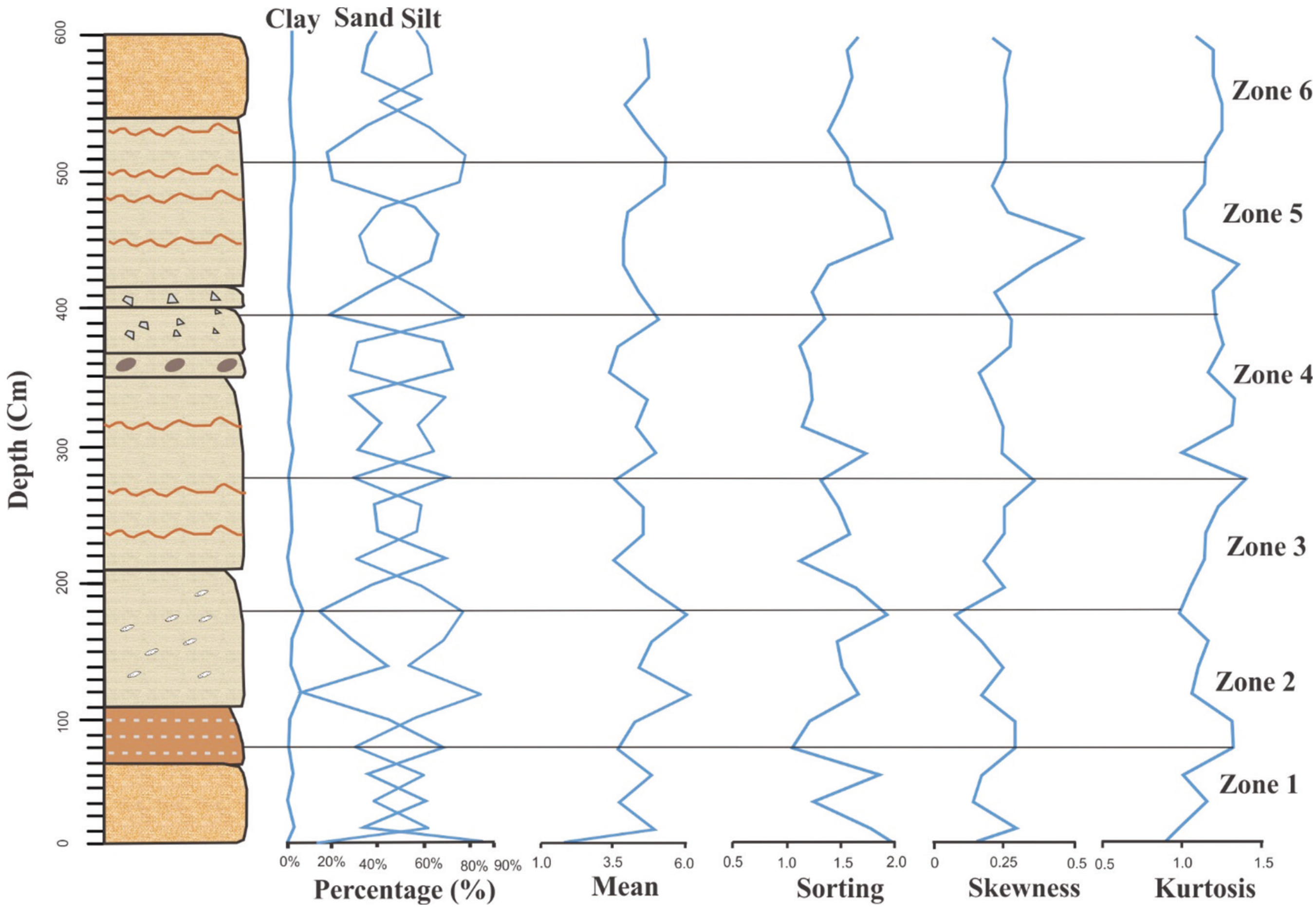

Figure 4: Variation in sand, silt, and clay (in percent), mean grain size, sorting, skewness and kurtosis parameters for the Bhikiyasain sediments.

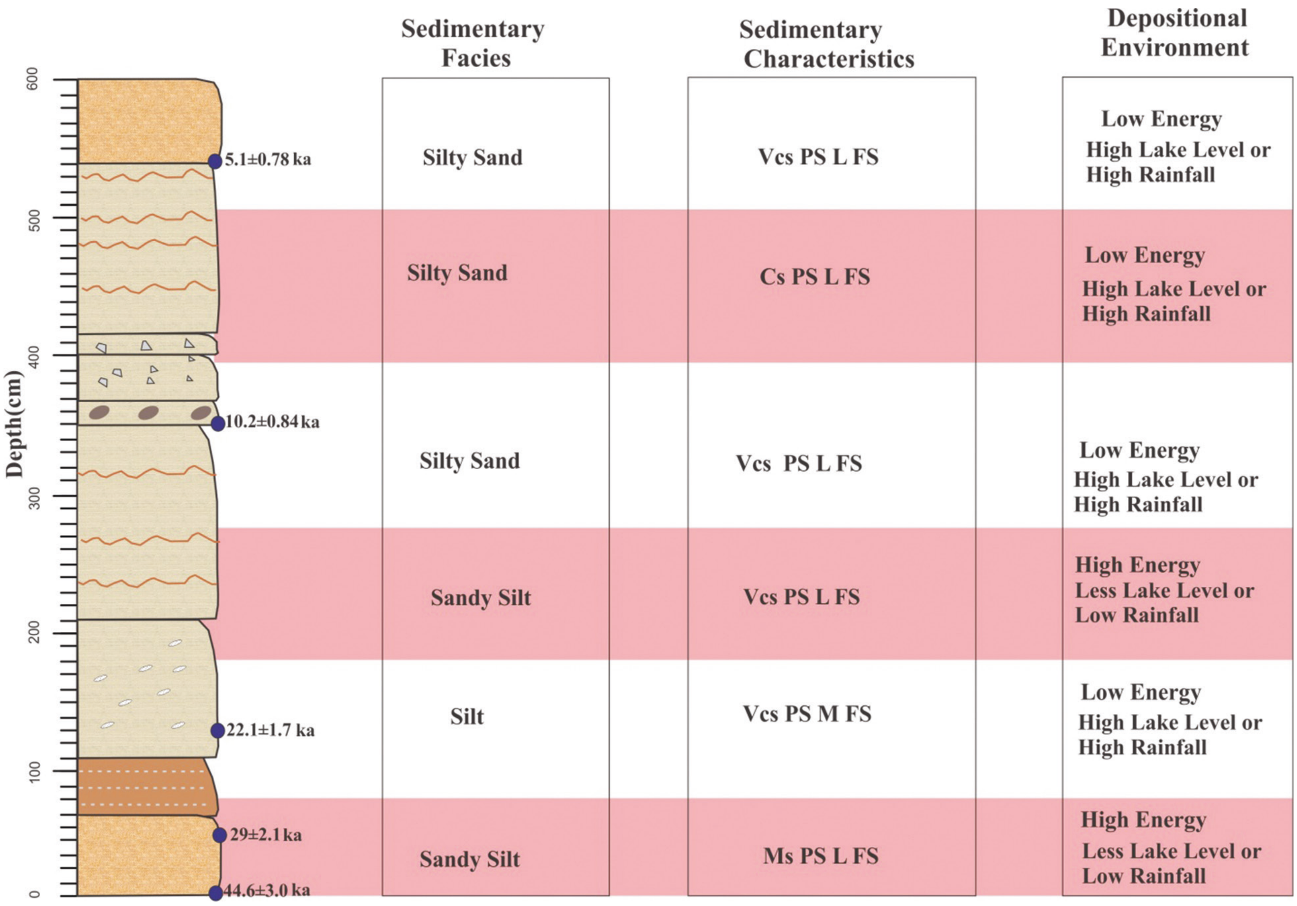

Figure 5: Litho-facies in terms of sedimentary facies, sedimentary characteristics, and depositional environment (Vcs, very coarse silt; Ms, medium silt; Cs, coarse silt: PS, poorly sorted; FS, fine skewed; M, mesokurtic; L, leptokurtic).

(2.1%) are present. Overall sand percentage fluctuates between 33.8 and 85.1%, the silt varies between 14.2 and 62.4% and the clay ranges from 0.6-3.8%. The sand concentration is very high (see Figure 5) in this zone, suggesting high energy depositional environment. It also suggests the occurrence of low rainfall or arid conditions in the catchment (e.g., Warrier et al., 2013). The Zone-1 sample types vary between unimodal to bimodal in nature with a textural group of muddy sand and sandy mud.

Zone-2 (85-180 cm; 29±2.1-22.1±1.7 ka). The grain size ranges from 4.4-6.1$ (average 5.2$) which indicates medium to very coarse silt. The average sand at 26.4%, silt at 69.1% and clay at 4.5% are present, showing silt as a major component, followed by sand and clay. In general, sand oscillates within a range between 7.2 and 44.3%, while silt (85.9-53.4%) and clay (2.3-6.9%) are also in a significant amount. The silt concentration is highest (see Figure 5) in this zone, pointing to a low energy environment during the deposition of sediment in this sector. It also suggests higher precipitation compared to that in zone-1. The Zone-2 sample type varies between unimodal to trimodal in nature with a textural group of mud to sandy mud.

Zone-3 (180-275 cm; 22.1±1.7-10.2±0.84 ka).The grain size varies between 3.5 and 4.5 $ (average 4.0$) which indicates very fine sand to very coarse silt. The average sand at 54.4%, silt at 43.6% and clay at 2.0% are measured, showing sand as a major component, followed by silt and clay. On the whole, and percentage swings within a range between 38.3 and 69.2%, followed by silt (28.1-59.2%) and clay (2.8- 1.0%). The sand concentration is highest (see Figure 5), signifying high energy depositional environment and low rainfall or arid condition. The Zone-3 sample type is unimodal in nature with the textural group as muddy sand to sandy mud.

Zone-4 (275-390 cm;10.2±0.84 ka).The grain size ranges from 3.4-5.1 $ (average 4.3$) indicating very fine sand to very coarse silt. The average sand at

43.2%, silt at 54.8% and clay at 2.1% are present with silt as a major component, followed by sand and clay. In general, sand percentage fluctuates with a range between 19.1 and 71.8%, while silt (27.2-78.1%) and clay (1.0-3.5%) are comparatively in minor amounts. The higher silt concentration (see Figure 5) suggests low energy depositional environment and also points to the high rainfall or wet conditions in the catchment. The sample type of this zone is unimodal in nature with sandy mud to muddy sand textural group.

Zone-5 (390-500 cm; 10.2±0.84-5.1±0.78 ka). The mean grain size ranges from 5.3-3.8 $ (average 4.4$). The average sand at 43.6%, silt at 53.7% and clay at 2.7% are observed, showing silt as a major component, followed by sand and clay. Particularly, the sand percentage is fluctuating with a range between 65.8 and 17.9%, while the silt (78.1-31.7%) and clay (4.0-1.3%) also swing. The silt concentration is the highest which suggests a low-energy depositional environment associated with high rainfall or wet climatic conditions during the deposition. The Zone-5 sample types are unimodal to bimodal in nature with a textural group as sandy mud to muddy sand.

Zone-6 (500-600 cm; <5.1±0.78 ka). This zone is characterized by mean grain size from 3.9-4.7$ (average 4.5$) with very coarse silt to very fine sand. The average sand as 40.2%, silt as 57.2% and clay as 2.6% are present with silt as a major component, followed by sand and clay. Overall, sand concentration shows fluctuations with a range from 58.1-33.1%, while the silt (62.4-40.0%) and clay (3.21.9%) are noticed. The silt concentration is highest in this zone, which suggests a low energy depositional environment with high rainfall and wet climatic conditions during the deposition of this zone. The zone-6 sample type is unimodal in nature with a textural group as sandy mud to muddy sand.

The results on the concentration of grain size indicate that mainly the low energy environment existed during the deposition of the Bhikiyasain profile. Only zone-1 and zone-3 experienced high-energy environmental conditions. The low energy condition shows a high lake level at the time of deposition of sediment due to high precipitation. In such a climatic setting, the lake level was increased; the lake area expanded and the majority of fine particles were deposited, while the coarse particles would have been deposited near the lake shore (e.g., Menking, 1997). The high energy conditions suggest that the lake level was very low during the deposition which might be due to less rainfall under arid conditions. In this situation, the lake area would have shrunk, and the shore line shifted towards the center of the lake due to which the coarse sediment would have been deposited (e.g., Finney and Johnson, 1991; Shuman et al., 2001). Further, due to the strong hydrodynamic conditions, fine materials would not have been deposited.

During less rainfall, weathering in the catchment was less intense because of which the relative concentration of coarse particles was higher compared to that of fine particles. The overall pattern of grain size distribution indicates that the sediments of the Bhikiyasain profile have different modes (unimodal> bimodal >trimodal) indicating the multiple sources for depositing sediments (see Last, 2001; Warrier et al., 2016). The dominant mode is unimodal which indicates the sediments in palaeolake have been supplied directly by stream and surface runoff (e.g., Srivastava et al., 2012; Warrier et al., 2016). Our results also suggest the samples belong to a relatively homogeneous or uniform source.

Statistical Analysis of Grain Size Parameters

The statistical parameters of the granulometric analysis (mean, sorting, skewness and kurtosis) were calculated following Folk (1954). These parameters play a major role in describing the effect of depositional processes (Freidman, 1961a,b). The grain size is a reflection of the capability of transporting mechanism, and skewness and sorting are considered environmentally sensitive parameters because both parameters characterize the kinetic energy of the depositing agent (Freidman, 1961a,b; Padhi et al., 2017). The skewness and kurtosis are used to differentiate the various climatic environments. The mean grain size is used as a main factor for determining energy conditions prevailing in the lake, which affects the deposition of the sediment (Folk, 1966; Purnawan et al., 2015). The details of the granulometric analysis of statistical parameters are as below:

Standard Deviation

The standard deviation measures the sorting or uniformity of the grain size distribution. It also represents the fluctuation in the hydrodynamic condition of the depositional environment (Sahu, 1964). In Zone-1, the sorting of samples varies from 1.1-2.0, indicating poor sorting of samples. The sorting in Zone 2 varies between 1.5 and 1.9 which also indicates the poorly sorted sediments in this zone. The sorting values of Zones 3, 4, 5 and 6 range from 1.1-1.6, 1.1-1.7, 1.2-2.0 and 1.4-1.7, respectively. Almost all the zones have poorly sorted sediments, suggesting limited transportation of sediment from the catchment. The poorly sorted characteristics of the sediment suggest the sediment deposited under the low energy environment (e.g., Blot and Pye, 2001; Padhi et al., 2017). In the case of low lying lakes, an additional influx of poorly sorted sediments from local sources, downslope from the adjoining hills or elevated areas, is a common feature (Verkulich and Melles, 1992) which reduces the sorting as well as affects the other grain size parameters.

Skewness

Skewness is defined as a major grain size distribution that shows the grain spread characteristics in the tails of the distribution. A symmetrical curve with an axis has a fine size tail and displays a positive skewness value, while coarse material shows negative skewness values. The skewness value for Zone-1 ranges from 0.1-0.3 and this represents the samples are finely skewed. The skewness values for Zone 2 show that the samples are symmetrical to finely skewed. The skewness value of zones 3, 4, 5 and 6 range from 0.2-0.4, 0.2-0.3, 0.2-0.5 and 0.2-0.3 respectively, meaning that the samples are fine to very finely skewed (Zone-3), finely skewed (Zone-4), very fine skewed to finely skewed (Zone-5) and finely skewed (Zone- 6). Variability in the skewness values might be due to changes in the intensity of wind and hydrodynamic conditions.

Kurtosis

Kurtosis is defined as the degree of peakedness of distribution and it reflects the sharpness of the grain size distribution. A sharp peak curve points to better sorting in the center point of the grain size distribution than in the tails while the flat peak curve shows vice-versa (Folk, 1966). The kurtosis values for Zone-1 range between 0.9 and 1.3, indicating that the samples are platykurtic, leptokurtic and mesokurtic in nature. Zone-2 is characterized by values between 1.0 and 1.2, suggesting the samples are mesokurtic to leptokurtic in nature. In Zone-3, the values are 1.1-1.4, pointing to the leptokurtic in nature. Zone-4 portrays a kurtosis value from 1.0-1.2, indicating the samples are mesokurtic to leptokurtic. The kurtosis values of 1.0-1.3 in Zone-5 signify leptokurtic to mesokurtic nature. Zone-6 is represented by the kurtosis values as 1.1-1.2, indicating that the samples are leptokurtic to mesokurtic in nature. Our results suggest variability in the kurtosis values from Zone-1 to Zone-6. This variability might be due to changes in the flow characteristics of the depositional medium. In general, the leptokurtic nature of sediments dominantly lies in all the zones which represent variable energy conditions. The leptokurtic nature of the sediments also indicates deposition in the less efficient sorting the environment of the lake

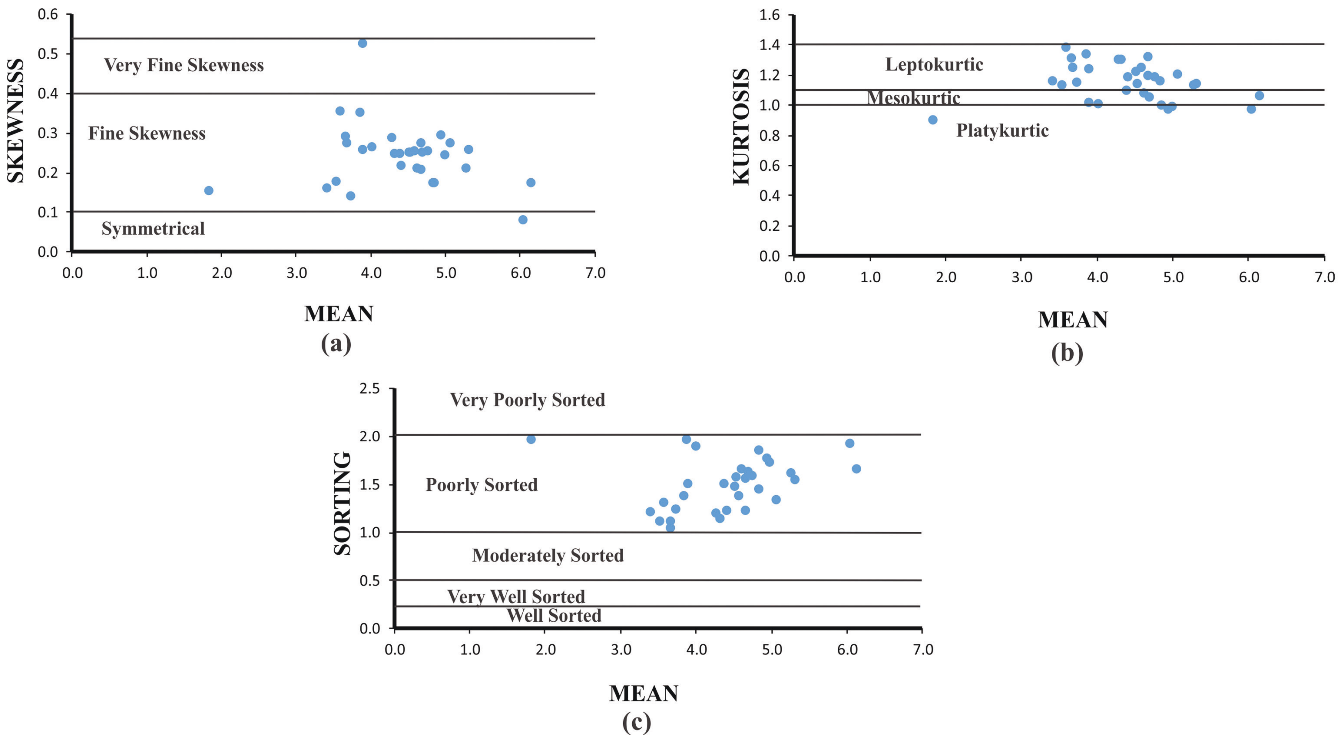

Figure 6: Bivariate plots (a) mean vs. skewness, (b) mean vs. kurtosis, (c) mean vs. sorting.

while mesokurtic and platykurtic distributions can result from the existence of different modes having less differentiated size ranges.

Bivariate Plots of the Profile

The bivariate plot was used to understand the energy condition, depositional setting, hydrodynamic condition and agent of deposition of grain size with respect to transporting medium.

Mean Size (Mz) Versus Skewness (SK)

Mean vs. skewness bivariate plot (Fig. 6a) reveals skewness value varying from very fine to symmetrical in nature. The values of very fine skewed range from 0.5 to 0.4, fine skewed (0.3-0.1) and symmetrically skewed (0.1). Figure 6a shows the clustering of sediments in the fine-skewed zone, pointing to finely skewed sediments. Finely skewed sediments might be formed due to the addition of silt to the sand component.

Mean size (Mz) Versus Kurtosis (KG)

The mean vs. Kurtosis plot (Figure 6b) shows that a majority of the sediments are leptokurtic as the values range between 1.1 and 1.4. The mean size range is from very fine sand to coarse silt, displaying a very leptokurtic distribution. The rest of the section, consisting dominantly of silt, displays a mesokurtic to platykurtic distribution. The profile consisting of sand units shows the platykurtic distribution.

Mean Size (Mz) Versus Sorting

For the Bhikiyasain lake profile, the mean vs. standard deviation plot (Figure 6c) shows the scattering of the sediments in poorly sorted regions. This indicates that most of the samples are poorly sorted. The degree of sorting decreases as the mean grain size shifts from sand to silt. The poorly sorted characteristics of the sediments suggest that these were deposited in the low-energy environment (Blot and Pye, 2001; Padhi et al., 2017).

Conclusion

We conclude that the lake was formed around 44ka BP due to tectonic movement along the Bhikiyasain fault, a subsidiary fault of the Ramgarh Thrust and breached around 5 ka BP possibly due to reactivation of the subsidiary fault. The grain size analysis is a reliable proxy to determine the mechanism of sediment supply, depositional environment and changes in the level of the lake. From the grain-size distribution study, we infer that the exposed section of the basin is composed of three primary grain-size components-sand, silt and clay. The grain-size studies show that nearly all the sediments are unimodal in nature. The unimodal distribution of the paleolake sediments shows that the sediments were supplied as a result of fluvial action. The results obtained from the ternary plot suggest that the dominance of silt is followed by sand and clay. The zone-wise distribution of the whole profile also suggests the highest silt concentration in all the zones except Zone-1 and Zone-3. A higher concentration of silt represents the low energy depositional environment during the sediment deposition. It also suggests the high rainfall or wet climatic conditions in the catchments. The higher amount of sand concentration in Zone-1 and Zone-3 represents the higher energy depositional environment and less rainfall under arid climatic conditions. To describe the capability of transporting mechanism and differentiate various climatic environments and determine the energy condition prevailing around the lake, the statistical parameters of granulometric analysis (mean, sorting, skewness and kurtosis) were calculated. Considering the standard deviation of the sediments, we infer that the deposit is poorly sorted, pointing to its less transportation from the catchment under a low energy environment. The skewness of the samples varies between symmetrical to very finely skewed which shows the change in the intensity of wind and hydrodynamic conditions of the lake. The kurtosis values vary from platykurtic, leptokurtic and mesokurtic in nature. Variability in the kurtosis value suggests a change in the flow characteristics of the depositional environment. In addition, the leptokurtic nature of sediments dominantly lies in all the zones, showing variable energy conditions in the lake. The bivariate plot of the profile also suggests that the deposit is poorly sorted and finely skewed with leptokurtic nature almost throughout the palaeolake profile.

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