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Sedimentological and Grain Size Characteristics of Two Lake Cores from Himachal Pradesh, India

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Abstract: Two lake cores from Khajjiar (length 746 cm) and Rewalsar lakes (length 647 cm) in Himachal Pradesh (India) were retrieved to understand the sedimentological characteristics and variation in grain size distribution. Both the lake cores are Upper Holocene in age. The Rewalsar lake sediments are composed predominantly of silt with small amounts of clay, whereas the Khajjiar sediments contain sand, silt and clay and both cores have high carbonaceous matter. The standard deviation ranges from 0.88 φ to 2.56 φ for Khajjiar lake and from 0.957 φ to 2.264 φ for Rewalsar lake, indicating poorly to very poorly sorted core sediments. The values of the Kurtosis vary between 0.678 φ and 1.205 φ for Khajjiar lake and from 0.8 φ to 1.2.4 φ for Rewalsar lake, viewing platykurtic to leptokurtic nature. Further, the skewness value ranges from -0.097 φ to 0.240 φ for Khajjiar lake and 0.079 φ to 0.25 φ for Rewalsar lake revealing fine to symmetrical skewness model. The bivariate plots by using the grain-size parameters were also interpreted. The Total Organic Carbon (TOC) is higher in the Khajjiar lake sediments (0.9 to 31.2%; av. 10.6%), compared to that in the Rewalsar lake sediments (1.0 to 9.0; av. 2.6%). The sedimentological characteristics indicate that the energy conditions were linked to the climatic conditions prevailing in the area. In general, the Khajjiar lake core is composed of relatively coarser sediments and more affected by arid conditions while the fine fraction of the Rewalsar shows the consequence of lower energy conditions. The Khajjiar lake shows the transition from fluctuating conditions (zone 1) to humid (zone 2) to arid (zone 3), while the Rewalsar shows the change from fluctuating (zone 1) to humid conditions (zones 2 and 3). The similarity between zone 1 and 2 of both the lake profiles shows that both lakes have experienced similar climatic conditions during the deposition, revealing domination of fluctuating and arid conditions.

Keywords: Lake core sediments; Statistical parameters; Grain size analysis; Total Organic Carbon (TOC); Depositional environment.

Introduction

Various natural archives from the Indian Himalaya such as lake sediment cores, speleothems, fossils, tree rings and ice cores can be used to provide information about environmental conditions of the past (Sinha et al., 2005; Juyal et al., 2004, 2009; Kotlia et al., 2010, 2016, 2018; Yadav et al., 2014, 2017; Demske et al., 2016; Lone et al., 2017). The palaeoclimatic study is extremely useful to appraise probable future environment (Overpeck et al., 1997; Evans et al., 1998; MacGregor et al., 2011). The key site to study the palaeoclimate is the Himalaya as it plays a crucial role in the atmospheric circulation, behaviour of Indian Summer Monsoon (ISM) and

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Westerlies (Pant et al., 1998, 2006; Ghosh et al., 2003; Basavaiah et al., 2004; Juyal et al., 2009; Kotlia et al., 1998, 2010; Kotlia and Joshi, 2013; Joshi and Kotlia, 2015). Being a powerful high-resolution proxy of local and regional scale, every lake is a unique body of water and establishes a dynamic system that combines various factors like climate, environment, tectonics, palaeontology and palaeoseismicity (Kotlia, 1985, 1992; Yuretich, 1989; Lambiase, 1990; Valdiya et al., 1996; Gierlowski-Kordesch and Kelts, 2000; Last, 2001; Kotlia and Rawat, 2004; Pietras and Carroll, 2006; Adrian et al., 2009; Warrier et al., 2016; Kothyari et al., 2019; Taloor et al., 2019). With an uninterrupted sequence of sediments, lakes are very responsive to the climate and have tremendous potential to provide continuous as well as abrupt episodes of climate change as sediments are deposited into the lake from the surrounding catchment (Phartiyal et al., 2003, 2009; Pietras and Carroll, 2006; Kotlia and Bisht, 2020).

The grain-size distribution of sediments reflects the energy conditions that affect the particle size and texture during transportation and deposition. Thus, grain-size analysis has long been used as consistent as well as a powerful tool to characterise the sedimentary processes, sediment source and depositional settings, associated with environmental conditions and regional climate (Visher, 1969; Middleton, 1976; Ghosh and Mazumder, 1981; Tucker, 1991; Kumar et al., 2020a,b). Generally, the grain outline is described as roundness or angularity of the grains and is controlled chiefly by the mode and distance of transportation, time and particle size (Goudie and Watson, 1981; Kleesment, 2009; Costa et al., 2013). The grain size parameters have also been used to distinguish grain size distribution of sediments to deduce variations in sediment source and hydrodynamic conditions (Inman, 1952; Blott and Pye, 2001; Fournier et al., 2014; Zhang et al., 2017). The concentration of the TOC is a major parameter for studying the abundance of organic matter in sediments (Last and Smol, 2001). The lakes in the mountainous area are usually preserved with high sediment organic matter due to rapid conditions, multiple processes and anoxic conditions at the lake bottom with high productivity (Meyers, 2003; Chaudhary et al., 2013); thus, the TOC can be an important parameter with grain size characteristics to understand lake dynamics.

Studies based on numerous grain size and organic matter for modern and palaeolakes have been conducted all across the Himalayan region for obtaining climatic variability and depositional settings (Kotlia et al., 1997a, b; 2000, 2008, 2010; Juyal et al., 2009; Chaudhary et al., 2013; Nag et al., 2016; Lone et al., 2017; Sanwal et al., 2019; Diwate et al., 2020; Kotlia and Bisht, 2020). In this study, we have selected lakes based on the climatic conditions, precipitation, water depths, catchment lithology and surrounding vegetation. This paper presents the preliminary investigations of Khajjiar (KJR) and Rewalsar (RWL) lakes in Himachal Pradesh using sedimentary characteristics and other parameters in order to decipher the depositional environment and its relation to the precipitation rate over the region.

Study Area

Khajjiar Lake (KJR)

The saucer shaped and fresh water Khajjiar lake (32°26′ N, 76°32′ E) has a radius of approximately 60-80 m and is situated at about 1900 m above the mean sea level in a valley middle of Pir Panjal and Dhauladhar ranges (Saini et al., 2008; Singh and Banyal, 2012) (Figure 1). It is situated about 25 km from Chamba district and designated as “The Mini Switzerland of the Himachal Pradesh”. The water body is surrounded by Deodar-mixed forests and is fed mainly by groundwater, slim streams (limited runoff) and precipitation (Saini et al., 2008). The lake has an oval shaped ‘floating island’ of grasses and reeds (Sharma and Singh, 1974). The average annual rainfall is about 800 mm and the area experiences ISM rains in July-September and nearly 15% of the total rainfall is contributed by the Westerlies. The winters are cold and bitter, summers are mild and temperature ranges from –10°C to 35° (Singh and Banyal, 2012). Based on the water chemistry of the lake water, Saini et al. (2008) concluded that the major ion chemistry was dominated by carbonate source rock weathering.

Rewalsar Lake (RWL)

Approximately 22 km from Mandi town in Himachal Pradesh, the oval shaped fresh water Rewalsar lake (76°50′ E, 31°33′ N) is located at an altitude of 1400 m (Figure 1). This open lake is situated in the eastern slopes of the Lesser Himalaya, to the north of middle Siwalik and south of the Main Boundary Thrust (MBT) and is surrounded by the Late Quaternary deposits (Sarkar et al., 2016; Gaury et al., 2018). Measuring 225 m in length and 60 m breadth, the maximum and minimum water depths of the lake are 6.5 m and 2.5 m, respectively. The lake receives moderate to high annual rainfall, around 1240 mm, mostly during the ISM (Singh et al., 2020). The area of the lake basin is about 3.6 ha, and the lithology of the catchment area has light coloured sandstone interlayered with grey siltstone and shale (Das

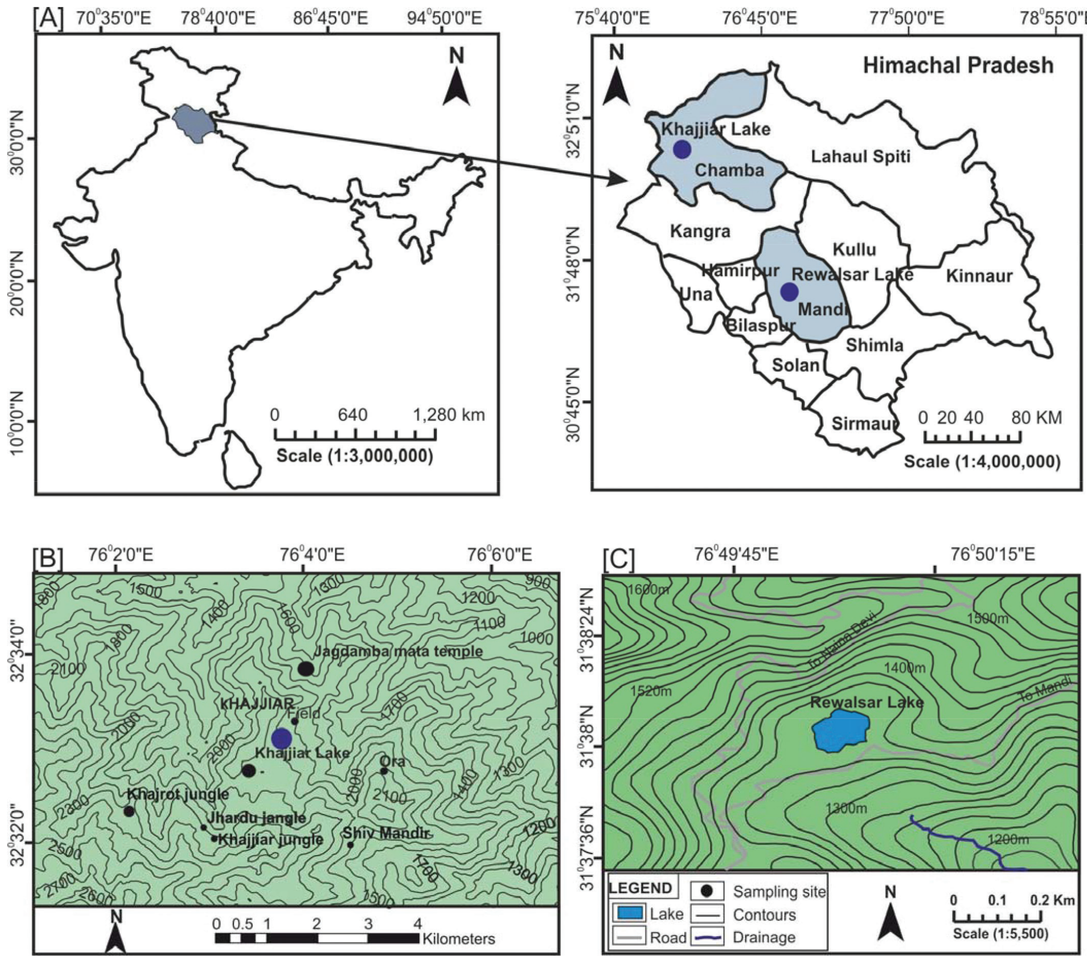

Figure 1: Study Area. (A) Map showing locations of lakes; (B) Contour map of Khajjiar Lake and (C) Contour map of Rewalsar Lake (After Gaury et al., 2018).

and Haake, 2003). The surface inflow to the lake occurs from the catchment area and seasonal inlet streams. These seasonal inlets and a single outlet are present in northern and southern parts of the lake, respectively (Sharma and Chauhan, 1988; Sarkar et al., 2016). Das and Haake (2003) argued that the RWL sediments were derived from the metamorphic terrain. Based on the hydrochemistry of RWL water, Gaury et al. (2018) confirmed that the lake water collected during pre- and post-monsoon seasons was unsuitable for drinking.

Materials and Methods

In the summer of 2018, 765 cm and 647 cm long cores were extracted from the KJR and RWL lakes respectively using Livingstone corer. The uppermost 62 cm and 76 cm parts of the cores respectively could not be used for analysis, as this material was lost during the drilling process. A preliminary visual inspection of the cores was done and idealised lithological profiles were generated to visualise the macroscopic properties of the sediments (Figure 2). The cores were split into two halves along the length and images were captured using a high-resolution camera and then sliced at a regular interval of 1 cm. The samples were stored in a secular location and stainless steel spatula was used for sub-sampling after which the sediment vials were immediately capped and locked to avoid contamination. The sub-samples were prepared by drying >50°C in an electric oven. Based on the lithological variation, a total of 34 samples from KJR and 36 samples from RWL were selected for the grain size analysis. Insufficient sediment quantity and abundance of vegetative matter from 62-250 cm in the KJR core prevented the sample selection for analysis. Each sample was chemically treated to prepare for the grain size analysis using the International Pipette Method and/or Hydrometer method (Jackson, 1956; Knuze, 1965). To remove carbonates and soluble salts, 10 ml sodium acetate (NaOAc) was added in 2 gm of each sample and heated for 1 hour

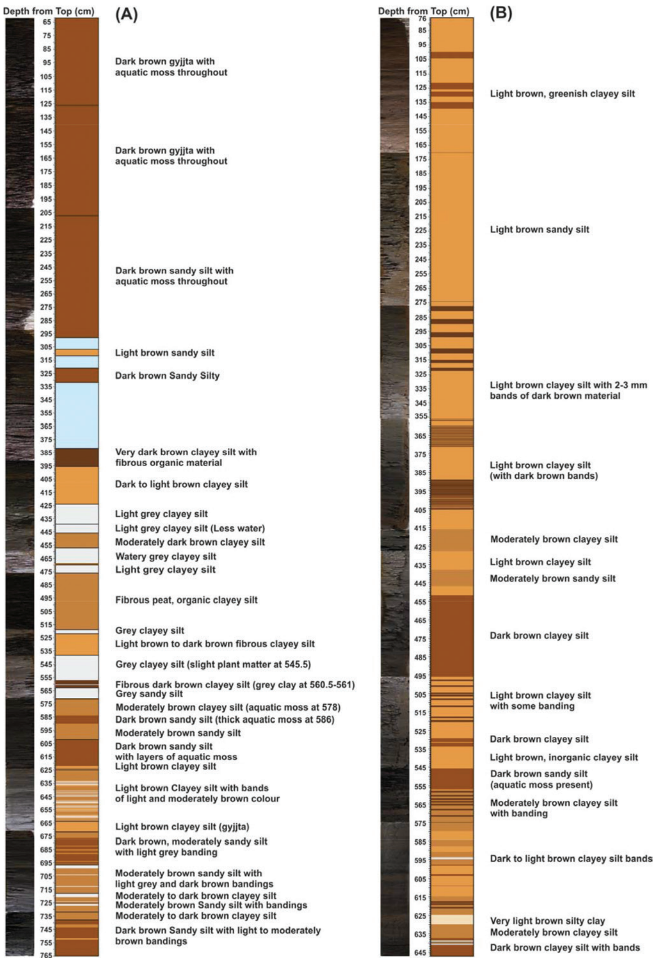

Figure 2: Core photograph with the lithological details. (a) Khajjiar Lake and (b) Rewalsar Lake.

on the water bath. Subsequently, the samples were centrifuged and drained supernatant two times and this was followed by the treatment of hydrogen peroxides (H_2O_2) for removing the organic matter. After adding 2 ml H_2O_2, the samples were stirred and allowed time for effervescence or frothing to subside and further put on the water bath for 1 hour. After boiling, the samples stayed for a full night. The next day, the tubes were centrifuged and the supernatant was drained. The sample residue was finally treated using the sodium-dithionite-citrate method to remove free iron oxides. In this method, 10 ml sodium bicarbonate ($NaHCO_3$) and 0.2 ml sodium citrate dihydrate were added to the treated sample and the mixture was put on the water bath and 0.2 gm of sodium dithionite ($Na_2S_2O_4$) was added and the suspension was stirred for 15 minutes. Afterward, the samples were centrifuged using distilled water. Finally, the grain size analysis was carried out by Laser Diffraction Particle Size Analyser (LPSA). The data output was processed by using the Gradistat software (Blott and Pye, 2001).

Approximately 1 gm homogenised sample was used for the TOC analysis (see Agrawal et al., 2015) for pre-treatment of samples. Analysis was done by using an Isotope Ratio Mass Spectrometer (IRMS). Both the analyses were performed in the Geochemistry Laboratory of Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow. Other statistical calculations were obtained by using Microsoft Excel and SPSS software. The basal horizon (sample no. KJR 764) was AMS radiocarbon dated as 4,718 ± 31 yr. BP by using 500KV pelletron at Inter-University Accelerator Centre (IUAC), New Delhi. For the RWL sediments, the basal ages have been proposed as 3,200 yr. BP (Singh et al., 2020).

Results

Both lake cores have similar compositions and are composed of sand, silt and clay. The ternary plot diagram (see Folk and Ward, 1957) shows that both KJR and RWL sediments have dominance of silt followed by clay and sand (Figure 3). The silt content of KJR has average value of 67.5% (38-44.4%) with secondary clay of 16.8% (3.9-42.7%) and sand with 15.7% (0-48.3%). Similarly, the RWL sediments reveal the dominance of silt with an average value of 81.6% (36.1-90.2%), followed by clay with 15.1% (4.5-22.0%) and a minor amount of sand as 2.8% (0-26.5%) (Figures 4-5).

Statistical Parameters

The sample statistics parameters (mean, mode, standard deviation, skewness and kurtosis) were calculated

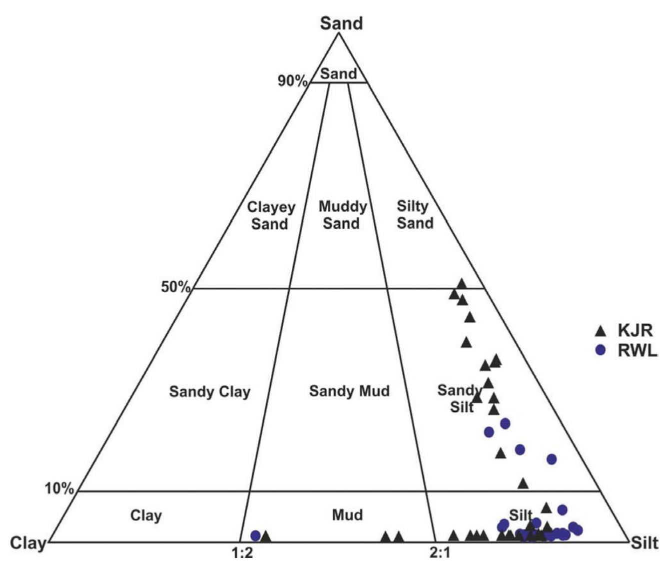

Figure 3: Ternary plot showing the distribution of sand, silt and clay percentages (Folk and Ward, 1957). (Khajjiar lake, KJR; Rewalsar lake, RWL).

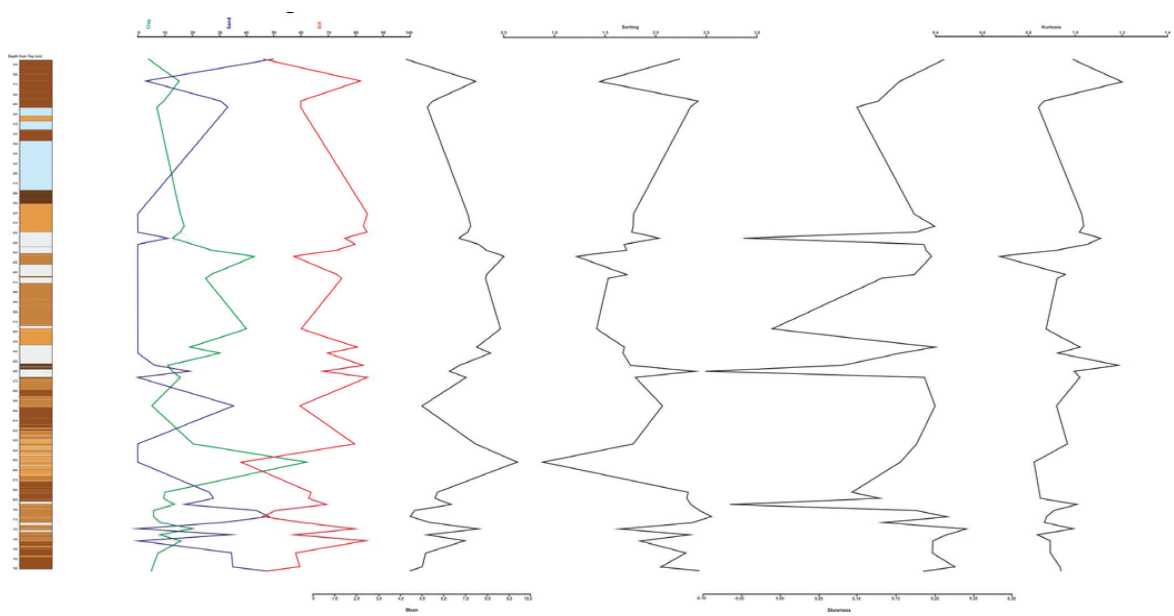

Figure 4: Down-core variation in the sand%, silt%, clay%, mean grain size, sorting, skewness and kurtosis parameters for the Khajjiar lake sediments.

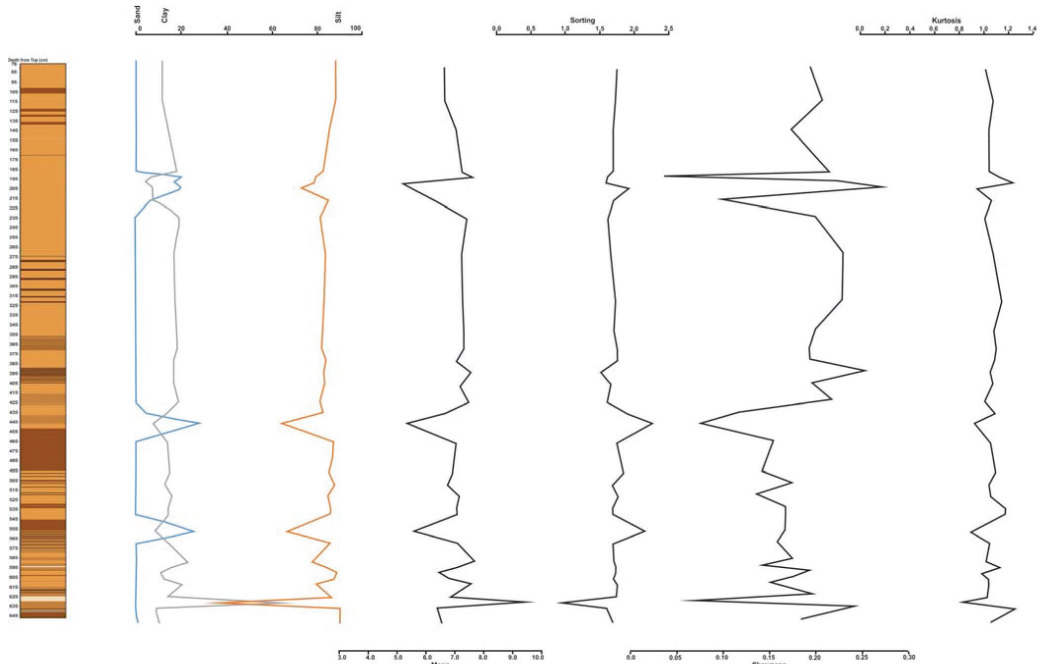

Figure 5: Down-core variation in the sand%, silt%, clay%, mean grain size, sorting, skewness and kurtosis parameters for the Rewalsar lake sediments.

following the study by Folk (1954). These parameters play an important role in delineating the influence of depositional processes (Freidman, 1961). While mean grain size is a reflection of the competency of transport mechanism, skewness and standard deviation are considered as environmentally sensitive parameters, thus considered as very important indicators (Freidman, 1961a, b; Padhi et al., 2017). The mean grain size (MGS) or average grain size of the sediments is regarded as a major factor for an index of energy conditions, which affects their deposition (Folk, 1966; Purnawan et al., 2015). Sahu (1964) defined the mean grain size as an indicator of the central tendency of the sediment and argued a simplest way to give single value for granulometric characterisation of sediment. The MGS of sediments ranges between 4.261 φ and 9.387 φ with an average value of 6.63 φ representing clay to very coarse silt category for the KJR. The MGS of the RWL sediments ranges from 5.540 φ to 9.419 φ with an average value of 7.009 φ designating clay to coarse silt. The MGS of KJR has a coarser fraction of silt compared to the RWL sediments. The average MGS represents the overall relatively higher energy conditions with more fluctuations in energy level for the KJR, compared to the RWL sediments (Hakanson and Jansson, 1983).

The standard deviation of grain size measures the sorting or the uniformity of the grain-size distribution (Srivastava et al., 2012). The values of standard deviation show differences in kinetic energy or velocity for two different modes of deposition (Sahu, 1964). The standard deviation ranges from 0.88 φ to 2.56 φ for the KJR and from 0.957 φ to 2.264 φ for the RWL. The sediments are moderate to poorly sorted in both lakes. It was found that the KJR sediments are very poorly sorted as compared to the RWL sediments.

Skewness is a measure of the asymmetry of the frequency distribution, i.e., the proportion of coarse or fine fractions, which marks the position of the mean with respect to the median. A symmetrical curve with excess fine material shows a positive value, whereas excess coarse material points to a negative value and zero value is indicated by a symmetrical curve (Sahu, 1964). The skewness values range between -0.097 φ to 0.240 φ for the KJR and 0.079 φ to 0.25 φ for the RWL. The sediments of both the lakes are symmetrical to finely skewed. However, most of the RWL sediments are finely skewed but the higher percentage of sediments shows symmetrical distribution compared to the KJR sediments.

Usually, the kurtosis is regarded as an expression of the peakedness of the grain-size distribution. According to Sahu (1964), it is a measure of sorting rather than peakedness and the ratio of sorting within the central 90 percent to the sorting in the central 50 percent defines the kurtosis. Folk and Ward (1957) and Mason and Folk (1958) considered kurtosis to be a significant grain size analytical tool. In our profiles, kurtosis values vary between 0.678 φ and 1.205 φ for the KJR and from 0.8 φ to 1.2.4 φ for the RWL. A large part of both the lake profiles exhibits mesokurtic nature. The leptokurtic nature of sediments is observed more in the RWL sediments while the platykurtic nature is dominant in the KJR sediments.

Bivariate Plots

To understand different depositional settings, the energy condition of depositing agency, changes in hydrodynamic conditions and the geological significance of the grain size parameters with respect to the transporting medium, a number of researchers have produced bivariate plots by combining the grain size parameters (Folk and Ward, 1957; Stewart, 1958; Sahu, 1964; Friedman, 1967; Srivastava et al., 2012; Kanhaiya et al., 2016; Padhi et al., 2017).

The plot of skewness vs. mean (phi) for KJR shows that most of the sediments are finely skewed and only medium and very fine silt sediments are symmetrical in nature. The RWL shows the clustering of sediments in the fine skewed zone (Figure 6A). Thus, the majority of samples fall in the medium to fine silt with positive skewness. The mean vs. standard deviation plot for both the lake sediments shows an increase in sorting value with the increased size of the lake sediments (Figure 6B). The scattering shown in the plot of the kurtosis vs. mean (phi) indicates that both the lake sediments as a whole are dominated by mesokurtic type sediments (Figure 6C). Medium and fine silt sized sediments are mainly mesokurtic to leptokurtic in nature, while the clay and coarse to very coarse silt sediments fall under platykurtic to the mesokurtic zone. The plot of the kurtosis vs. skewness shows that the fine skewed sediments fall in the platykurtic to leptokurtic for the KJR and mesokurtic to leptokurtic zone for the RWL. However, the symmetrical sediments fall approximately at the boundary of platykurtic and mesokurtic for RWL while mesokurtic to leptokurtic for the KJR (Figure 6D). The ideal way to identify the environment is by plotting skewness against kurtosis because these parameters reflect the changes in the tails of the distribution curves and are the most sensitive to the transport mechanism (Runge, 2017). The plot between the kurtosis vs. standard deviation (phi), showing the presence of very poorly to poorly sorted sediment of KJR falls in the mesokurtic and leptokurtic zone while the moderately sorted sediments lie in the platykurtic zone. As far as RWL sediments are concerned, platykurtic sediments are moderately sorted and mesokurtic sediments are very poorly to poorly sorted, indicating the leptokurtic sediments (Figure 6E). The plot of the skewness vs. standard deviation (phi) of the sediments shows that the moderately sorted sediment lies in the platykurtic zone, poorly sorted sediments show the clustering in mesokurtic and leptokurtic and very poorly sorted sediments are mesokurtic (Figure 6F).

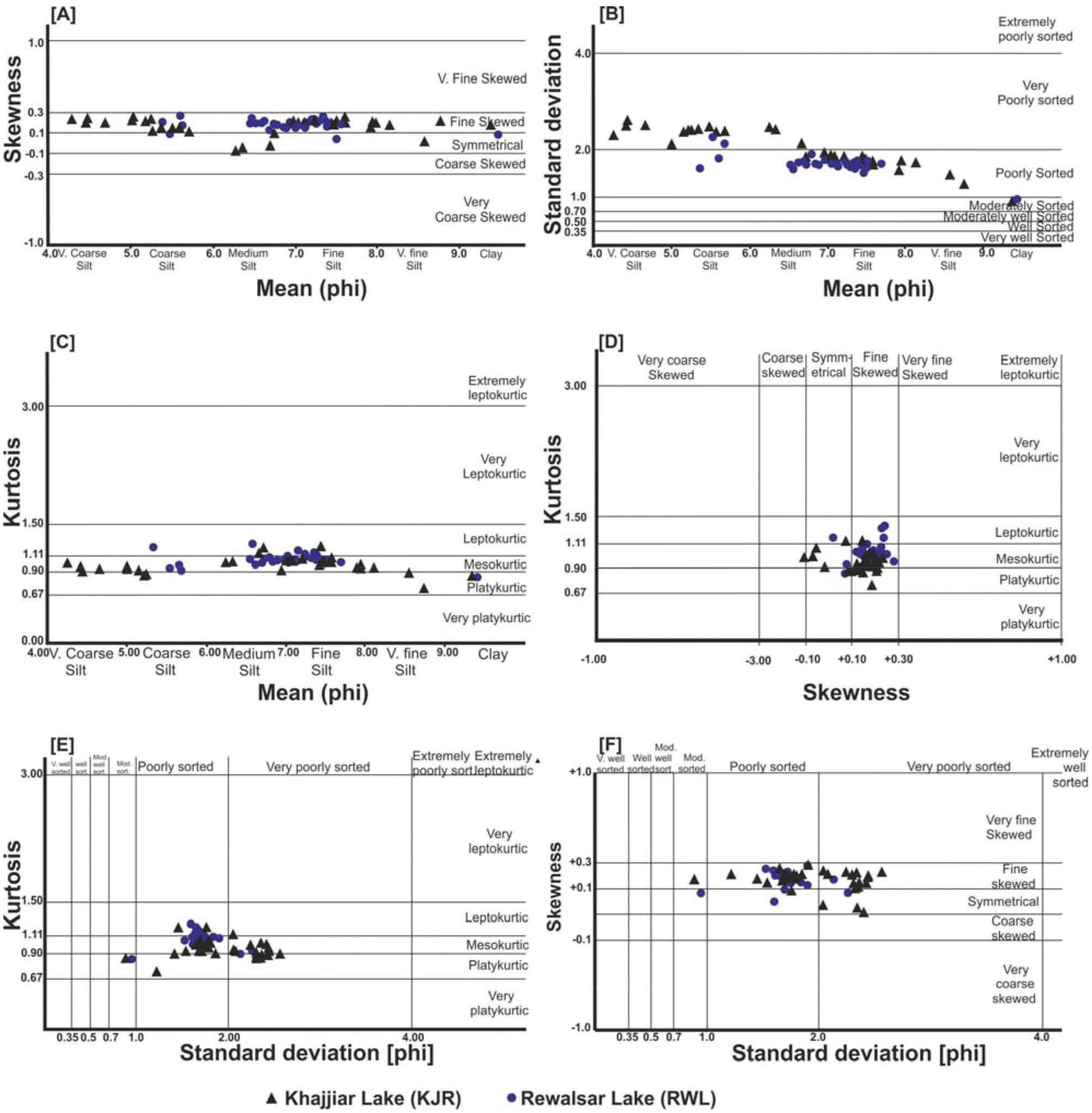

Figure 6: Bivariate plots. [A] mean vs. skewness, [B] mean vs. standard deviation, [C] kurtosis vs mean, [D] kurtosis vs. skewness, [E] kurtosis vs. standard deviation and [F] skewness vs. standard deviation.

Litho-facies

By combining grain size distribution and visual sedimentological observations of the cores, the sedimentary litho-facies were identified and their description is based on the sand-silt-clay ratio in the ternary plot (see Folk and Ward, 1957). For this study, the facies description for both the lakes was synthesised according to compositional and textural characteristics, mainly grain size and laminations (Table 1, Figures 7-8).

Total Organic Carbon (TOC)

The TOC values show temporal variation for both the lake cores. For KJR, the TOC ranges from 0.9 to 31.2% (average 10.6%), while for the RWL, it ranges from 1.0 to 9.0% (average 2.6%). The TOC data set shows a significant correlation with sand, silt and clay for KJR while RWL data do not show any significant correlation. For KJR sediments, a significant positive correlation was calculated between TOC and sand (*p*

Table 1: Characteristics and interpretation of the litho-facies associations for Khajjiar and Rewalsar lake sediments

Facies (Code)	*Description of sedimentary facies*	*Khajjiar lake (KJR)*	*Rewalsar lake (RWL)*	*Interpretations*
Sandy silt (Ss) (Coarsest facies)	Silt > sand > clay Colour variations from light to brown (dominantly darker shades), Presence of organic matter and aquatic moss.	This litho-facies forms 54.7% of the overall sediments. Textural parameters: Silt (45.9-81.9%) > sand (0-50%) > clay (3.9-15.2%); Coarse silt (9.7-34.7%) > medium silt (8.9-26.7%) > fine silt (9.1-45.5%); average MGS 5.297 φ; poorly to very poorly sorted (1.1451-2.555 φ); finely skewed to symmetrical (0.065-0.226 φ); platykurtic to leptokurtic (0.840-1.205 φ); unimodal to polymodal. Physical features: Variable in brown shades, 11.5 cm to 97 cm thick layers, laminations and bandings at some parts, ample amount of aquatic moss and organic matter observed. Sub-facies: Non-laminated sandy silt sub-facies **(Ssn)** Present at the top (250-395 cm) and the lower (571-625 cm) part of the core with silt facies. Laminated Sandy silt Sub-facies **(Ssh)** 1 mm-2.5 cm thick laminations and bands; sand percentage lower than silt and clay percentage relatively higher than Ssn facies; Present as 11 to 27 cm thick layers at the lower part (698, 718 & 732 cm) of the core with S facies.	This litho-facies form 8.58% of the overall sediments. Textural parameters: Silt (65.5 – 78.7%) > sand (6.7-26.5) > clay (4.5-8.4%); Coarse silt (30.7-53.5%) > medium silt (14.7-15.7%) > fine silt (10.5-19.5%); average mean grain size 6.033 φ; Poorly sorted to very poorly sorted (1.597 to 2.264); finely skewed to symmetrical (0.042 to 0.267); platykurtic to leptokurtic (0.900 to 1.230); unimodal to polymodal. Physical features: Variable in brown shades, 5 cm to 49 cm thick layers, laminations absent; the presence of organic matter, aquatic moss observable at some places. Sub-facies: Non-laminated Sandy Silt Sub-facies **(Ssn)** Present at the top (171– 219 cm), middle (438–452 cm) and lower (546–557 cm) part of the core.	High fraction of sand and coarse silt fractions indicate high-energy conditions for these facies (Hackson and Jansson, 1983; Nag et al., 2016; Padhi et al., 2017). Presence of coarse grain sediments (Kotlia and Bisht, 2020) and aquatic moss growth is favourable during the shallow water conditions related to arid conditions. Some laminations and bands may have been due to fluctuations in velocity while transporting sediments (Doeglas, 1968) or may be formed in low energy conditions under insignificant bioturbation (Kemp, 1996; Verschuren, 1999).

Silt (S)	Silt >>> Sand and clay This facies dominates the entire cores. Silt is the dominant constituent of this facies.	It consists of about 42.6% of the overall facies spectrum**.** Textural parameters: Silt (38-84.3%) > sand (19.25%)> clay (11.1-62.0%); fine silt (28-45.6%) > coarse silt (0-33.2%) > medium silt (0-26%) and fine silt (28-45.6%); av. MGS 7.454 φ; very poor to moderately sorted (0.889-2.391 φ); finely skewed to symmetrical (-0.097-0.240); platykurtic to mesokurtic (0.826-1.113 φ). Physical features: Variable in brown shades and grey; 2 to 47 cm in thickness, laminations and bandings at some part; fibrous peat and organic matter observed at some part. Sub-facies: Non-laminated silt sub-facies (Sn) Present as 2-43 cm thick bands of grey and brown shades at 382, 522, 697, 718, 732cm depths; fibrous peat present at some part. Laminated Silt sub-facies **(Sh)** 1 mm laminations to 3 cm thick bands of grey and brown colour; present as 47 cm thick horizon at 625 cm; lacks organic matter.	It consists of about 90.54% of the overall facies spectrum. Textural parameters: Silt (78-90.25%) > sand (0-6.8%) > clay (8.3-22 %); fine silt (24.9-46.5%) > coarse silt (13.4-39%) > medium silt (19.3-28.3%); av. MGS (7.119 φ); poorly sorted (1.529–1.900); finely skewed (0.121–0.252); mesokurtic to leptokurtic (0.988–1.244). Physical features: Greenish and variable brown shades; laminations and bands (2-3 mm thick); organic matter observed at some layers. Sub-facies: Laminated silt sub-facies **(Sn)** Dominant throughout the core (at 76-170 cm, 219-439 cm, 452-546 cm, 556-625 cm and 630-647 cm).	Dominance of lower grain size sediments can be related to low energy conditions (Nag et al., 2016). The condition of high precipitation can be inferred by the higher silt percentage (Peng et al., 2005) and humid conditions (Kotlia and Bisht, 2020). Higher percentage of silt can also be related to both natural input and anthropogenic activity (Singh and Sharma, 2012) and may be due to the higher gradient of the catchment and short distance of sediment transport (Diwate et al., 2020). Increase in number of laminations and bandings infer the greater fluctuations in velocity of transporting sediments (Doeglas, 1968).
Mud (M)	Silt and clay >>> sand This litho-facies constitute only silt and mud for both the lakes.	Overall, 2.7% belong to this category. Textural parameters: Silt (57.3 – 60%) ~ clay (42.7 – 57.3%); av. MGS is 8.682; poorly sorted (1.221-1.419 φ); fine skewed to symmetrical (0.195-0.011 φ); mesokurtic (0.678-0.877 φ). Physical features: Grey to moderately dark brown; present as 3-11 cm thick layer.	Overall, 0.88% belong to this category. Textural parameters: Clay (63.9%) > Silt (36.1%); av. MGS is 9.419; moderately sorted; symmetrical; platykurtic; bimodal distribution. Physical features: Very light brown; 5 cm thick layer.	Lowest energy conditions and quite environment (Sahu, 1964; Nag et al., 2016; Warrier et al., 2016; Kotlia and Bisht, 2020) Clay particles are considered as the very fine suspended load of the fluvial sediment supply. These particles suggest still water deposition in the lake and may be transported to the lake over large distance (Vandenberghe, 2013; Xiao et al., 2013).

< 0.01; r=0.666) whereas, the TOC shows significant negative correlation with silt and clay ($p < 0.01$; r = -0.507 and -0.426) (Tables 2-3).

Table 2: Pearson coefficient correlation between different variables of Khajjiar lake sediments

Variable	*Sand*	*Silt*	*Clay*	*TOC*
Sand	1			
Silt	-0.723**	1		
Clay	-680**	-0.16	1	
TOC	0.666**	-0.507**	-0.426**	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 3: Pearson coefficient correlation between different variables of Rewalsar lake sediments

Variable	*Sand*	*Silt*	*Clay*	*TOC*
Sand	1			
Silt	-0.391*	1		
Clay	-0.354*	-0.716**	1	
TOC	0.252	-0.124	-0.020	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Discussion

Lake sediments often exhibit polymodal distribution and reflect a mixture of sedimentary mechanisms. Therefore, sediment size and texture of lake sediments provide useful information on the mode of transportation and energy conditions that forces particles entering a lake system as well as hydrodynamic and depositional history (Mason and Folk, 1958; Friedman, 1961; Sahu, 1964; Visher, 1969; Hakanson and Jansson, 1983; Xiao et al., 2013; Runge, 2017). Since the hydrodynamic processes and the unique morphology of a lake may also affect the deposition in the lake (Dietze et al., 2012; Xiao et al., 2013), grain size analysis can serve as a reliable proxy to characterise the mechanism of sediment supply, evolution of the depositional environment and changes in the water level (Digerfeldt, 1986; Dearing, 1997; Boyle, 2001).

Due to differences in the local weather conditions, two lakes, e.g., Khajjiar and Rewalsar situated in the Lesser Himalayan terrain were selected to carry out the sedimentological studies. Both the lakes belong to almost the same chronological framework (Late Quaternary) (Sharma and Chauhan, 1988; Singh et al., 2020). The catchment area of the RWL consists of steep slopes with a higher sedimentation rate (3.3 cm/year) and Quaternary sediments (Sarkar et al., 2016; Diwate et al., 2020). The tectonic activity in the NW Himalaya has triggered the erosional process coupled with the cold and dry conditions prevailing in the area (Kumar et al., 2018; Diwate et al., 2020; Singh et al., 2020).

The sediments of both the lakes are composed of three components, i.e., sand, silt and clay. The silt is the dominant component followed by clay and sand and the dominance of silt and clay can be linked to the high precipitation rate (Figures 4-5). The temporal variation of sand, silt and clay of KJR fluctuates throughout the core while for the RWL, silt and clay share the same trend. The dominance of silt over sand and clay has also been reported from nearby Renuka lake of Himachal Pradesh which is situated in SE of the RWL (Diwate et al., 2020). The sediment size for the RWL is not wide comparatively to the KJR, suggesting the homogenous deposition of the source material for the RWL (see Figures 4 and 5). Comparatively coarser sediments were observed in KJR than the RWL signifying relatively high-energy conditions for KJR and low energy conditions for the RWL (e.g., Sahu, 1964; Hakanson and Jansson, 1983; Nag et al., 2016; Warrier et al., 2016; Kotlia and Bisht, 2020). A significant negative correlation of sand were observed with silt (KJR: $p < 0.01$, r = -0.723; RWL: $p < 0.05$, r = -0.391) and clay (KJR: p < 0.01, r = -680; RWL: $p < 0.05$, r = -0.354) for both the lake cores (Tables 2, 3). However, a significant correlation was found between silt and clay (p < 0.01, r = -0.716) for RWL (Table 3). There is a positive correlation between the TOC and sand percentage (r = 0.666) for KJR while the RWL lacks a significant correlation (r = 0.252). This pattern of grain size distribution indicates that the sediments of KJR have different modes (polymodal > bimodal > unimodal > trimodal) indicating the multiple sources of sediment deposition (see Last, 2001; Warrier et al., 2016). Therefore, sediments in the KJR could have been supplied directly by gravitation transport from the nearby higher area along with the catchment area that drains into the lakes by streams and surface runoff (Srivastava et al., 2012; Warrier et al., 2016). A majority of samples of the RWL are of unimodal and bimodal distribution except for a few samples belonging to trimodal and polymodal distribution, suggesting relatively homogenous/uniform sources. Overall sediments of both the lakes belong to platykurtic to leptokurtic nature but dominantly lie in the mesokurtic zone. Poor winnowing action may be attributed to the platykurtic nature and variable energy conditions can be inferred by the leptokurtic behaviour of sediments (Padhi et al., 2017). The presence of different modes possessing a less differentiated grain size range could be the reason for the dominance of mesokurtic distribution in the RWL sediments. Very poorly to moderately sorted characteristics of both lakes suggest low to the fairly high energy of depositing medium (Friedman and Sanders, 1961; Blot and Pye, 2001; Padhi et al., 2017). Fine skewed to symmetrical distribution is identified for both profiles. The samples displaying wide spread tail towards the coarse grain-size end indicate positive skewness. The changes in the values of skewness may have been created by the addition of silt due to the changes in the intensity of wind and hydrodynamic conditions (Spencer, 1963; Duane, 1964; Thomas et al., 1972, 1973; Sly et al., 1983).

The past lake level can also be assumed from the grain size of sediments, related to the variation in the precipitation intensity. The coarse sediments represent low water level conditions and the fine sediments indicate the rise in the water level (Hakanson and Jansson, 1983; Peng et al., 2000; Zhang et al., 2003; Chen et al., 2006; Conroy et al., 2008; Nag et al., 2016; Kotlia and Bisht, 2020). A little amount of water is necessary for plant growth and in the case of lakes, a low volume of water is necessary for the growth of organic matter. The TOC analysis shows that the organic matter is abundant in the KJR (0.9 to 31.2%; av. 10.6%) compared to that in the RWL (1.0 to 9.0; av. 2.6%). A significant positive correlation coefficient between sand and TOC and a negative correlation of TOC with silt and clay in the KJR indicates a direct link between grain size and organic productivity. The bivariate plots between the grain size statistical parameters are also used to give an insight into the energy conditions of the depositing medium. A significant correlation is observed between Standard deviation and MGS for both the lake cores, indicating more sorting with decreased mean grain size.

Litho-facies analysis was defined based on fractions of sand, silt and clay using a ternary diagram of Folk and Ward (1957). Sediments of both the lakes are assigned as sandy silt, silt and mud litho-facies. The temporal variation in grain size sediments of KJR and RWL are shown in Figures 4-5. Based on sedimentary characteristics, our study suggests the following three zones for the KJR (Figure 7).

Zone-1: From the bottom to 572 cm, high fluctuations in sand silt and clay percentages are noticed. Alternate bands of sandy silt and silt facies are present showing fluctuations in the energy conditions. Finely or coarsely distributed laminations throughout this part indicate fluctuations in the current velocity of the supplying medium (Doeglas, 1968).

Zone-2: From 572 to 396 cm core depth, mud litho-facies interlayered with silt litho-facies indicate decreasing energy conditions and raised water level compared to zone-1. This part appears to indicate enhanced humid conditions and higher water levels than the lower part as the sand percentage decreases with increasing silt and clay.

Zone-3: From 396 cm to the top of the profile, the dominance of sandy silt facies suggests higher energy conditions. The increased fraction of sand and coarse silt with decreasing clay towards the top depicts a drop in water level and hence an arid environmental regime. Broadly, three zones can be identified in the RWL core as below (Figure 8):

Zone-1: The basal part from bottom to 439 cm has micro laminations representing fluctuations in the energy condition, which may be due to the variation in the velocity of supplying medium. As a whole, this part shows the alternation of sandy silt with silt litho-facies depicting high and low energies respectively, i.e., fluctuating energy conditions. At 625 cm depth, a major drop in water level indicates a sudden increase in clay fraction with decreased silt fraction.

Zone-2: From 439 to 219 cm, overall sediments reveal more or less stable conditions with lesser water levels compared to zone-1. This zone is also dominated by the silt facies, inferring relatively low energy conditions.

Zone-3: From 219 cm to the top of the profile, sandy silt and silt facies suggest increasing and then decreasing energy conditions.

Although various zones in both the lake profiles possess different thicknesses a similarity between the energy conditions can somehow lead to a correlation of zones. Zone-1 and Zone-2 (KJR and RWL) show fluctuating patterns followed by relatively low energy conditions. The Zone-3 of the KJR depicts high energy conditions, but this zone in the RWL indicates low energy conditions, followed by high energy conditions (Figures 7 and 8).

Conclusion

The study of grain size analysis of the lake cores from Khajjiar and Rewalsar lakes of the Himachal Pradesh

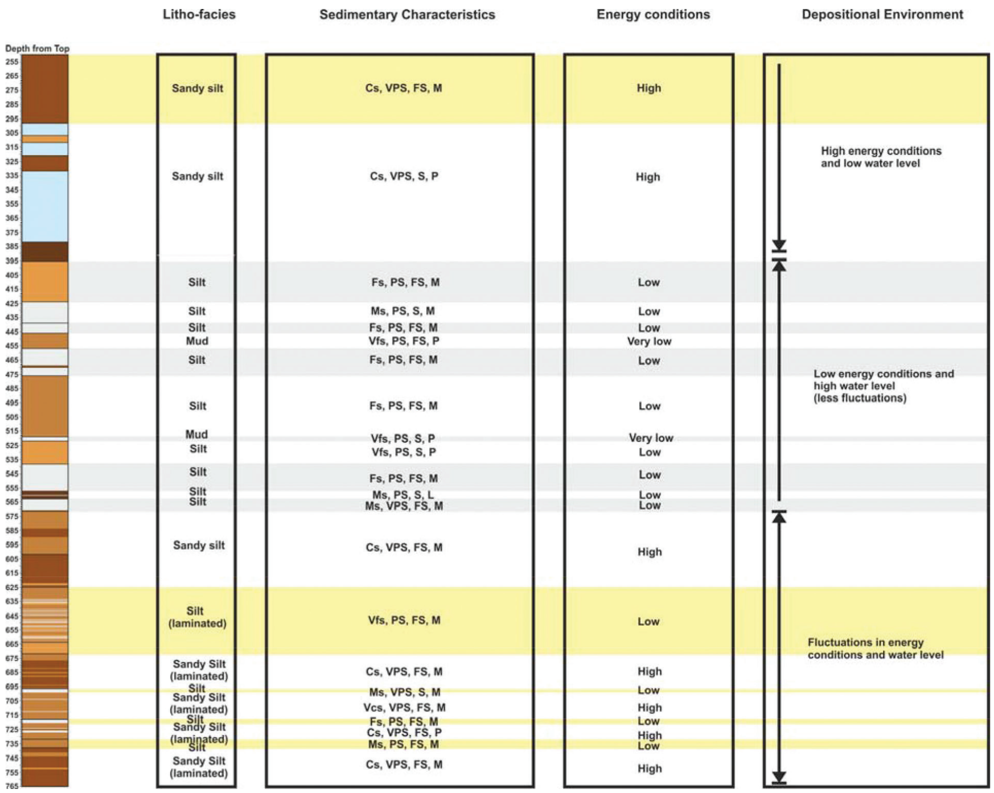

Figure 7: Sedimentary characters, energy conditions and depositional environment of the Khajjiar (KJR) lake sediments (Cs= Coarse silt, Ms= Medium silt, Fs= Fine silt, Vfs= Very fine silt, VPS= Very poorly sorted, PS= Poorly sorted, FS= Finely skewed, S= Symmetrical, L= Leptokurtic, M= Mesokurtic, P= Platykurtic).

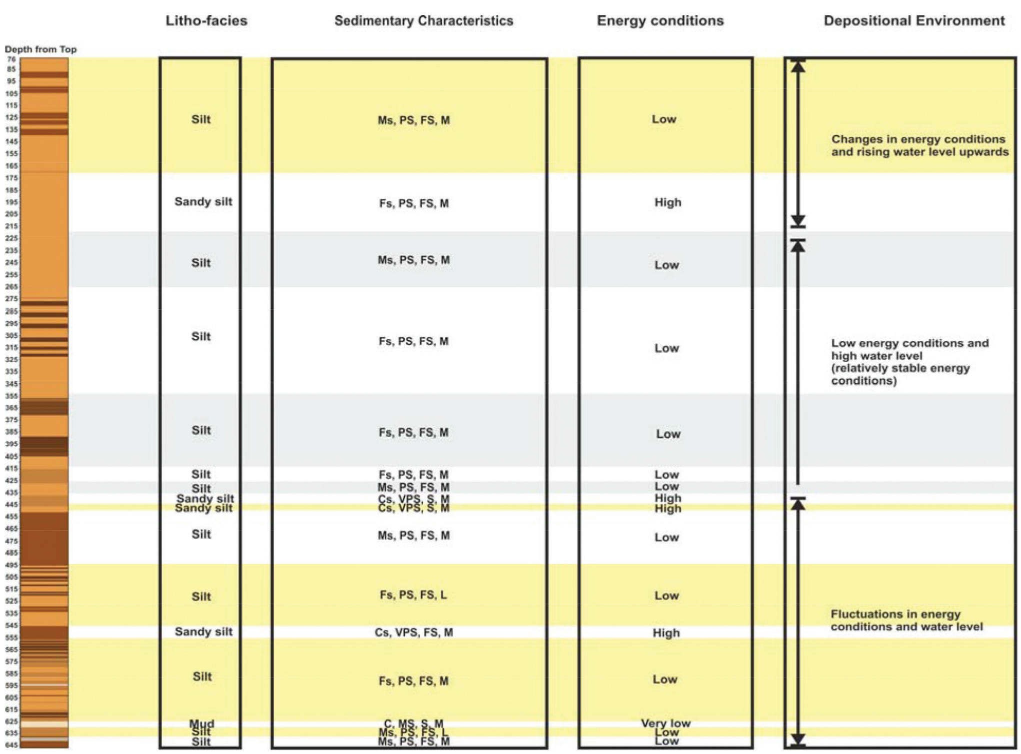

Figure 8: Sedimentary characters, energy conditions and depositional environment of the Rewalsar (RWL) lake sediments (abbreviations as in Figure 7).

provides potential information about the processes related to transportation and deposition of sediments. From the obtained data, it is concluded that the primary grain size components for Khajjiar lake are silt, sand and clay while silt dominates over the clay component in the Rewalsar lake. Relatively coarser sediments in the KJR core are assumed to indicate a relatively high-energy environment for KJR, whereas somewhat finer-grained sediments of the RWL point to the low energy setting. Both the lakes reveal poorly to very poorly sorting with fine to symmetrical skewness. The kurtosis values for Khajjiar lake range from platykurtic to leptokurtic, suggesting the fluctuation in energy conditions for the depositing medium. For the Rewalsar lake sediments, these values fall in the mesokurtic zone. Accumulation of fine silt and clay is ascribed to warm climate and lake level to rise because of substantial monsoon, while relatively colder phase and shallow water conditions suggest for the coarser grain size sediments. Based on sedimentological characters, both the lakes show three zones. It appears that the Khajjiar lake was more affected by less precipitation and high energy conditions compared to the Rewalsar lake. The Khajjiar lake shows the transition from fluctuating (zone-1) to humid (zone-2) to arid (zone-3) conditions while Rewalsar shows fluctuating (zone-1) to humid (zones 2-3) conditions. The similarity between zone-1 and zone-2 of both lakes shows that the study area may have experienced similar climatic conditions during the deposition of sediments.

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