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Optically Stimulated Luminescence (OSL) Dating of Sediments from Himalaya

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Abstract | Optically Stimulated Luminescence (OSL) dating gives the age of most recent daylight exposure or heating of samples to >400°C or the formation events of authigenic minerals. These correspond to the age of sedimentation and burial, ages of thermal events like contact heating by lava flows and heating during faulting and sand dyke formation, and the formation of a mineral via chemical precipitation. With the first observation of OSL in 1985, this method now occupies centre stage in Quaternary Geochronology. The use of OSL method for sediments from Himalaya began over three decades ago. The method has since provided chronology for a variety of events, such as past glaciation events, formation ages of river terraces, paleo–lacustrine deposits, landslides, floods, seismic events with substantive new insights into timing and style of geological processes.

Theoretically, the dating range of method is present to a Million years, and this critically depends on two factors, viz. luminescence properties of mineral and their radiation environments. The general working range using quartz is 200ka, and using feldspars is up to Brunhes Matuyam Boundary. Extensions beyond this limit are currently being explored.

1 Introduction

The range of the OSL dating methods cover a time period of a few years to several glacial-interglacial cycles that enable Quaternary geologists to blend historical data with paleodata. Basic robustness of this method accrues from the fact that the age of the sediment is determined using ubiquitous minerals like quartz and feldspar that constitute the sediment. This removes any ambiguity between the strata and the sample being dated. This contrasts with the case for radiocarbon dating, where a correlation between sample and the strata is assumed. Secondly, the method relies on internal calibration and provides calendar ages, whereas radiocarbon needs external calibration.

Aitken (1998) provides an introduction to this method and reviews of variousapplications of luminescence dating are found in Boreas (2008 special publication).

1.1 *The method*

Luminescence dating uses Quartz and feldspar as dosimeters of environmental radiation. The natural environmental radiation field arises due to decay of natural radioactivity, viz. U, Th and K, while a minor contribution is provided by cosmic rays. The radiation field comprises alpha, beta and gamma rays. On irradiation, the mineral lattice suffers ionization and some of the free charges produced in the processare trapped in lattice defects (electon or hole traps) (Fig. 1). As the decay times of natural radioactivity is in the Giga annum (Ga) range, the radiation field on Mega annum (Ma) time scales (save cases of geochemically caused radioactive disequilibrium) is reasonably assumed to be constant. Constant exposure from environmental radiation induces ionization in mineral lattice at a constant rate, and this in turn implies a cumulative increase

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in trapped charges from a given time of zero trapped charges concentration to the time of measurement.

On laboratory excitation, the charges are released and some of these radioactively recombine to produce luminescence (Fig. 1). Laboratory calibration enables conversion of this light to radiation dose units and measurement of natural radioactivity enables computation of annual radiation dose.

The age equation is

$$Age = \frac{Total\ trapped\ charges}{Annual\ rate\ of\ charges\ induction}$$

$$= \frac{Total\ luminescence\ or\ paleodose}{Annual\ dose}$$

where paleodose is the laboratory dose that provides the same luminescence intensity as received by natural sample.

Events dated by this method are the events that ensure that at these instances, the trapped charge concentration is reduced to zero or near zero. This can occur either via heating to 400°C or more, or via a day light exposure or is *ab initio* zero in case of chemical precipitates. For sediments, the daylight exposure is the zeroing mechanism, and depends on the mode and medium of sediment transport – sub aqueous or sub-arial. Mode of transportation and sediment load determines the amount and nature of daylight available to the sediment grain during transport, and this in turn decides the extent of zeroing.

In a terrain like the Himalaya, glacial sediment with limited transport duration under high sediment load condition may show *partial and heterogenous zeroing* at a grain level. *If ignored,* partial bleaching of grains can lead to age overestimation, but protocols now exist to deal with these issues, and in general, it is assumed that a sample was partially and heterogeneously bleached. A straightforward approach is to measure single grains and then the data used on individual grains to obtain ages on the most bleached grains, but this at times is not possible if the light output from single grains is insufficient for a proper analysis. Generally, a large data set of measurements of OSL ages is constructed using sub portions of each sample, and then statistically analyzed to obtain optimum results.

Partial bleaching in various environments has been addressed by several workers, and we refer to reviews by Wallinga, (2002) and Rittenour (2008) for fluvial sediments, and by Owen et al., (1997), Richards et al., (2000), Fuchs and Owen, (2008) for glacial deposits. Unequally bleached sediments are common in nature, however, sediment deposited under exceptional conditions, as during polar winters, can be considered as beached (Wallinga, 2002). Erosion of river banks during sediment transport can cause mixing of grains that lead

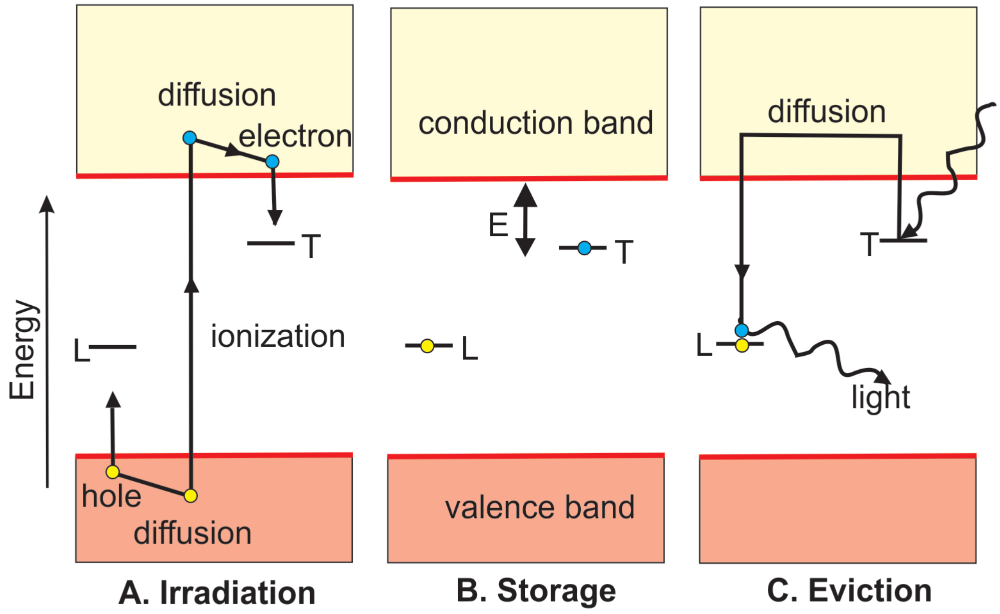

Figure 1: Diagrammatic representation of the formation of luminescene traps (i) ionization leads to the formation of holes and eviction of electrons from valance band. (ii) Electrons should be stored in deeper traps. Preferred luminescence centers should be deeper than 1.6 eV. (iii) During laboratory exposure of the quartz crystal the electrons move from shallow traps to deeper traps producing light (after Aitken, 1998).

to scattered distribution of results (Rittenour, 2008). A scatter in OSL ages is a common way of detecting partial bleaching (discussed in Wallinga, 2002). Various statistical models as least age (minimum 5% of De values; Olley et al., 1998), Central Age Model (CAM), Minimum Age Model (MAM) and Finite Mixture Model (FMM) (Galbraith et al., 1999; Galbraith 2005) are used to calculate age of the sample from scattered De values. Measurements are commonly made on coarse (90–210 μm) and fine (4–12 μm) grained sediment to minimize the effect of different track length of these two radiation types.

In general, as per basic physics, quartz bleaches more rapidly than feldspars. Added advantages of quartz as a natural dosimeter accrues from it being without any internal radioactivity, and it being more resistant to weathering compared to feldspar. The difficulty of quartz accrues from its limited dose range that implies early saturation. Feldspar, on the other hand, is attractive as these have high luminescence sensitivity and higher saturation dose. However, a difficulty arises from anomalous (athermal) loss of trapped charges or luminescence on storage (Wintle, 1973). More recent studies, however, provide a reasonable robust methodology to correct athermal fading using laboratory experiments (Thomsen et al., 2008). In practice, the choice of mineral depends on a variety of factors, and generally both provide consistent results.

Determination of age comprises two measurements. First is the measurement of paleo dose or equivalent dose via luminescence measurement, and second, the annual dose via the measurement of elemental concentration of radionuclides.

Single Aliqout Regenerative (SAR) method is now used for the measurement of paleodose (Fig. 2). It is an advanced method based on Multiple Aliquots Additive Dose (MAAD) (Fig. 2). Application of SAR in Himalayan fluvial sediment is discussed in Jaiswal et al., (2008), where despite low luminescence the quartz grains could be analyzed. Glacial sediment from Himalaya were initially considered unsuitable for dating due to high *recuperation* (a case of thermal transfer) after bleaching (Rhodes and Pownall, 1994). However, this is not the case always; with the development in the technique, OSL dating is now being extensively used for glacial sediment analyses (Juyal et al., 2009; Nawaz Ali et al., 2013; Mehta et al., 2014). With the advancement in OSL method, dating of young (<1000 years) sediment is also possible with precision (Madsen and Murray, 2008). A good introduction to methodological aspects of Luminescence dating is provided by Morthekai and Nawaz Ali (2014).

Dose rate estimation includes the rate of natural radiation in the depositional environment, water content and cosmic radiation. Cosmic ray contribution depends upon the sample latitude, altitude and thickness of overburden; the effect of cosmic ray can be measured using the equation given in Prescott and Stephan (1982) with precise measurements of sample depth from surface. The effect of latitude is significant near the poles, as the shield provided by earth's magnetism gets thin. The ionic radiation that the sample is exposed to can be determined by evaluating the concentration of U, Th, K and Rb at sample location. Natural radiation is considered to be homogeneous, however, the presence of a radioactive mineral such as zircon may lead to inhomogeneous distribution of ionic radiation. Radiation inhomogeneity in sediments is discussed in detail in Singhvi and Wagner

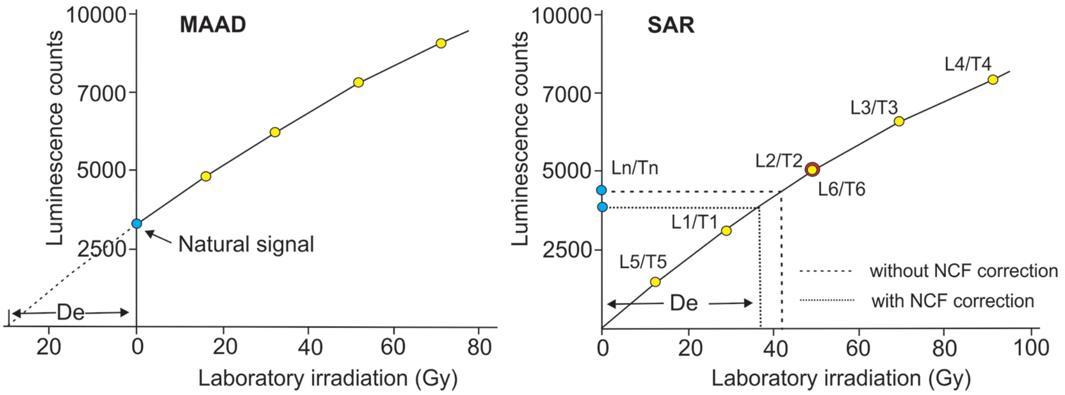

Figure 2: Diagram demonstrating additive dose (MAAD) and regenerative (SAR) dose method used for OSL dating. In MAAD, the De is obtained by extrapolation however in SAR the De is obtained by interpolation. The NCF correction applied in SAR controls the De scattering.

(1986). Using energy conversion equation given by Ademiec and Aitken (1998) annual radiation can be calculated. Various instruments such as X–Ray Fluorescence (XRF), Gamma spectrometer, Ge detector, flame photometry, ICP–MS etc. can be used for elemental concentration. Water content in a sample affects the sample age significantly. It is difficult to measure the maximum water attained by the sample, since deposition though during the analysis present day water content is essentially measured. A change in water content by 10% may lead up to 8% age over estimation (Guedes et al., 2013).

2 Application of OSL in Dating Sediments from Himalaya

OSL dating in sediment from Himalaya was attempted first by Sharma and Owen (1996) to date glacial events of Garhwal Himalaya, India. Various methodological aspects are discussed on the applicability of OSL in Himalayan sediments (Rhodes and Pownall, 1994; Rhodes and Bailey, 1997; Rhodes, 2000). An important aspect of OSL of Himalayan sediments was low luminescence sensitivity, but despite this, accurate ages were obtained from various regions and environments of the Himalaya (see Fig. 3). Some of the important results and their scientific import are summarized below.

2.1 *Glacial deposits*

The glacial deposits show partial bleaching and low luminescence sensitivity due to their limited exposure to the daylight and fewer erosion-sedimentation cycles (Owen et al., 1997). Glacial deposits of Hunza valley of Karakoram, North Pakistan were the first to be dated using TL method (Derbyshire et al., 1984). Quartz and feldspar grains from till deposits of Kanchenjunga Himal, eastern Nepal were dated using Single Aliquot Regenerative (SAR) method (Tsukamoto et al., 2002), and consistent ages based on feldspar and quartz gave chronologies of glacial events as 5–6, 8–10, and at 20–21 ka.

Studies by Rhodes and Pownall (1994) on glacial deposits of Gangotri, India, brought out some difficulties in the use of OSL method for glacial sediment, nonetheless, five major glacial advancement stages at ~63–11 ka (Bhagirathi stage), ~7 ka (Kedar stage), ~5 ka (Shivling stage), ~1 ka (Bhujbas stage), ~300–200 years BP (Bhujbas stage) were inferred (Sharma and Owen, 1996; Barnard et al., 2004). Studies by various workers suggested that the western Himalaya (Zanskar and Lahul area) experienced 4–5 stages of major glaciation during ~78 ka to Little Ice Age (LIA) (Taylor and Mitchell, 2000; Owen et al., 1996). Glaciation in Central Himalaya was variable among the valleys, in the upper Ganga valley, glaciation took place at 63–5 ka, ~5 ka and during LIA in the

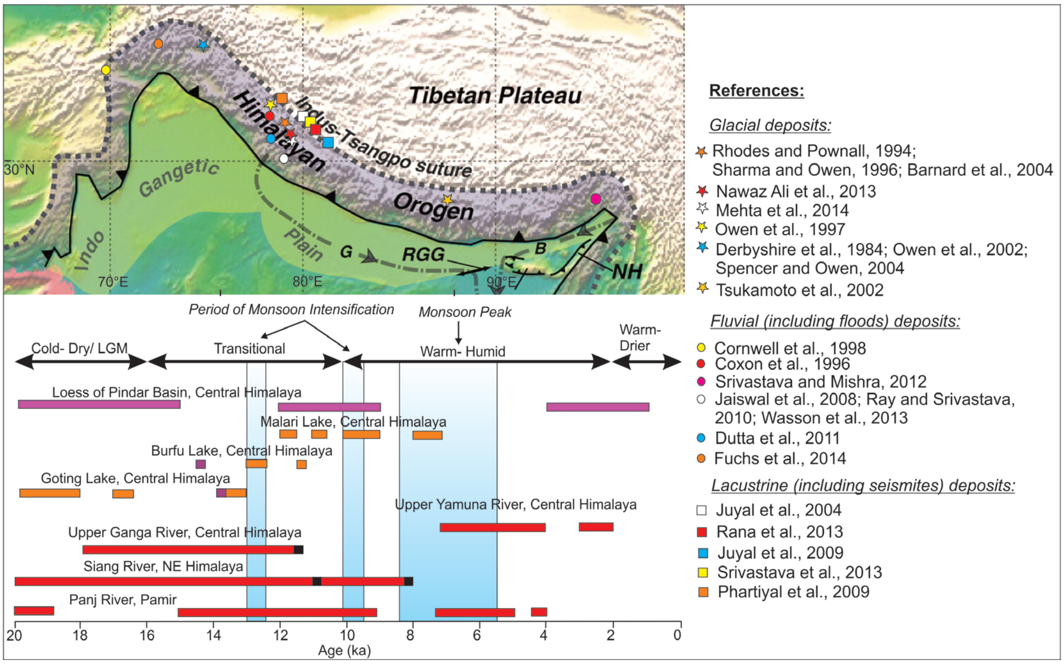

Figure 3: (A) Few important studies on climate change using OSL as a tool are shown in the map, these studies are discussed in the text. The background map is from Yin et al., (2009). (B) Important studies in Central Himalaya discussed in section 2.2, 2.3 and 2.4 are compared with the global climatic conditions in past 20 ka. The results are asynchronous with the global data. Background map is from Kale et al., (2004).

Bhagirathi valley (Sharma and Owen, 1996), ~12 ka and ~4.5 ka in the Alaknanda valley (Nainwal et al., 2007), ~13 ka, ~9 ka, ~7 ka and ~5 ka in Chorabari, Kedarnath (Mehta et al., 2012). Parallel ages of glacial advancement at ~20 ka, ~16 ka, ~8 ka, ~6 ka and ~3 ka in Tons valley were obtained using Cosmogenic Radio Nuclide (CRN) and OSL dating methods (Schereler et al., 2010; Mehta et al., 2014). Review on extensive dating of Himalayan glacier deposits suggest that the major glaciation periods, experienced by most of the Himalayan glaciers, can be grouped as 18–20 ka and 30–60 ka, which is not synchronous to the global ice volume maximum (Fig. 4, Benn and Owen, 1998).

2.2 *Loess deposits*

The distribution and formation of loess deposits in central Asia has been long debated. The oldest loess deposit of central Asia formed as a result of frequent dust storms dated as 2–2.5 Ma (Dodonov and Baiguzna, 1995), however, the first glacial loess deposit from India was reported by Pant et al., (1978). Thermo Luminescence (TL) dating of ~300 ka old eolian loess deposits of Kashmir valley revealed that the area witnessed at least three major warm periods between 50–80 ka (Bronger et al., 1987; Singhvi et al., 1987). A glacial loess from central Himalaya suggest that the region experienced three drier climatic conditions at >15–20 ka, >9–12 ka and >1–4 ka, and soil forming episodes at 16–12 ka and 9–4 ka (Pant et al., 2005). The asynchronicity in glaciation- deglaciation cycle of the Himalayan glaciers and limited studies on loess confines a regional climatic picture (Fig. 3).

2.3 *Glacial lake deposits*

Difficulty in the use of 14C dating for lacustrine deposits of the Himalaya was reported by

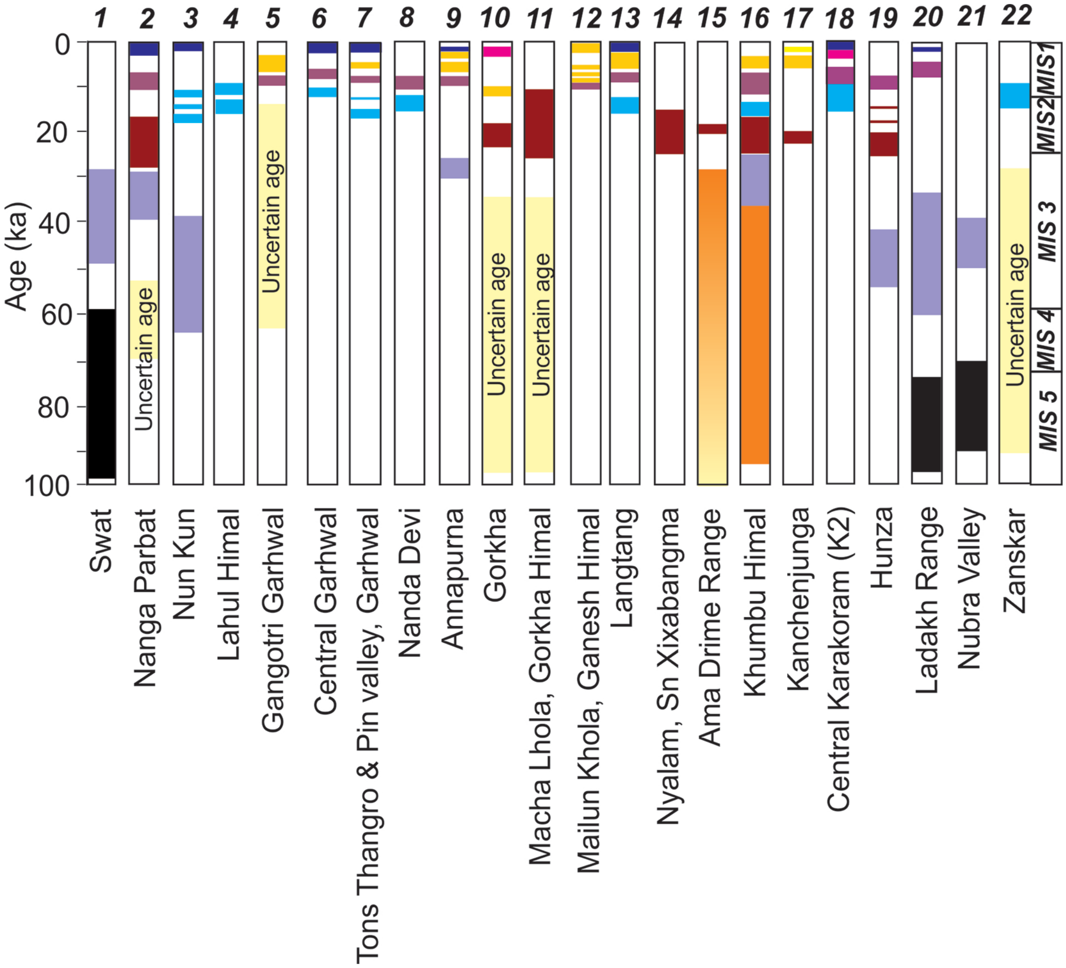

Figure 4: Glacial advancement periods of major Himalayan glaciers are compiled in Owen et al., 2012. Some of the results are redrawn to display the major glaciation phase in Central and Trans Himalaya. Note the regional glacial advancement periods at 18–20 ka and 30–60 ka. References used in the figure are mentioned separately.

Juyal et al., (2004). Radiocarbon ages on sediments derived from lime stone terrains suffer from hard water effect. Use of OSL dating provided stratigraphically sound ages on lake sediments, and based on this, the climatic record at Goting and Burfulakes, Central Higher Himalaya was provided (Juyal et al., 2009, Beukema et al., 2011). Evidence of stronger monsoon at 25 ka, 23.5–22.5 ka, 22–18 ka, 17–16.5 ka and after 14.5–13 ka are reported from Goting lake deposits (Juyal et al., 2009). However, the Burfulake was fed by glacier from ~15.5–14.5 ka, followed by the warming event at 14.5 ka, since ~13.2 ka–12.5 ka and at ~11.3 ka monsoon was strong, with a decline at ~12.5 ka (Beukema et al., 2011).

Another lake named Malari lake near Goting was dated and phases of intensified monsoon dated as ~11.5 ka, ~11–10.5 ka, ~10–9 ka and ~8–7 ka (Srivatava et al., 2013). In the Trans Himalaya, the strengthened monsoon and formation of lake in the Spiti valley took place between 50–30 ka and 14–6 ka corresponding to the MIS–3 and MIS–1 respectively (Phartiyal et al., 2009). Expansion of lakes in the Himalaya has been correlated with increased humidity (Fig. 3, Benn and Owen, 1998). Presently, glacial lakes in the Himalaya are forming at the highest rate in response to global warming (Bajracharya and Mool, 2009).

2.4 *Fluvial deposits*

The Himalaya supports world's seven most sediment loaded fluvial system including the Ganga, the Brahmaputra and the Indus (Milliman and Meade, 1983). The Ganga river deposits 520 million tons sediment annually to the Bay of Bengal (Goodbred, 2003), which makes it the largest sediment transfer system in the world. 95% of the total sediment gets transported during the monsoon (Goodbred, 2003) when the suspended sediment concentration is highest (Chakrapani and Saini, 2009). The sediment of the rivers are transferred from source to sink in multiple cycles with storage enroute in form of river terraces and transported to the basin during optimal climatic conditions (Srivastava et al., 2003). The longer the duration or of sediment burial better are the luminescence signals (Rittenour, 2008). A minimal time of 1–2 ka between sediment generation in Himalaya and its deposition in the Bay of Bengal is suggested (Goodbred, 2003). Despite its low luminescence sensitivity, sediment from Himalaya was sufficiently well behaved to provide satisfactory ages. (Jaiswal et al., 2008). Regional aggradation episodes in upper Ganga valley took place around 49–25 ka and 18–11 ka, followed by valley incision after 11 ka (Ray and Srivastava, 2010).

In the adjacent Yamuna valley aggradation occured in five phases with 37–24 ka being the major episode (Dutta et al., 2011). Out of these five aggradation phases of Yamuna valley three aggradation phases (7–4 ka; 3–2 ka; <2 ka) were in the Holocene (Dutta et al., 2011). All the above ages were obtained using quartz and SAR protocol. Using various techniques as Blue LED stimulation on Quartz, IRSL stimulation on Feldspar at 50°C and IRSL stimulation on Feldspar at an elevated temperature of 225°C, it was found that the age obtained using latter two methods gives overestimated ages due to partial bleaching (Srivastava and Mishra, 2012).

SAR ages on quartz suggest that the NE Himalaya witnessed almost continuous aggradation from >21–8 ka with incision phases at <21 ka, 11 ka and 8 ka (Srivastava and Mishra, 2012). The terrace ages in Panj river valley, Pamir, revealed five major phases of aggradation (23–19 ka, 15–9 ka, 7–5 ka and <5 ka), these ages with the precise measurements of terrace thickness were used to infer the valley incision rate (Fuchs et al., 2014).

Srivastava (2012) suggested that Himalayan rivers had major aggradation during LGM and MIS–3 followed by valley incision after LGM (Fig. 3) and that the sediment budget is also govern by catchment glaciation– deglaciation cycles (Srivastava, 2012; Chaudhary et al., 2015).

2.5 *Palaeofloods*

OSL dating combined with geomorphology is very useful in understanding Quaternary catastrophic floods (Kale et al., 2003). A set of 40 flood sequences in Peshawar valley, Pakistan was dated using TL method, inferring that the youngest flood sediment is ~139 ka old (Cornwell, 1998). OSL dating of flood deposits from Lahul Himalaya suggest major flood events during 36.9±8.4 to 43.4±10.3 ka ago (Coxon et al., 1996). The flood deposits are difficult to date due to their low sensitivity and partial bleaching. However, successful attempts to date several recent flood events along with comparable 14C dates were made in Yihe river basin, east China (Shen et al., 2015). The quartz grains used for dating Yihe flood deposits were well bleached, however, despite a mixed source for flood deposits, seven out of eleven floods in Garhwal Himalaya were successfully dated for past 1000 years (Wasson et al., 2013). Authenticity of the ages was validated by the known ages of the last flood event in both studies (Shen et al., 2015; Wasson et al., 2013).

The most recent flood in the Garhwal Himalaya occurred in 2013 due to abnormal rainfall that resulted from a unique meteorological event. This was preceded by another major flood in the same valley that took place in 1970. It was initially suggested that deforestation in the lesser Himalaya resulted in such a large flood with high sediment load. Isotopic studies and optical dating suggested large floods at 800 years of similar type, suggesting that deforestation alone need not be implicated for large floods (Wasson et al., 2008). Flood occurrence in Garhwal Himalaya does not correspond with the climatic anomalies, suggesting that the major floods in the Himalaya are generated due to glacial or landslides lake outburst phenomenon (Wasson et al., 2013) with climate as a subordinate.

2.6 *Tectonic events*

Sunlight exposure and heating can also reset luminescence in a grain. During faulting events both thermal and pressure can result in resetting of luminescence (Banerjee et al., 1999; Porat et al., 2007). Based on these facts successful dating of fault gauge and soft sediment deformation structures have been carried out for parts of the Himalaya. Direct dating of fault gauge and river terraces of Tistariver, along Main Himalayan Thrust (MHT) by Mukul et al., (2007) suggested that the MHT was emplaced in Darjiling Himalaya around ~40 ka and out of sequence thrusting began since ~20 ka.

Dating the seismic events using seismites was first reported from Spiti valley, NW Himalaya, where 4 major seismic events (>6.5 Ma) took place between 26–90 Kaalong Kaurik–Chango Fault (Banerjee et al., 1997). The evidences of seismic activities along the major Himalayan faults during the Quaternary period have been reported from various parts of the Himalaya (Kumar et al., 2006; Lavé et al., 2005). Recent studies show that dormant-considered-South Tibetan Detachment System (STDS) was active in recent past (Juyal et al., 2004; Juyal et al., 2009; Rana et al., 2013). The major seismic event along STDS of magnitude >6.5 occurred between 17 ka and 13.5 ka, whereas the fault was active from 20 ka to 11 ka (Rana et al., 2013).

3 Conclusion and Future Prospects

OSL dating is the most useful dating method for the Himalayan sedimentary deposits, and provides opportunity to measure a wide age range (from the present to several glacial- interglacial cycles). Recent developments in the OSL methodology, particularly in SAR, have widened its acceptance to a larger group of geoscientists working in various environments. Advanced luminescence methods such as Thermally Transferred -OSL (TT-OSL), post Infra-Red-Infra-Red (pIRIR_{290}), Stimulated luminescence, can help in dating much older (>200 ka) deposits. Successful application of these methods on Himalayan sediments will expand the knowledge of Himalayan surface processes for an extended time range. Some of the yet unresolved questions in Himalaya where chronology can help are

1. In thousands of years timescale it is difficult to identify change in source from sediments in a fluvial system, thus, dating sediment generated and deposited in a particular zone (eg. Higher Himalaya or Lesser Himalaya) can provide more reliable results on climate change.
2. Most of the archeological sites are still untouched in terms of finding relation between the change in civilization corresponding to changes in climatic conditions and surface processes. In the light of the available information about the Himalayan climate, changes the archeological events can be better understood. Limited use of dating in Himalayan archeological sites needs immediate attention.

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