Optically Stimulated Luminescence Dating of Fluvial Sediments: Applications and Implications to Paleoseismology and Paleoclimatology

Summary

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1. Introduction

Evolution of landform is a consequence of several processes that range from the physical and chemical weathering of rocks to production of sediments and finally their transportation and deposition. These processes are governed by climate and tectonics and in time domain; they can range from an instantaneous event to a slowly occurring phenomenon. In geological time scale, the earth surface is being continuously modified by agencies like water, wind, glaciers etc. The riverine processes (fluvial system) have dominated the earth by sculpturing the landforms and in the process creating new sedimentary archives.

Fluvial systems are both erosional and transporting agency. They not only create its own sedimentary archives such as terraces, flood plain, alluvial fans etc. but also provide sediments to the lakes and oceans. There are two major controlling factors that govern the fluvial systems viz. tectonics (generate sediment and enhance the river gradient) and climate that helps in weathering, transport and deposition of the sediments. Tectonic and climate leave their distinct impression on the sedimentary record, it is however difficult to de-convolute these. Hence in order to ascertain the relative amplitude and periodicity (if any) of climatic and tectonic events, absolute chronology becomes an important aspect.

Till recent years, radiocarbon was used to ascertain the timing of various events that are preserved in the sedimentary archives. However, its usage has been limited due to the paucity of suitable dating material (organic carbon), sample strata ambiguity and limited time range (<50 ka.). Compared to this, recently developed luminescence method provides direct dating of the depositional event and unlike radiocarbon is not limited by sample availability (Quartz and Feldspar). The method can date geological events from the present up to ~1Ma.

Considering the dynamic nature of the Himalaya, it can be suggested that spatial and temporal variability in sedimentation was influenced by climate and tectonics. However, in order to ascertain the timing of these events and to quantify relative contribution of sediments in various geomorphological settings (viz. alluvial fans, fluvial terraces etc.), the timing of major phases of sedimentation in order to estimate the recurrent frequencies of such events is needed. The time parameters for land resource provide also an important input on planning and management.

Luminescence dating primarily relies on the extent of pre-depositional bleaching. Sediments transported by the Himalayan Rivers may suffer from inadequate bleaching due to the attenuation of daylight spectrum in respect of flux and spectral range. Processes such as turbidity caused by glacial melt, aspect of slopes and contribution from massive sediment transport event such as landslide debris etc imply potential situations for incomplete bleaching. Therefore, before applying the technique for quantification of climate and tectonic processes, it is important to examine the applicability of the method in the fluvial environment.

2. Objectives and thesis structure

In insulating solids, luminescence arises due to its ionization with radiation. The processes involve are, (i) absorption of energy– creation of free charges due to ionization; (ii) Storage– some of these charges get trapped at selected defects for finite times ranging from few seconds to 10^7 seconds depending on the charge environment and the ambient temperature; (iii) stimulation– the stored charges can be de-trapped by energy supplied by either thermal (heating) or optical stimulation and (iv) luminescence emission- on de-trapping some of these charges recombine radiatively and yield luminescence. If heating stimulates charges, the process is called Thermally stimulated luminescence (TSL) or Thermo-luminescence (TL) and if it is due to exposure of any optical stimulation, it is termed as 'Optically Stimulated Luminescence' (OSL). (Aitken, 1985, 1998)

On burial, further exposure to daylight ceases and re-accumulation of charges is initiated due to the ambient radioactivity. This process continues unabated till excavation. The net luminescence acquired in a grain is determined by the rate of irradiation (luminescence production) and the duration of burial. As luminescence is proportional to radiative dose, age equation can be written as:

Age = Paleodose / Dose rate

The Paleodose is expressed in Gray (1Gy=1Joule/kg) and is defined as the laboratory beta dose that produces same amount of luminescence as natural sample having same luminescence sensitivity. The sensitivity is defined as number of photons emitted per unit dose of absorbed radiation per unit weight of sample. The rate of radiation energy (dose rate) produced by radioactive element is computed by measuring the concentration of radioactive elements viz. ^{238}U, ^{232}Th, ^{40}K and Cosmic Rays.

The widely used techniques for paleodose determination are, (i) the Multiple aliquot method and (ii) the Single aliquot/Single grain methods. In the multiple aliquot techniques, a statistically valid age using a large number of grains is obtained. In this technique, however an averaging of grains of different sensitivity and bleaching histories is made. This implies some difficulties in dating samples with poorly defined bleaching history. The Single Aliquot / Single Grain method aims at obtaining ages at the level of few tens of grains to the level of a grain such that samples grain of varied bleaching histories can be isolated. The objectives of the present study were to examine the applicability of this technique to various fluvial archives and test the robustness of pre-depositional bleaching. The results thus obtained were interpreted to construct the past seismic and climatic events in Himalaya. The work has been presented in following chapters in this thesis as summarized below–

3. Chapter wise detail

Chapter-1: Introduction: This chapter describes various dating methods for quaternary sediments and the merits of luminescence dating. Basic principles and methodology of luminescence dating is discussed in some detail. Applicability of the method to fluvial sediments is reviewed. The chapter describes in detail the various sampling sites.

Chapter-2: Experimental procedures and protocols: This chapter describes the various experimental methods and protocols used in the measurement of OSL. It includes the sample preparation, measurement protocol, analysis and an outline of the instruments used. New analysis that includes assessment of spatial heterogeneity of the beta dose from a beta source, the use of Linearly Modulated-OSL and partial bleach method is presented. The homogeneity in the beta dose was analyzed at single grain level and the result was discussed.

Chapter-3: Natural Sensitivity changes and its corrections: This chapter deals with change in sensitivity during natural OSL measurements if not accounted for it can lead to erroneous estimation of paleodoses. A measurement protocol has been discussed for correcting the sensitivity change in natural sample. Finally the results obtained on fluvial samples have been presented and a comparison with and without ncf is given.

In the SAR protocol, change in sensitivity is monitored by a fixed text dose that follows after the natural OSL measurement and there is no provision to ascertain and monitor the sensitivity change prior to natural OSL measurement. There is a possibility of change in natural sensitivity due to preheat and OSL measurement. Hence an appropriate correction needs to be done for obtaining reliable chronology. This correction is called the natural correction factor (ncf). The present study has shown that ncf can vary between 20 – 30% and in few cases can be as high as 50%. If the samples are not corrected for natural sensitivity changes, it may lead to higher age estimate (~7 – 38%). Based on the above study a modified SAR protocol was developed called as Natural Sensitivity Corrected- Single Aliquot Regeneration (NSC-SAR) protocol. This was successfully applied in all the samples that were investigated in the present study.

Chapter-4: **Limits and Applicability of Standardized Growth curve:** This chapter describes a methodological advance in the application of the SAR protocol. The applicability of SGC on samples of analyzed from different depositional environment in Himalayan is presented.

In conventional SAR protocol, enormous TL/OSL reader time is consumed. On an average a sample of ~10 ka would require 4 – 5 days of machine time due to multiple cycles of irradiation, preheat and OSL measurements. It reduces the data throughput in case of partially bleached fluvial sediment in which a large number of aliquots are required for statistical analysis of the distribution of paleodoses. The application of SGC provides an opportunity to produce large number of paleodoses in a short time. The SGC analysis can be applied to any set of sample, where the regression coefficient of a SGC based on 20 aliquots is >90%. Application to samples with lower regression coefficients is likely to be less accurate if one wishes to apply this on very young fluvial sediments where minimum paleodose is considered for age estimation. Most importantly, it was demonstrated that SGC works very well for samples that had minimum lithological variability (single provenance). Considering this, SGC has limited applicability for the Himalayan sediments that originate from complex lithologies.

Chapter-5: **Bleaching in Fluvial Sediments:** In this section, experimental data on the dose distribution of various samples collected from four geological settings in Himalayan terrain are presented and discussed with reference to their depositional environment. Various parameters that provide an estimate on the extent of bleaching are discussed. In the present work, bleaching characteristic of fluvial archives that were deposited under varying hydrological regime viz. suspension fall out, high sediment load environment, flash flood sedimentation was investigated. The most bleached aliquots were isolated from the dose distribution by employing least 10% of the paleodose. These paleodoses were averaged to get the age estimate for various fluvial samples. These are–

(i) Sediment bleaching during flash flood– Flash flood in Himalaya is associated with breaching of landslide induced temporary reservoirs and last for few hours to few days. Such floods occur under poor light (overcast sky) condition with high sediment water ratio. In the present study an attempt has been made to investigate the extent of bleaching experienced by the flash flood sediments during 1970's Alaknanda flood as a function of distance from the origin and grain size too in Alaknanada basin. A systematic sampling of 1970's flood sediment along the downstream of the Alaknanda river (source to the ~250 km downstream) was done. The paleoflood history has been reconstructed from the Alaknanda basin at Srinagar where five floods of increasing magnitude were recorded.

In the peak flood sediments, no systematic change in bleaching was observed, although mean grain size of the sample decreased as a function of distance. However, the flood plain fine sediment showed significant reduction in geological luminescence. This inference was drawn based on the SAR age obtained on these samples. The peak flood sample yielded ages ranging from 4 ka to 2 ka where as the flood plain fine sediment gave 0.4 ka for 1970 flood. The study suggests that in flash flood deposits, a closer age can be obtained on sediments that remained in suspension for long time.

(ii) Suspension fallout- slack water deposits– These are deposited in the tributary streams away from the trunk channel during high floods. Flood water when enters the tributary stream looses its energy. This facilitates the sequential deposition of sand, silt and clay. Alternately it can be suggested that sediment remain in suspension for long time particularly the silt and clay hence well bleached. This aspect was examined in the slack water deposit at Raiwala.

A total of 14 floods of increasing magnitude were identified. The wide dose distribution of palaeodoses obtained on the sand horizons (rapid sedimentation) indicates partial and heterogeneous bleaching of the minerals comprising the flood sediments. In view of this, least 10% of the paleodoses were taken to reconstruct high magnitude floods in the Ganga.

(iii) High sediment load alluvial fan deposit– Alluvial fan is a characteristic feature of mountain fronts where a sudden drop in topographic relief occurs. A stream emanating from the mountain abruptly loses its energy and deposits its load as a fan shaped body. Dimension of alluvial fans varies from few km to hundreds of km in extent. Thus, in order to create such a large sedimentary bodies it is important to have (a) high sediment supply and (b) hydraulic energy for transporting the sediment. Large volume of sediments can be generated either by climate (glacial grinding, or physical weathering) or by tectonics (physical break down of rocks). Sediment transport generally is facilitated during the transitional climatic condition (arid to humid). Thus chronology of fan sequences can provide information about past climate and/or tectonic history. However, in view of their transportation under high sediment water ratio, bleaching of sediment was expected to be partial.

In the present study Yamuna-Ganga (mega fan and piedmont fan) sequences were investigated for luminescence characteristic and chronology using SAR protocol on Quartz mineral extracts. Samples from mega fans showed a normal distribution suggestive of moderate bleaching of the sediments before deposition. This implies that sediment generation occurred during the arid climatic condition thereby leading to prolong sun exposure; however, piedmont fan sediments have shown poor bleaching as compared to mega fan sediments.

(iv) Paleosesimic study in the lower Tista basin– Seismicity in Himalaya is associated with major boundary thrusts. Episodic activity along these thrusts is manifested in the development of various geomorphic features. Fluvial terraces are one such feature that responds to the seismicity by way of their vertical offsets and development of unpaired terrace sequences. Unlike seismities that can be generated by the activity along distal thrusts (far field effect), incised terraces are related to the proximal thrusts. In view of this, dating of the incised terraces provides information about the palaeoseismic activity along the thrust.

In the lower Tista valley 5 incised terraces are developed in between the South Kalijhora Thrust (SKT) and Andherijhora Thrust (AT). The terrace sequence is differentiated by distinct vertical offsets ranging from 20 m to 2 m suggesting varying temporal changes in sub-critical condition of the wedge. A suite of 4 samples from terrace T_5 to T_0 was analyzed by standard SAR protocol. A wide paleodose distribution suggests poor bleaching of the fluvial sediments. The dating of modern sand from the Tista River further corroborated this. Age based on the mean paleodose of modern sand was 700 years, whereas least 10% paleodose provided 50 ± 50 a. Additionally, the mean age of the modern sand provided a limit to the systematic offset and for older samples this implied a marginal correction.

<u>Chapter-6</u>: Implications to Paleoseismology and Paleoclimatology

This chapter deals with application of luminescence ages in various sedimentary environments. Climatic and tectonic implications of luminescence ages obtained on alluvial fan, paleoflood and incised fluvial river terraces have been presented.

(i) Slack water deposit at Raiwala– A total of 14 floods of increasing magnitude were identified since last 2.6 ka at Raiwala, in Haridwar. The results shows that a maximum of 6 floods of high magnitude occurred between 2.6 to 1 ka implying recurrent interval of high magnitude flood was once in a 260 years. The frequencies of flood increased from 1 ka to 0.8 ka during which 8 floods were recorded suggesting one major flood after every 25 years. Absence of flood sediment above 0.8 ka event indicates decrease in the flood magnitude in the upper Ganga catchment.

(ii) Luminescence chronology of Yamuna Ganga alluvial fan sedimentation– Luminescence chronology on 20 m thick incised fan sediment indicates that the deposition occurred in three pulses at 14 ka, 9 ka and 8 ka. Compared to this, piedmont fan samples show relatively poor bleaching (RSD >50%). Based on limited ages it can be suggested that piedmont fan sedimentation occurred during 2 ka- 1 ka. A comparison with regional climate records suggest that fans provide a sensitive record of climate changes.

(iii) Luminescence chronology of fluvial terraces in Tista valley and their paleoseismic implication– In the recent times there is significant evidences to suggest that sesimicity is concentrated around MBT and MFT. This is very well demonstrated in the Sikkim-Darjiling Himalaya where raised fluvial terraces and gravel bed indicate that the region was active during the Quaternary. However, the geomorphic manifestation of sesimicity lacked absolute chronology.

In the present study activity along the MBT and its splays are chronologically constrain. The ages from fault gouge of South Kalijhora Thrust (SKT) (0.5 km south of Main boundary thrust) and main frontal thrust (MFT) indicated that lesser Himalaya experienced a regional phase of tectonic activity around 40 ka. Following this, the active deformation front subsequently moved north of the mountain front to the footwall of the MBT around 20 ka. Subsequent deformation and topography building near the MBT then caused additional blind imbricate faults to develop south of the mountain front at 14 ka and 6 ka. The two active fronts may have, therefore, evolved in a coupled manner; with the building of a critical taper in the footwall of the MBT.

Further evidence of seismicity are obtained comes from the raised fluvial terraces. Chronology of the fluvial terraces suggests that there were three major event of incision caused by the tectonic activity associated with the splays of MBT viz. the AJT and SKT. These events are dated to 7.7 ka, 4.4 ka and 1.4 ka respectively. This would imply that the terrain is uplifting at rates varied between 3-10 mm yr^{-1}.

Chapter-7: Conclusion and Future Possibilities: This chapter outlines results obtained from the present study and also describes the future prospect of extending this work in similar geomorphic and climatic settings.

Conclusions

Present study enabled the following inferences

(i) Fluvial samples suffered from heterogeneous bleaching as indicated by wide and positively skewed paleodose distribution histograms.

(ii) It was demonstrated that natural correction factor (ncf) plays important role in palaeodose estimation, if not taken into account, the ages may offset by up to 30%.

(iii) Variability in the Standard Growth Curve (SGC) technique suggests that it can be applied successfully to such samples where SGC have regression coefficient >0.9. This implies that SGC is sensitive to the heterogeneous origin of Quartz.

(iv) Luminescence study of flash flood sediments from the Alaknanda basin suggests that to some extent bleaching is independent of the distance of transport but show a grain size dependency.

(v) Chronology of monsoon dominated slack water deposit shows evidence of 14 major floods during the last 2.6 ka and 0.8 ka suggesting enhanced southwest monsoon. This is the first record of post Holocene humid climate obtained from the fluvial record in the region.

(vi) Chronology of mega fan sediment suggests that fan sedimentation occurred in pulses during the transition climatic regime. Three major events of mega fan aggradations were identified between 14 ka, 9 ka and 8 ka. The piedmont fan sedimentation post date mega fan aggradations episode and were dated to 2 ka to 1 ka.

(vii) Luminescence dating of incised terraces in the Tista River suggests that incision was favored by the temporal changes in the sub-critical condition of Andherijhora (AJT) and its sympathetic thrust during 7 ka to 1 ka. These are the first evidence that indicate AJT was active during the Holocene.