Chapter 1

Introduction

1.1 Introduction

Geomorphology deals with the quantitative understanding of processes and amplitude of erosion and sedimentation on the earth. Geomorphology investigates landforms and the processes that sculpt them. The processes can range from the physical and chemical weathering of rocks to the production of sediments caused by climate and tectonics. In the time domain, these processes can range from an instantaneous short-lived event to a slowly occurring phenomenon spanning few million years (Miall, 1996; Kale, 2001). In general, climatic and tectonic processes are periodic. It therefore, becomes necessary to estimate the recurrence intervals of these events so as to understand and model the nature of the underlying geodynamic processes for a better assessment of risk and hazards associated with such changes. Geodynamic processes that lead to creation, transport, deposition and preservation of sedimentary records are climate and tectonics and proper understandings of their relationship to these forcing functions are keys to geomorphologic science and geological correlations.

The present thesis deals with understanding of the processes and chronology on one such sediment archive – the fluvial sediments to further understand the paleoclimate changes and paleotectonic events. Sedimentary archive of a river system depends on, (i) production; (ii) transfer; (iii) deposition and (iv) preservation, of sediments. These elements are controlled by a variety of factors ranging from the weathering of the source rocks to fluvial discharge and sediment load. Fluvial sediments occur variously as lake sediments, flood plain sediments, terraces, fans and delta, and their potential for paleoclimate and tectonic studies has been well established (Gregory and Benito, 2003). Techniques such as sequence stratigraphic methods, paleomagnetic polarity reversals etc. enable development of a hierarchy of depositional events. However, absolute chronology that enables quantitative estimates of rates of processes and their recurrence intervals has so far been difficult, due to lack of chronometric methods.

Himalaya is a consequence of collision of two converging continental plates viz., the Indian and the Asian plate. In Himalaya, under-thrusting the Indian plate beneath the Asian plate accommodates a part of the plate movement and the rest is accommodated on the surface by folding and thrusting. When compressional stress exceeds the strain limit of these rocks, they fail along the faults producing earthquakes, landslides and landslide induced floods and geomorphic features such as raised terraces and seismites are formed. Chronology of these deposits and their physical parameters provide a means to deduce long-term slip rates and the rates of strain release. Current quantitative estimates of the Himalayan Seismic Hazard are based on Global Positioning System (GPS) data that has been used to compute slips between the Indian and the Asian plates (Bilham et al., 1997; 2001). Though of significance, the GPS data so far spans only a decade, too small duration to assess geodynamic processes. Consequently, a longer-term perspective is needed. This needs securely dated landform features that are caused by tectonic events. The present study is amongst the few contributions to quantitative paleoseismology of Himalaya, which deals with an estimation of the timing of paleotectonic events and will eventually help in the identification of buried faults, estimation of earthquake magnitude and amplitude of slip along the faults and the recurrence interval of past earthquakes. Present structure of the Himalayan orogeny is a consequence of tectonic and climatic processes as well (Phadtare, 2000; Pratt et al., 2002; Juyal, 2004; Hodges et al., 2004; Whipple and Meade, 2004; Burbank, 2005; Leier et al., 2005). The present study attempts to use alluvial fans, slack water deposit and terraces to reconstruct past climate changes and past seismic activities in Himalaya.

Luminescence method provides a direct dating of the depositional event of sediments using their constituent minerals viz. Quartz and feldspar. The method provides the age of deposition of sediments without any ambiguity of sample/strata correlation. The age range (100 a – 500 ka) and the availability of the dating material (i.e. Quartz/feldspar), makes this method applicable to almost all of the mid to late Quaternary deposits. Quartz and feldspar act as natural dosimeters that provide a cumulative record of the radiation exposure from the naturally occurring radioactive elements viz., ^{238}U, ^{232}Th and ^{40}K in sediments. The technique relies on the fact that mineral grains constituting the sediments are exposed to adequate daylight resulting in a photo bleaching of the geological luminescence to a zero or near zero residual value. This event reset the luminescence clock. Typically few tens of seconds of daylight exposure is sufficient to achieve a near total photo bleaching. This criterion is adequately met in case of wind-transported sediments due to the availability of full daylight flux and its short wavelength spectra. However, in the case of fluvial sediments, such a total bleaching may not be reached, due to attenuation of daylight both in respect of its flux and energy spectrum, the water column, its sediment load and turbulence. The daylight spectrum shifts towards the red wavelength when the bleaching cross section drops down by nearly an order of magnitude or more. Thus, even though a short duration of daylight (typically 30-50 seconds of full spectrum) is required for clear daylight photo bleaching, the fluvial sediments may be bleached partially prior to deposition. Methodologically, the present thesis explored the feasibility of luminescence dating for fluvial sediments from a terrain with a high topographic relief implying rapid transportation and deposition of sediment by the fluvial system. A variety of fluvial environments that exists in the Himalayan terrain, were examined. These are–

(i) Flash flood sediment
(ii) Low energy, slack water deposit
(iii)High energy alluvial fan deposit and
(iv)Tectonically uplifted, fluvial terraces.

The basic philosophy was to examine validity of the basic assumption of luminescence dating technique on samples with age controls. In the process new protocols were developed, tested and applied. A brief summary of existing dating methods for fluvial sediments is given below to provide a perspective on the need of luminescence dating.

1.2 Brief description of existing dating method for quaternary sediments

Several dating methods have been employed for the chronology of fluvial sediments. These can be grouped in two categories – (i) relative and (ii) absolute chronometric techniques. In relative chronometric methods, techniques like order of superposition, Paleomagnetism, Amino acid Racemization and other chemical methods are used. The absolute dating techniques include radiocarbon, K-Ar, U-series, ^{210}Pb, radiocarbon, luminescence, cosmic rays produced isotopes etc. A comparison of these methods is provided in Table 1.1.

(i) Paleomagnetism–The present direction of earth's magnetic field changes approximately once a million years from normal to reversal and vice versa. Sediments deposited under free air fall or still water condition preserve the direction of ambient earth's magnetic field known as Depositional Remnant Magnetism (DRM). The continuous gradual change in virtual geomagnetic pole (VGP) is known as secular variation that varies from place to place. The movement of VGP gives a succession of normal (parallel to the present) and reverse (180° out of phase with the present) polarity transitions that are preserved as DRM in the sedimentary rock record. These normal and reverse polarity transitions are chronologically constrained by absolute dating using the dating of volcanic ash layers or index fossils. Thus based on the constant sedimentation rate, successive normal and reverse polarity in the stratigraphy can be assigned absolute ages. The most notable reversal events in the Quaternary era are the Brunhes-Matuyama boundary at 780 ka and the Blake event at 110 ka. (Hailwood, 1989; Aissauoi et al., 1993)

Table 1.1. Age range and material used in various dating techniques for quaternary material. (After Singhvi and Banerjee, 2003)

Methods	Age Range	Samples
1. Paleomagnetism	0.1 Ma – 2 Ma	Sediments
2. Amino-acids	0.1 ka –500 ka	Bones, cells and tooth
3. U Series	100 a – 350 ka	Calcite, bones, corals, shells
4. K-Ar / Ar-Ar	1 ka – >>1 Ma	Volcanic material
5. Fission Track	> 50 ka	Slags and volcanic materials
6. Radiocarbon	1950 AD – 50 ka	Wood, bones, coral, shells, etc
7. Electron Spin Resonance	1 ka –1 Ma	Bones, tooth, coral, volcanic ash
8. Luminescence	100 a – >500 ka	Pottery and sediments

Recently identified, geomagnetic excursion is a brief (<80°) but significant departure of VGP from the geocentric axial dipole that remains for ~10^3 years. This is an intermediate type of geomagnetic behavior between secular variation and polarity transition (King and Peck, 2001; Sangode et al., 2002). At present the use of excursions and short events to provide stratigraphic control and chronology is promising but requires extensive further study.

(ii) Aminoacid racemization–Amino-acids are found in two forms- 'L' (leavo rotator) and 'D' (dextro rotator) having same chemical formula but different structural symmetry. Racemization is the process of converting L form to D form. 'L' form is dominant in the living tissue that converts into 'D' form when the tissue dies and the ratio L/D used as a chronometric tool. The racemization rate depends on the organism type and temperature. Racemization rate is higher in warm condition and consequently undetermined temperature fluctuations lead to systematic error in age estimates. The temperature constraint implies that method has been successful in cool/temperate regions where the average sediment temperatures are low and nearly constant. On the other hand, in the tropics, the method has not found sufficient usage in view of high seasonal changes in temperature. The materials used for the dating are bones, shell and tooth and the age range is 100 a – 500 ka. (Bender, 1974; Bada et al., 1984)

(iii) Radiocarbon dating (^{14}C)–Radiocarbon is probably the most used radiometric dating method to date young sediments (Wohlfarth, 1996). The method depends on the production of ^{14}C from atmosphere. Low energy cosmic ray neutrons interact with ^{14}N to form ^{14}C in the upper atmosphere. ^{14}C so produced, reacts with O_2 to form $^{14}CO_2$, which is chemically similar to $^{12}CO_2$. The CO_2 is fixed in various organic and inorganic reservoirs such as plants, animals (via photosynthesis) and carbonates. When the plant or organisms die, they stop taking ^{14}C from the environment and the ^{14}C present in them decays with a half-life of 5730 years. Measurement of ^{14}C activity in the organic matter enables calculation of the time of cessation of ^{14}C intake. Absence of organic matter in fluvial sequences, uncertainty in the relationship between sample and the strata makes it difficult to use this method. Short half-life of ^{14}C isotope limits its usage only up to ~ 40 ka. Further the technique assumes ^{14}C production was uniform in the past which is not the case as studies on tree rings, corals and varves has demonstrated that ^{14}C production varied in time due to change in cosmic ray fluxes and this calls for calibration of radiocarbon ages (Stuiver et al., 1998). Contamination of the samples by either the 'dead' or the 'modern' carbon from organic and inorganic carbon (carbonates) can alter ages substantially and has been a major impediment in the routine use of the method. Methodologically accelerator mass spectrometry (AMS) technique have now made it possible to achieve high precision ages on small (~ few mg) samples by measuring the concentration of ^{14}C directly without waiting for its decay.

(iv) Cosmogenic radio nuclide dating (^{10}Be and ^{26}Al)–Interaction of Cosmic ray particles such as with rocks and sediments produces radioactive nuclides such as ^{10}Be and ^{26}Al, via reaction such as Quartz and Feldspar provide ideal target material. Due to cosmic ray exposure the concentration of insitu produced ^{10}Be and ^{26}Al increases and can be used as a time marker, provided off course that the production rate of these nuclides could be accurately determined that requires a rigorous understanding of the changes in (a) the cosmic ray flux through time and (b) the irradiation geometry. Though a promising method, in accreting sediment sequences problems due to time dependent changes in shielding makes the cosmic ray age model dependent. Further complications arise due to periods of quiescence/soil formation in sediment accretion, erosion and finite inheritance of radioactivity makes the application difficult (Nishiizumi et al., 1989; Lal, 1991).

(v) Uranium series dating–This is another radiometric dating technique which uses the short lived isotopes of Uranium (U) and Thorium (Th) decay series. Disequilibrium in the Uranium series decay chain has been used extensively to date pure carbonates. The isotope of U remain in solution in seawater where the uranyl ion (UO_2^{2+}) tends to form carbonate complexes {e.g., $UO_2(CO_3)_3^{4-}$}, which allow it to co precipitate with calcium carbonate. As a result, Calcium carbonate minerals such as calcite and aragonite typically contain appreciable concentration of U but lack Th. However, occurrence of pure carbonates in continental setting is rare; furthermore, correction for detritus Thorium is often necessary. The trace element in the carbonate can be used to date material up to about 350 ka old (Ivanovich et al., 1992; Kaufman, 1993).

(vi) K-Ar/Ar-Ar dating–K-Ar dating has been extensively used in geochronology. Potassium has a small radioactive component ^{40}K, which has a half-life of 1.2 billion years. ^{40}K decays by two possible modes, namely ^{40}Ar and ^{40}Ca. Being an inert gas, ^{40}Ar keeps accumulating in the lattice of potassium bearing mineral and does not form any chemical bond. In suitable cases, Ar gas can remain in the lattice over geological time scales. By measuring the concentration of K and Ar, age of the mineral can be computed. This method is suitable only for sedimentary sequences containing volcanic ash layer that ensures the trapping of Ar molecules from the atmosphere only during its formation (Quidelleur et al., 2001). A significant problem with this method is the diffusion of Ar from rocks leading to underestimation of ages. The problem of Argon loss has been overcome by the Ar-Ar method (Faure and Mensing, 2005). First ^{39}K is converted to ^{39}Ar by neutron bombardment to know the ^{40}K as ^{40}K and ^{39}K ratio is fixed in the rock. ^{39}Ar and ^{40}Ar can be measured together in the mass spectrometer. The principle of the Ar-Ar method is therefore the use of ^{39}Ar as a proxy for ^{40}K.

(vii) Fission Track–Fission track (FT) is the radiation-damaged path left by two heavy fragments of uranium-fission. The tracks are formed by the spontaneous fission of ^{238}U with a half-life of $8.2x10^{15}$ a. The tracks are enlarged by chemical etching to a microscopically visible size of >15 micron length. The tracks accumulate with time, and consequently their number is a measure of the elapsed time, i.e. the age of the material. Although many minerals and glasses contain fossil fission-tracks, only a few of them, mainly zircon, apatite, sphene and various glasses can be used for the quaternary (~10^6 years). This is because the uranium content should be high to produce a sufficient number of fission tracks in the available 10^4 to 10^6 years. The tracks are removed at a blocking temperature and thus reset the clock. Apatite has 90°C blocking temperature and zircon around 300°C. Hence it is useful in determining rate of uplift and exhumation of rocks if geothermal gradient is known (Hurford and Green, 1982)

The clue for interpreting fission-track ages is the stability of tracks. Fission tracks are unstable, a phenomenon known as fading. Elevated temperatures accelerate the fading process and fading causes shortening of etch able track length. The resulting track loss tends to lower the apparent fission-track age.

(viii) Electron Spin Resonance (ESR)–ESR relates to detection of the concentration of trapped charges due to ionization on absorption of radiation dose from the ambience of the sample to be dated. Thus the trapped charges are proportional to the concentration of ambient radioactivity and time elapsed since the material formed e.g. tooth, bone etc. Some of the trapped charges have a net spin, making them paramagnetic. These act as free magnets, and can be detected by placing the sample under a magnetic field. In the simplest case, these individual magnets can occupy two energy states ($m_s = +1/2$ & $-1/2$) when placed in a magnetic field and the population is higher in lower energy state. It is then possible to cause transition of charges from low-energy state to high-energy state, using appropriate microwave energy. The amount of microwave energy absorbed is proportional to trapped charge concentration and with appropriate calibration using a laboratory Gamma dose, the ESR absorption intensity can be converted into absorbed dose. In ESR dating of bones and tooth, the radiation dosimetry involves some basic assumptions arising due to the uptake of U during burial. In the case of tooth enamel, the post mortem uptake of uranium implies that the present day value of uranium cannot be taken *per se* for dose-rate calculation. Instead, depending on the nature of the sample and the site, the dose is calculated on the basis of either the linear uptake or an early uptake. The dating range of ESR spans 1ka - 1Ma years and is ideally suited to directly date organic remains, provided the dosimetry is established unambiguously (Ikeya, 1993, Mathew et al., 2004). The forgoing makes it clear that as yet no secure method exists for middle to late quaternary fluvial sequences.

Luminescence methods have the potential of providing direct dating of the depositional event of sediments without any ambiguity of sample/strata correlation. The age range (100a -1Ma) and the availability of the dating material (i.e. Quartz/feldspar) that are ubiquitous, make this method applicable to nearly all kind of Quaternary sediments.

1.3 Luminescence Dating- Basic Principles

Luminescence dating is a radiation damage technique, which uses the natural radioactive elements present in the sediment viz. U, Th and K. The minerals used for dating are Quartz and feldspar, which are ubiquitous. The luminescence production in minerals is explained by the band theory of solids. There are three basic steps for luminescence emission. These are–

(i) Production of charges– The passage of ionizing radiations arising from the decay of natural radioactive elements viz. U, Th and K induces ionization in the Quartz and feldspar. The charges are excited from valence band to conduction band after ionization and are free to move in the lattice (Aitken, 1985; 1998) (Fig. 1.1).

(ii) Trapping and storage– Some of these charges get trapped at defects of the crystal. Residence time of these charges range from a few seconds to a few million years and depends on the temperature, energy levels and charge environment of the charge trapping centers.

(iii) Eviction– The stored charges get de-trapped with energy stimulus, either optical or thermal. These travel in the lattice and at suitable site and radiatively recombine to produce luminescence.

If thermal heating does the stimulation of these charges, the process is called Thermally Stimulated Luminescence (TSL or TL). If it is done by light exposure, then the process is termed as Optically Stimulated Luminescence (OSL). Depending upon the wavelength of optical source for stimulation, such as Green Light Stimulated Luminescence (GLSL), Infra red Stimulated Luminescence (IRSL) and Blue-Green Light Stimulation (BGSL) are routinely used. The intensity of luminescence thus produced is proportional to radiation dose and under some assumption can be related to the time of burial of the sediment. In this, the concentrations of the radioactive elements in the sediment can be measured. The dating range over which this technique is used is small enough as compared to half lives of these radioactive elements viz. U, Th and K, implying that as a first approximation, the radiation flux is constant through the burial

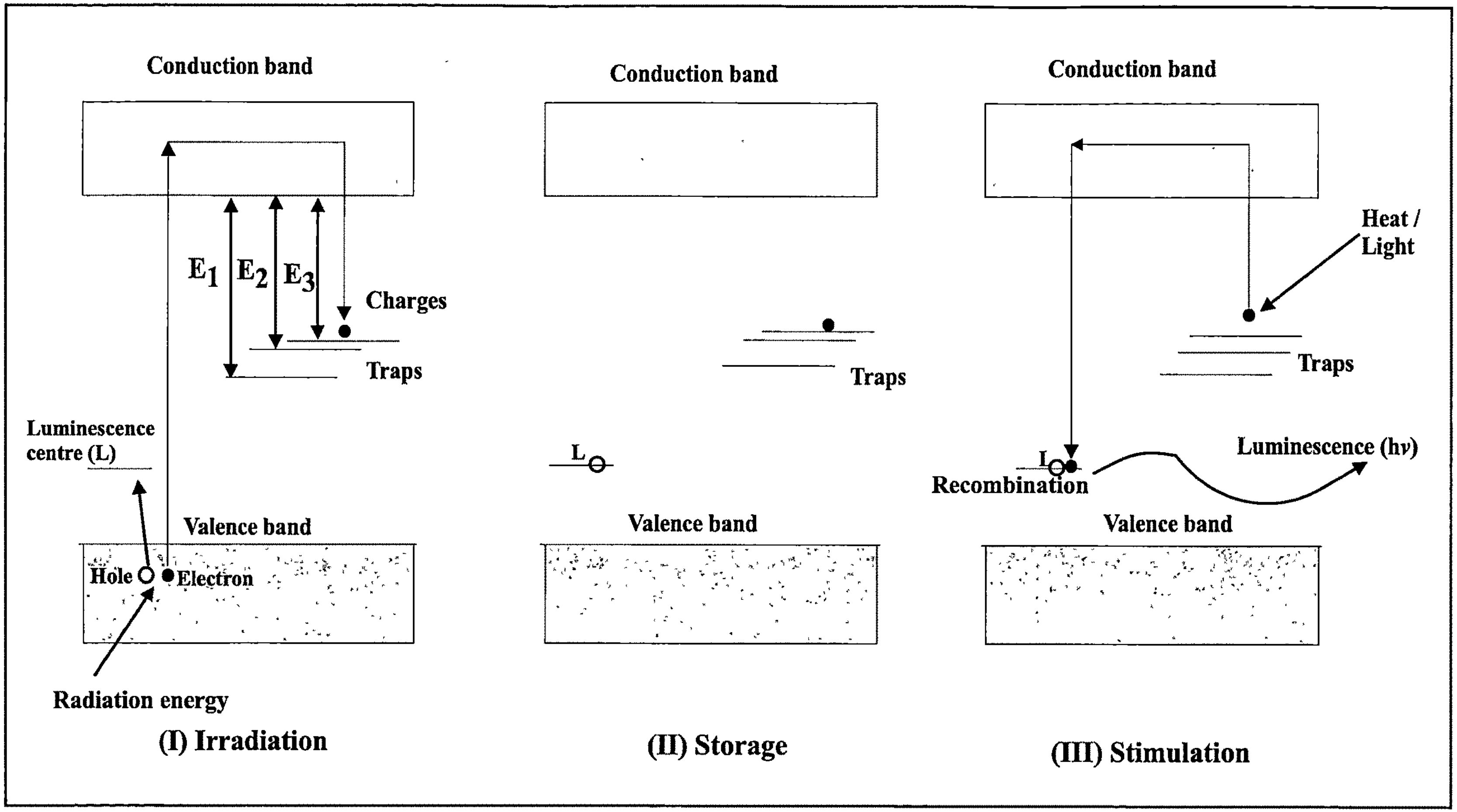

Figure 1.1. Three processes of luminescence production in an insulating solid; (i) absorption of radiation and production of charges; (ii) storage of charges in the defects of the crystal to up to a few Ma and (iii) eviction of charges from the traps on heating/ light exposure and production of luminescence on recombination of these charges. (After Aitken, 1986)

history. Quartz and feldspar mineral act as sensitive radiation dosimeter of this radiation due to the radioactive viz. U, Th and K in the sediment. Luminescence method dates the event of last sun exposure/heating of the sediment grains. In view of this luminescence dating of the sediments relies on the fact–

(i) The natural radiation environment of the sediments arising due to the decay of natural radioactive elements viz. ^{238}U, ^{232}Th and ^{40}K along with cosmic rays provides a constant flux of radiation to the natural mineral constituting the sediments.

(ii) These minerals viz. Quartz/feldspar act as sensitive radiation dosimeters to record these radiations with constant sensitivity, in a cumulative manner and preserve this record over geological time.

(iii) The daylight exposure of the sediment/minerals photo-bleaches the geological signal during their transport to a zero or near zero level.

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.

1.4 Age equation

After burial of a sediment, the naturally occurring minerals e.g. Quartz and feldspar, act as natural dosimeter and absorbs radiation from the radioactive element viz. U, Th and K from the sediment. Thus the luminescence signal in Quartz and feldspar is proportional to the time of burial and the concentration of radioactive elements. This signal acquired after the burial of the sediment can be measured in the laboratory. The age estimation needs two parameters, (i) amount of signal accumulated over burial period (measured as equivalent radiation dose) and (ii) rate of ambience radiation absorbed by the Quartz/feldspar. The unit of amount of energy absorbed is defined as Gray (Gy)(1Gy =1 Joule/kg).

The Quartz/feldspar obtained from the natural setting has variable luminescence response at grain level due to, (i) varying amount of impurities (ii) type of defects present and (iii) varying thermal history at source. Therefore, it is important to ascertain the sensitivity of these minerals (response to radiation dose). This can be estimated in the lab by irradiating the Quartz sample using artificial radiation source e.g. ^{90}Sr, then measure the luminescence output to compare with the luminescence received from the naturally irradiated sample. This is termed as Paleodose or accrued dose. Hence Paleodose (P), expressed in Gy, is the amount of laboratory dose given to the mineral to produce same amount of luminescence as the sample, as received.

The second important parameter is to measure the rate of radiation given to the sample in the natural setting. This can be done my measuring the amount of radioactive elements in the sediments. Usually the dose rate is expressed in terms of Gy/ ka.

The age equation is based on the fact that, (i) natural radiation environment is a mixed radiation field comprising alpha, beta and gamma rays and (ii) the luminescence produced by highly ionizing alpha particles (per unit dose) is substantially lower compared to those by weakly ionizing radiation (beta, gamma and cosmic rays) due to number of charges produced in a short track of alpha particle path is much higher than the available traps. Hence most of the charges are wasted with respect to the luminescence production. These factors are accounted for by defining an alpha efficiency parameter a such that,

a = luminescence per unit alpha dose / luminescence per unit beta dose

and by computing the annual dose as a sum of contribution from all the radiation components i.e.

$$\textbf{Age} = \textbf{total luminescence} / \sum_{\alpha,\beta,\gamma,c} \{(\textbf{luminescence / unit dose}) \times (\textbf{dose / year})\}$$

Combining above two relations, the age equation reduces to

$$\textbf{Age} = \textbf{Equivalent beta dose (or Paleodose)} / (aD_\alpha + D_\beta + D_\gamma + D_c)$$

Where D_α, D_β, D_γ and Dc represents the dose rate contribution from alpha, beta, gamma and cosmic rays respectively. In dating of coarse-grain Quartz, the alpha dose affected skin (typically 10-15 micron thick) is removed by etching. Hence in dating the coarse grain Quartz, the age equation further reduces to

$$\textbf{Age} = \textbf{Equivalent beta dose (or Paleodose)} / (D_\beta + D_\gamma + D_c)$$

The events dated by this method are the event that de-traps the acquired geological luminescence in a sample to the residual level. Hence this method is used to date last heating event of pottery, baked clay, last daylight exposure of the sediment and formation of minerals e.g. gypsum etc.

1.5 Optical bleaching of the sediment

The basic assumption of luminescence dating is the extent of photo bleaching or thermal heating. Typical time for resetting is ~few tens of seconds of cloud free daylight for sediments or few seconds of thermal heating at 500°C in case of pottery. In case of aeolian sediment and sample of archaeological importance (e.g. pottery) this assumption is reasonably met. In the case of fluvial sediment, this may or may not be satisfied due to following reasons,

(i) Attenuation of sun light due to depth of water column and turbidity
(ii) Transport distance of the sediment
(iii) Sediment coagulation by clay
(iv) Inverse dependence of bleaching efficiencies with stimulating wavelength

In view of this bleaching of the sediment grains in fluvial environment is likely to be incomplete and heterogeneous. Kronberg (1983) found that a wide range of wavelength from the solar spectrum bleached the TL of K-feldspar. Significant bleaching occurred in a sample kept at 7 m of clear lake water. Gemmell (1985; 1988) examined the bleaching of fine grain minerals in suspension through laboratory and field experiment. For dense suspension (>1 g/l), a limited reduction in TL was seen depending on flow rate. Godfrey-Smith et al. (1988) showed the photo-luminescence signal of Quartz and feldspar are well bleached by sunlight within a few minutes to few hours, which also progresses during overcast condition, and that the bleaching rate observed was proportional to the light level. Berger and Luternaur (1987) have demonstrated that the intensity at 4 m depth in a turbulent river is ~10^4 times less than at the surface and severely attenuated below 500 nm and above 690 nm of the wavelength of that light (Fig. 1.2). Ditlefsen (1992) examined bleaching of the sediment in a 75 cm column of water for different concentration of suspended matter. He observed that for dilute suspension (<0.02 g/l), optically stimulated luminescence was reduced by 95% within 20 hrs whereas the TL was reduced only by 25-50%. In the more dense suspension (>0.05 g/l), light level was reduced significantly primarily due to the suspended particles rather than by the turbulence. Fuller (1994) has shown the attenuation of the UV component of the solar spectrum as it passes through water. The attenuation occurs in still water and increases under turbid water conditions, where fine grained particle scatter light.

These results, suggests that heterogeneous and incomplete bleaching is a likely for water-lain (fluvial) sediments. Laboratory experiments suggest that TL signal takes 5-6 hrs to bleach on daylight exposure whereas OSL signal bleaches in a few tens of seconds. Proszynska-Bordas et al. (1992), Murray et al. (1992), and Kamaludin et al. (1993) applied successfully this technique on fluvial sediment. On the other hand Gemmell (1997) & Forman and Ennis (1992) did not find TL dating suitable for dating fluvial sediments.

Similarly OSL dating has been applied to fluvial sediments. Balescu and Lamothe (1994) established chronostratigraphy between ^{14}C, ESR, amino acid, TL and IRSL dates with two exceptions. Murray (1996) concluded that luminescence dating offers a considerable improvement over other techniques including ^{14}C for dating recently transported fluvial sediments. Single Aliquot Regeneration (SAR) technique provided insight into the variability of paleodoses caused by heterogeneous bleaching (Murray and Roberts, 1997). Olley et al. (1998) examined 70 years old flood sediment from the Murrumbidgee River and found that age computed from mean paleodose varied from 400 – 1000 years depending on the grain size with the coarser size being relatively better bleached. The minimum age computed from least 5% of the dose distribution provided consistent age. Thomas et al. (2004) investigated fluvial deposit in Anantpur district, south India, using small aliquots and single grain technique having ^{14}C age control. The average ages were 200 years off from the ^{14}C age of 507 ± 40 years. However, doses calculated from leading edge method (Lepper et al., 2001) gave consistent ages. Zhang et al. (2003) found an overestimation of 200 years in averaged OSL age in a fluvial sediment containing 700 years old potsherd. When they applied the method similar as given by Fuchs and Lang (2001), results were consistent with the expected age. Rittenour et al. (2003) dated three, channel belt deposit from the lower Missisippi valley using luminescence. All the optical ages were in good agreement with geomorphological relationship and the existing radiocarbon age control. Chen et al. (2003) compared to radiocarbon ages with OSL ages from a core of ~200 m thick sediment in the subsiding

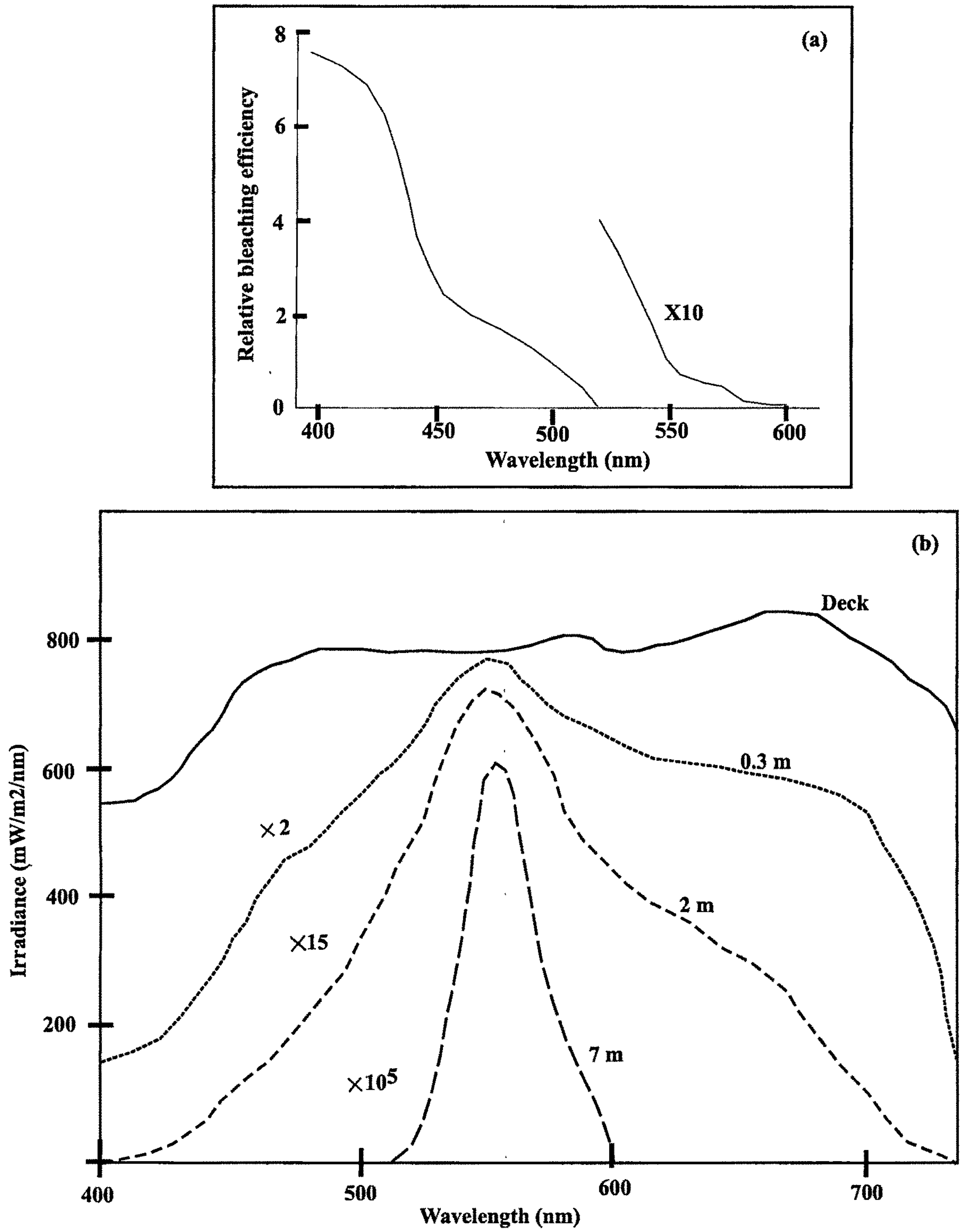

Figure 1.2. (a) Decreased bleaching efficiency with respect to increase in wavelength (after Aitken, 1998). (b) Attenuation of daylight intensity in the water as a fuction of depth. As depth increases, the intensity of daylight decreases rapidly together with the cut off of lower wavelength spectrum. (After Berger, 1990)

southwestern coastal plain of Taiwan. He found a good agreement in the optical ages and radiocarbon ages up to 14 ka suggesting well bleached sediment. However, modern sediment from the channel deposit gave the ages from few hundred years to 12 ka, which is surprising.

Summarizing, that results from above discussed examples and similarly several more various geomorphological archives have shown that partial bleaching of fluvial sediment still remains a potential problem in the luminescence dating and is the field of active research that needs extensive study.

1.6 Luminescence dating techniques

Initially the luminescence method was applied on pottery and sediments from desert environments that are supposed to be free from any problem of resetting of luminescence clock. Hence the techniques involved in evaluating ages for such samples were applied successfully viz. multiple aliquot additive dose (MAAD) and multiple aliquot regeneration (MAR). These techniques involve a large number of aliquots (typically 30-40) to calculate a single age. This technique assumes that all the aliquots used in the measurement are having equal thermal/bleaching history, which is true for baked pottery or wind blown sediments, but may or may not be true in case of partially bleached sediments and thus can lead to erroneous ages. These techniques are discussed in detail in chapter-2, "Experimental Procedures", of the thesis.

Huntley et al. (1985) gave the concept of single aliquot analysis. Duller (1991) took the initiative to do some analysis on fine grain using IRSL and applied Single Aliquot Additive Dose (SAAD) method in which OSL readout, irradiation and dose growth curve was constructed on an aliquot, avoiding inter aliquot comparison. In this, OSL readout is done for 0.1 second, which ensures an insignificant loss of signal and then same aliquot was irradiated followed by preheat. OSL is readout again for the same amount of time. This is repeated 4-5 times and a growth curve is constructed between OSL counts and laboratory added beta doses. The intercept of this growth curve on the dose axis gives the paleodose. Significant amount of signal loss was observed in each cycle because of preheat. Hence in the last, this was corrected by repeating measurements for preheat only. Duller (1994a; 1994b) suggested correction procedures for the loss in

OSL intensity due to preheat. Stokes (1994) applied this procedure successfully on Quartz from aeolian contexts with good agreement between single aliquot additive dose and multiple aliquot methods. Galloway (1996) and Murray and Roberts (1997) summarized procedure for SAAD on Feldspar and Quartz respectively.

The luminescence sensitivity can change due to light or heat treatment. This limits the use of SAAD, as there is no provision to correct for sensitivity changes at each stage of irradiation/preheat cycle. Due to significant drop in sensitivity during measurement of natural signal, this method was unsuccessful when applied to samples of river Loire in France (Colls, 1999). Single Aliquot Regeneration (SAR) method developed by Murray and Roberts (1997) provides for OSL sensitivity changes during preheat and measurement. In this method, OSL is readout for 60-100 seconds to record and bleach the natural signal. The same aliquot is then given a small test dose (<10-20% of paleodose) followed by preheat and OSL measurement. This signal is used to correct for any change in sensitivity, which would have occurred during natural OSL measurement. Then on the same aliquot, a cycle of incremental laboratory doses, preheat and OSL measurements is carried out along with test dose measurement at appropriate instance to construct sensitivity corrected growth curve. The sensitivity corrected natural OSL is interpolated onto this growth curve to estimate the paleodose. This method is used widely to date water-lain sediments as well as aeolian sand too. Typically a large number of aliquots (~50-100) are analyzed and a large number of paleodoses are obtained. The distribution of paleodoses then permits the use of optimum paleodose value. This was not possible using multiple aliquot methods. The SAR method has several advantages over multiple aliquot methods–

(a) Inter-aliquot normalization is not required as all the measurements are done on one aliquot.
(b) Small sample size is required which makes it suitable for small amount of sample with low yield of Quartz e.g. pottery and ceramics.
(c) High precision data due to large number of paleodoses from the same sample and these being independent measurements, an standard error on mean is used.

(d) SAR technique gives a range of paleodoses, thus enable estimation for degree of bleaching in a sample. A poorly bleached sample will show a large scatter of doses having high standard deviation of the data.

The most bleached part is the fraction yielding the lowest paleodose. For older samples, the amount of partial bleaching may not be significant proportion of the natural signal. Jain et al. (2004) reviewed the work of OSL dating on fluvial sediments and categorized the sample in two sections, (i) <1 ka old sample; (ii) >1ka old. These authors suggested that the minimum age model is successful in <1 ka old sample and mean age is preferable for the samples >1 ka old, as the residual signal was a small proportion of the natural signal build during extended burial of the samples. However, it may be pointed out that this boundary is only indicative and will change with a variety of factor ranging from the dose rate, the sensitivity and the pre-depositional bleaching.

1.7 Estimation of bleaching using SAR

Li and Wintle, (1992) and Li (1994) suggested a procedure to estimate the extent of bleaching by analyzing a plot of natural luminescence intensities against their respective paleodoses. They argued that in a well-bleached sample, individual aliquots will have identical paleodoses but may show a wide variation in natural intensities because of varying sensitivity of individual grains. However, poorly bleached sample will show a wide variation in both, paleodose and brightness. This is a useful method to graphically represent the extent of bleaching, but does not enable for quantitative analysis.

Clarke (1996) suggested some threshold values to determine the degree of bleaching based on scatter in the paleodoses. In young samples, if the standard deviation (Sd) of all the paleodoses is below an arbitrary number 5, the sample was considered well bleached. It is noteworthy that the scatter in the data due to experimental factors (measurement errors in dose growth curve, beta source heterogeneity and variation in environmental natural dose due to heterogeneity in natural beta dose) can lead to standard deviation of up to 20-30% of the paleodose. For samples >1-2 ka, the scatter on paleodoses decreases as a proportion of the mean paleodose with the age of the sample. In view of this, Clarke (1996) defined some additional parameters (Sn, defined as ratio of standard deviation to the mean of paleodoses) to determine the degree of bleaching. According to that,

When $Sn < 0.05 \Rightarrow$ majority of the grains are well bleached.

If, $0.05 < Sn < 0.1 \Rightarrow$ moderately well bleached

If, $0.1 < Sn < 0.15 \Rightarrow$ moderately poorly bleached

If, $Sn > 0.15 \Rightarrow$ poorly bleached.

On the basis of above if $Sd > 5$ and $Sn > 0.1$, indicates poorly bleaching and if $Sd > 5$ and $Sn < 0.1$ then it means that sample was poorly bleached at time of deposition but it is no more a hurdle for dating due to large burial time.

1.8 Estimating Paleodose from a Dose Distribution

From a measured distribution of SAR paleodoses, the determination of optimum paleodose for age determination is also difficult. Though average paleodose is used extensively to assign true paleodose, it basically compromises on bleaching history and nearly approximates a multiple aliquot analysis. Average value can be used when paleodoses distribution can be approximated to a narrow Gaussian distribution. For a skewed paleodoses distribution, the use of a mean paleodose is likely to yield erroneous results and aliquots with larger paleodose will bias the results.

Murray et al. (1995) examined the dose distribution from 70-year-old fluvial sample. The historical records provided a firm control of age. The dose distribution was not a simple Gaussian suggesting heterogeneous bleaching. The paleodose distributions were highly asymmetric, positively skewed and in only one case, the average De corresponded to the historical ages. Thus in orders to obtain the representative De, three largest paleodoses had to be discarded.

Olley et al. (1999) suggested that, "the more asymmetric the distribution, the greater the probability that the aliquots with the lowest dose more closely represent the true burial dose." It was stated that the asymmetry is because of two discrete subset of grains of different resetting history, however it is not clear that why there should be two discrete groups, because natural sedimentary processes are more likely to produce grains representing a continuum of solar exposures rather than discrete subsets of grains with uniform exposures.

Lepper et al. (2001) hypothesized that experimentally measured dose distribution is the convolution of the distribution arising from natural sedimentary processes and experimental error propagation. He tried to deconvolute the effect of experimental error and distribution arising from sedimentary processes.

Fuchs and Lang (2001) studied fluvial Quartz sediments from Greece on a small number of aliquots (N=10) due to very small amount of Quartz present in the sediment. A dose recovery test was done, which gave a relative standard deviation of 4%, which is the percentage ratio of standard deviation to the mean. This error was considered to be experimental error associated with the measurements. All the paleodoses were ranked in ascending order and standard deviation was calculated starting from the lowest two paleodoses to match it with experimental error of 4%. The number of paleodoses in each step was increased till these matched the experimental error. The relative standard deviation (RSD) defined as percentage ratio of standard deviation to the mean. RSD matches with the experimental error of 4%. Only those aliquots were considered for paleodose estimation whose relative standard deviation is ~ 4%. This approach provided ages in agreement with control/anticipated age.

Olley et al. (1998) suggested an approach utilizing the variation in paleodose in Quartz sediment. He represented the paleodose variation in a histogram constructed from typically small aliquot of 60-100 grains on each aliquot and concluded that the lowest 5-12 % of the paleodoses arranged in ascending order gave the optimum estimate of the true paleodose. He has successfully shown it by applying the technique on a 5 years old flood sample.

Zhang et al. (2003) worked on the fluvial sand from the Yongdinghe alluvial fan near Beijing city and suggested that the scatter in paleodose estimation due to experimental error and varying luminescence properties should be similar to the scatter of the first regenerated OSL as it is measured for a similar dose from each aliquot similar to dose recovery test. This suggested to use the relative standard deviation (RSD) in the first regenerated OSL as a surrogate for experimental error. The procedure given below enables selection of the most bleached aliquots–

1. The RSD of the sensitivity corrected first regeneration OSL is calculated (say RSD1).

2. The aliquots are ranked in ascending order of their sensitivity corrected natural OSL.
3. Beginning with the two aliquots with the lowest natural OSL, the RSD of the natural OSL is calculated by increasing one aliquot each time till it reaches to value when the value is equal to RSD1. Thus the preceding aliquots are considered as relatively well bleached.
4. Finally the average of these are taken as representative dose.

Summarizing, the determination of the most realistic paleodose from dose distribution is still a matter of active research. The dose distribution curve has been variously analyzed. For a narrow Gaussian distribution, the average can be the representative paleodose, however, in case of positively skewed distribution, the lowest values can be considered as true representative of the paleodose. The relative standard deviation (RSD) of the data serves as an indicator of the heterogeneity in paleodoses as it informs on the magnitude of deviation from the mean paleodose.

1.9 Luminescence dating and Himalaya

In India, Luminescence dating was initiated in the context of archaeological samples and later applied to aeolian and fluvial samples from the Thar Desert, southern Desert margin, Ganga plain and Himalaya. (Singhvi et al., 1982; Someshwar et al., 1997; Jain et al., 1999; Kale et al., 2000; Srivastava et al., 2001; Juyal, et al., 2003; Srivastava et al., 2003; Singh et al., 2003; Kar et al., 2004; Chamyal and Juyal, 2005). The mineral grains in Ganga plain sediments travel a distance of a few hundreds of km before entering into the Ganga plain from Himalaya. It can therefore, reasonably be assumed that such sediment in Ganga plain were adequately bleached before their deposition in different fluvial environment and this has been observed (Someshwar et al., 1997).

Himalaya provides a unique system that preserves the record of ancient to modern seismic and climatic regimes. Few studies have been done using luminescence techniques. Banerjee et al. (1999) dated fault gouges at Nainital, central Himalaya and inferred that a major tectonic activity in the region at around 40 ka. They have further suggested that geological luminescence in fault gouge was reset to zero by frictional heating during faulting event. More recently using luminescence dating of relict lake sediments in Garbyang basin in the higher Himalaya for paleoclimatic and paleoseismic studies (Juyal, 2004).

Himalayan comprises rocks of various lithologies, which on weathering provide sediments that are transported primarily by glacial melt and rain water. These sediments have Quartz grains of diverse luminescence properties. The high relief of the region implies rapid transport, but higher altitude of the region enables higher energy component in the daylight. Such a contrasting configuration of processes, one that favours rapid bleaching and the other that impede, made it necessary to examine their relative effects under various depositional settings. This is discussed further in the following section.

1.10 The objectives and scope of the thesis

Besides examining the prospects of dating on sediments from the Himalayan region for paleoseismology and paleoclimatology this thesis also explored new methodological avenues in the application of luminescence.

1.10.1 Methodological aspects

In Optical dating, the single aliquot regeneration method has been the preferred analysis protocol (Murray and Wintle, 2000). The natural signal is plotted on laboratory generated Luminescence–Dose growth curve. The luminescence generated growth curve is plotted such that any sensitivity change due to laboratory illumination and preheat is corrected for. In the thesis we examined two aspects related to the use of this method–

(i) Sensitivity changes during the read out of natural OSL– Stokes and Singhvi, (under preparation) suggested that the conventional SAR protocol did not take into account, the sensitivity changes during the read out of natural OSL. This could imply systematic offsets in age estimation. In this thesis that suggestion was examined for a variety of sediments and comparison on sensitivity corrected paleodoses and uncorrected paleodoses were made. In this, it was first demonstrated that the 110°C TL peak was correlated with BGSL signal and then this peak was used as a surrogate for the OSL sensitivity. Results indicate a significant sensitivity changes that can effect the ages significantly, if ignored.

(ii) Optimization of data throughput in SAR–In the dating of a partially bleached samples, a large number (typically 60-100) of aliquots are needed to construct a statistically valid dose distribution. Given that a typical SAR sequence requires 2-3 hours of machine time per aliquot. Analysis of a sample may take up to ~200 hrs (i.e. 7-8 days) of TL/OSL reader time. This limits the data throughput to 3-4 samples/month. To overcome this slow throughput somewhat, Roberts and Duller, (2004) suggested use of the Standard Growth Curve (SGC). In this approach, a fixed number of SAR growth curves of a sample are constructed. These are then merged to form a standard growth curve onto which the natural OSL of numerous aliquots are interpolated, thereby avoiding the need for constructing growth curve for each aliquot. The applicability and limitation of the method was tested further on samples from the above-discussed sequences and a criterion for its applicability was suggested and tested on samples of diverse depositional environment.

1.10.2 Feasibility of sediment dating from Himalayan terrain and their implications to Paleoseismology and Paleoclimatology

Various sedimentary archives in the Himalaya have preserved the signatures of paleoseismic and paleoclimatic events. However, their chronometry has been a problem due to difficulties in reliable application of the radiocarbon method. The applicability of luminescence dating for the sediments of different depositional environment was examined in detail. A brief survey of the geological archives and their bleaching aspects are as under–

(i) Sediment bleaching during flash flood–Flash floods in Himalaya are associated with breaching of landslide induced temporary reservoirs. These last for few hours to few days. Such floods can occur under poor light (overcast sky) condition with high sediment to water ratio. In the present study an attempt was 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. Both peak flood sediments (assorted sand) and winnowing phase of flood sediment (flood plain fine, silty-sand) were collected at 5 localities from Gohna Lake to Rishikesh (~250 km down stream) and analyzed using the standard SAR protocol.

(ii) Slack water deposits–Slack water deposit is found 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, near Haridwar in the state of Uttaranchal.

(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 body 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 extract.

(iv)Tectonically uplifted fluvial terraces–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 activity in the associated thrusts (Mukul, 2000). Present work deals with the luminescence dating of sediments from these terraces and then applied to infer about the seismic activity of the region.

1.11 Chapter wise details

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. Various measurement protocols such as the Single aliquot methods, multiple aliquot methods, are briefed. Applicability of the method to fluvial sediments is reviewed. The chapter describes the various geomorphologic archives studied in the thesis.

Chapter-2: Experimental procedures– This chapter describes the various experimental methods and protocols used in the measurement of OSL and age calculation. These include the sample preparation, measurement protocol, analysis and 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 (LM-OSL) partial bleach method and the extent of bioturbation and its effect on Luminescence dating in sediments, is described.

Chapter-3: Changes in natural OSL sensitivity and its implications to dating– Stokes and Singhvi (under preparation) recently suggested that the conventional SAR protocol does not take into account the change in Luminescence sensitivity during measurement of natural OSL. This effect occurs during preheat and luminescence readout. In the conventional SAR, the sensitivity is corrected using test dose measurement only after the natural OSL measurement. This implies that the sensitivity change during the read out of natural OSL is not accounted for and can lead to gross systematic errors. In this thesis, this aspect is examined in detail. In order to do so, the SAR protocol has been modified by, (i) demonstrating correlation of 110°C TL peak with the OSL peak and (ii) using the 110°C peak as a surrogate for sensitivity. Results on samples are discussed which indicate systematic offset. Most of the samples have shown sensitivity changes up to 20-30%, however, a few of them have shown up to 50%. This chapter describes the sensitivity changes and its possible repercussions on the samples collected in the Himalaya.

<u>Chapter-4</u>: Limit and applicability of standard growth curve– This chapter describes a methodological advance in the application of the SAR protocol, by suggesting the criteria for applicability of the Standard Growth Curve (SGC) for SAR. Single Aliquot Regeneration (SAR) is a widely used protocol in luminescence dating. However, a practical handicap is that it consumes considerable machine time implying a low data throughput. A practical solution towards increasing the data throughput has been suggested recently by Roberts and Duller (2004). In this merging a fixed number of laboratory generated growth curves generates a Standard Growth Curve (SGC) and the natural signal is read onto that curve to get the paleodose. This chapter describes the applicability of SGC on samples of different depositional environment in Himalayan.

<u>Chapter-5</u>: Fluvial sediments in diverse depositional settings and applicability of luminescence dating– 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 parameter that provide an estimate on the extent of bleaching is discussed and general inference on the extent of bleaching in various depositional domains within the fluvial regimes are discussed.

<u>Chapter-6</u>: Luminescence chronology of fluvial archives and its applications to paleoclimatology and paleoseismology– This chapter deals with geological interpretation of the ages obtained on various sediments as discussed above. It includes three sections -(i) Chronology and its implications in reconstructing paleocliamte of Yamuna-Ganga alluvial fan are discussed in detail; (ii) Chronology and paleo-flood record near Raiwala at Hardwar was described. It helped in computing the recurrence interval of a flood in the area; (iii) Chronology of uplifted river terraces in Tista valley with its application on Himalayan evolution in relation to Critical Wedge Taper model.

Chapter-7: Conclusion and Future Outlook- This chapter outlines results obtained from the present study and also describes the future prospect of the work presented in the thesis.

References

Aissauoi, D.M., McNeill, D.F. and Hurley, N.F., (eds.) 1993. Applications of paleomagnetism to sedimentary geology. *Society for sedimentary geology*, special publication, 49, 216 pp.

Aitken, M.J., 1985. *Thermoluminescence dating*. Academic Press, London.

Aitken, M.J., 1998. *An introduction to optical dating*, Oxford University Press, Oxford.

Bada, J. L., Gillespie, R., Gowlett, J. A. J. and Hedges, R. E. M., 1984. Accelerator mass spectrometry radiocarbon ages of amino acid extracts from California palaeoindian skeletons. *Nature*, 312, 442–443.

Balescu, S. and Lamothe, M., 1994. Comparison of TL and IRSL age estimate of feldspar coarse grains from waterlain sediments. *Quaternary Geochronology*, 13, 437–444.

Banerjee, D., Singhvi, A. K., Bagati, T. N., Mohindra, R., 1997. Luminescence chronology of seismites at Sumdo (Spiti valley) near Kaurik-Chango Fault, Northwestern Himalaya. *Current Science*, 73, 276–281.

Banerjee, D., Singhvi, A.K., Pande, K., Gogte, V.D. and Chandra B.P., 1999. Towards a direct dating of fault gouges using luminescence dating techniques: methodological aspects. *Current Science*, 77, 256–268.

Bender, M.L., 1974. Reliability of amino acid racemization dating and paleotemperature analysis of bones. *Nature*, 252, 378–381.

Berger, G.W. and Luternauer, J.J., 1987. Preliminary fieldwork for Thermoluminescence dating Studies at the Fraser river delta, British Columbia. *Geological Survey of Canada Paper* 87, 901–904.

Berger, G.W., 1990. Effectiveness of natural zeroing of the Thermoluminescence in sediments. *Journal of Geophysical Research*, 95, 12375–12397.

Bilham, R., Larsen K., Freymueller, & Project Idylhim members, 1997. GPS measurement of present day convergence across the Nepal Himalaya. *Nature*, 386, 61–64.

Bilham, R., Blume, F., Bendick, R. & Gaur, V.K., 1998. Geodetic constraints on the translation and deformation of India, implications for future great Himalayan earthquake. *Current Science*, 74, 213–229.

Bilham, R., Gaur, V.K. and Molnar, P., 2001. Himalayan seismic Hazard. *Science*, 293, 1442–1444.

Burbank, D.W., 2005. Cracking the Himalaya. *Nature*, vol. 434, 963–964.

Chamyal, L.S. and Juyal, N., 2005. Climatic events in Southern Thar Desert Margin and Higher Central Himalaya during the Last Glacial Stage (LGS): Possible linkages. *Himalayan Geology*, 26, 241–252.

Chen, Y.W., Chen, Y.G., Murray, A.S., Liu, T.K. and Lai, T.C., 2003. Luminescence dating of fluvial deposits on the southwestern coastal plain, Taiwan. *Quaternary Science reviews*, 22, 1223–1229.

Clarke, M.L., 1996. IRSL dating of sands: bleaching characteristics at deposition inferred from the use of single aliquots. *Radiation Measurement*, 26, 611–620.

Colls A.E.L., 1999. Optical dating of fluvial sediments from the Loire Valley, France. *M.S. dissertation*, Unversity of Oxford, Oxford, UK.

Ditlefsen, C., 1992. Bleaching of K-feldspar in turbid water suspensions : A comparison of photo and Thermoluminescence signals. *Quaternary Science Reviews*, 11, 33–38.

Duller, G.A.T., 1991, Equivalent dose determination using single aliquots. *Nuclear tracks And Radiation measurement*, 18, 371–378.

Duller, G.A.T., 1994a. Luminescence dating of poorly bleached sediments from Scotland. *Quaternary Science Reviews*, 13, 149–156.

Duller, G.A.T., 1994b, Luminescence dating using single aliquots: new procedures. *Quaternary Geochronology*, 13, 149–156.

Faure, G. and Mensing, T.M., 2005. *Isotopes: Principles and Applications*, John Wiley and sons, 896 pp.

Forman S.L. and Ennis G., 1992. Limitation of thermoluminescence to date waterlain Sediments from glaciated fjord environments of western Spitsbergen, Svalbard. *Quaternary Science Reviews*, 11, 61–70.

Fuller, I.C., 1994, Alluvial response to environmental change : luminescence dating of late quaternary sediment system. *Unpublished Ph.D. thesis*, University of Wales, Aberystwyth, UK.

Fuchs, M. and Lang, A., 2001. Optically Stimulated Luminescence dating of coarse-grain fluvial Quartz using single aliquot protocols on sediments from NE Peloponnese, Greece. *Quaternary Science Reviews*, 20, 783–787.

Galloway, R.B. 1996. Equivalent dose determination using only one sample: alternative analysis of data obtained from infrared stimulation of feldspar. *Radiation Measurement*, 26, 103–106.

Gemmell, A.M.D., 1985. Zeroing of the TL signal of sediment undergoing fluvial Transportation: A laboratory experiment, *Nuclear Tracks*, 10, 695–702.

Gemmell, A.M.D. 1988, Zeroing of the TL signal of sediment undergoing fluvioglacial Transport. An example from Austerdalen, Western Norway. *Quaternary science Reviews,* 7, 339–345.

Gemmell, A.M,D. 1997, Fluctuations in the thermoluminescence signal of suspended sediment In an Alpine glacial meltwater stream. *Quaternary Geochronology*, 16, 281–290.

Godfrey-Smith, D.I., Huntley D.J. and Chen, W.H., 1988. Optical dating studies of Quartz feldspar sediment extracts. *Quaternary Science Reviews*, 7, 373–380.

Gregory, K.J. and Benito, G., (eds.) 2003. *Paleohydrology, Understanding Global Change.* 390 pp., John Wiley and Sons Limited, England.

Hailwood, E.A., 1989. Magnetostratigraphy, 84 pp. Geological Society of London, *special report*, 19.

Hodges, K.V., Cameron, W., Ruhl, K., Schildgen, T. and Whipple, K., 2004. Quaternary deformation, river steepening and heavy precipitation at the front of the higher Himalayan ranges. *Earth and Planetary Sciences Letters,* 7012, 1–11.

Huntley, D.J., Godfrey-Smith, D.I. and Thewalt, M.L.W. 1985, Optical dating of sediments *Nature,* 313, 105–107.

Hurford, A.J. and Green, P.F., 1982. A user's guide to fission track dating calibration. *Earth and Planetary Science Letters*, 59, 343–354.

Ikeya, M.,1993. *New application of electron spin resonance dating, dosimetry and microscopy*, World Science, Singapur, New Jersey, Hong Kong, 520pp.

Ivanovich, M., Latham, A.G. and Ku, T.L., 1992. Uranium-series disequilibrium applications in geochronology. In M. Ivanovich and R.S. Harmon (Eds.), *U series* *disequilibria; Applications to earth, marine and Environmental Sciences*, 2nd ed., pp. 62-94. Clarendon, Oxford, UK.

Jain, M., Tondon, S.K., Bhatt S.C., Singhvi A.K., Mishra S., 1999. Alluvial and Aeolian sequences along the river Luni, Barmer district: physical stratigraphy and feasibility of luminescence chronology methods. In Vedic Saraswati, Radhakrishna B.P., Merh, S.S. (eds.) *Geological Society of India, memoir*, 42, 273–245.

Jain, M, Murray, A.S., Lars, Botter-Jensen, 2004. Optically Stimulated Luminescence Dating: How significant is incomplete light exposure in fluvial environments? *Quaternaire*, 15, 143–157.

Juyal, N., Kar, A., Rajaguru, S.N. and Singhvi, A.K., 2003. Chronostratigraphic evidence for episodes of desertification since the last glacial epoch in the southern margin of Thar Desert, India. In: A.S. Alsharhan, W.W. Wood, A.S. Goudie, A. Fowler and E.M. Abdellatif (eds.), *Desertification in the Third Millennium*. Swets & Zeitlinger (Balkema) Publishers, The Netherlands, 123–128.

Juyal. N., 2004. Chronology of Dryland sediments in western India and their correlation with the climate changes in Central Himalaya. *Unpublished Ph.D. Thesis* submitted to M.S. University of Baroda.

Kale, V.S., 2001. *Introduction to geomorphology*, Orient Longman Ltd.

Kale,V.S., Singhvi A.K., Mishra P.K. and Banerjee D., 2000. Sedimentary record and luminescence chronology of Late Holocene paleofloods in the Luni river, Thar desert, northwest India. *Catena*, 40, 337–358.

Kar, A., Singhvi, A.K., Juyal, N. and Rajaguru, S.N., 2004. Late Quaternary aeolian sedimentation history of the Thar desert. In: Sharma, Singh and De (eds.). *Geomorphology and Environment*, acb publication, Kolkata, India, 105–122.

Kamaludin, B.H., Nakamura, T., Price D.M., Woodroffe, C.D. & Fuji, S. 1993. Radiocarbon and thermoluminescence dating of the Old Alluvium from a coastal site in Perak, Malaysia. *Sedimentary Geology*, 83, 199–210.

Kaufman, A., 1993. An evaluation of several methods for determining ^{230}Th/U ages in impure carbonates. *Geochimica Cosmochimica Acta*, 57, 2303–2317.

King, J. and Peck, J., 2001. Chapter 4: Use of paleomagnetism in studies of lake sediments. *Tracking environmental change using lake sediments*, 1, Edited by, William M. Last and John P. Smol, Kluwer Academic Publishers.

Kronberg, C. 1983, Preliminary results of age determination by TL of interglacial and Interstadial sediments. *PACT*, 9, 595–605.

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: In situ nuclide production rates and erosion models. *Earth and Planetary Science Letters*, 104, 424–439.

Leier, Andrew L., DeCelles, Peter G. and Pellitier Jon D., 2005. Mountains, monsoons and mega fans. *Geology*, 33(4), 289–292.

Lepper, K., Agersnap, L.N. and McKeever, S.W.S., 2001. Equivalent dose distribution analysis of Holocene eolian and fluvial Quartz sands from central Oklahoma. *Radiation Measurement*, 32, 603–608.

Li, S.H. and Wintle, A.G. 1992, Luminescence sensitivity change due to bleaching of sediment. *Nuclear Tracks Radiation Measurement*, 20, 567–573.

Li, S.H. 1994, Optical dating: insufficiently bleached sediments. *Radiation Measurement* 23, 563–567.

Mathew, G., Gundu Rao, T.K., Sohoni, P.S. and Karanth, R.V., 2004. ESR dating of inter fault gypsum from Katrol hill range Kachchh, Gujarat: implications for neotectonism. *Current Science*, 87, 1269–1274.

Miall, 1996. *The geology of fluvial deposit*, Springer-Verlag.

Mukul, M., 2000. The Geometry and Kinematics of the Main Boundary Thrust and related Neotectonics in the Darjiling Himalayan Fold-and-thrust belt, West Bengal, India. *Journal of Structural Geology* 22, 1261–1283.

Murray, A.S., Wohl E., & East, J. 1992. Thermoluminescence and excess ^{226}Ra decay dating of late quaternary fluvial sands, East Alligator river, Australia. *Quaternary Research*, 37, 29–41.

Murray, A.S., Olley, J.M. and Caitcheon, G.G., 1995. measurement of equivalent doses in Quartz from contemporary water-lain sediments using Optically Stimulated Luminescence. *Quaternary Science Reviews*, 14, 365–371.

Murray, A.S., 1996. Developments in Optically stimulated Luminescence and photo-transferred Thermoluminescence datingof young sediment : Application to a 2000 years sequence of flood deposits. *Geochimica et Cosmochimica Acta.,* 60, 565–576.

Murray, A.S., Roberts, R.G. & Wintle, A.G., 1997. Equivalent dose measurement using a single aliquot of Quartz. *Radiation Measurement,* 27, 171–183.

Murray, A.S., Wintle, A.G.,2000. Luminescence dating of Quartz using an improved single aliquot regenerative-dose protocol. *Radiation Measurement,* 32 (1), 57–73.

Nishiizumi, K., Winterer, E.L., Kohn, C.P., Klein, J., Middleton, R., Lal, D. and Arnold, J.R., 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in Quartz from glacially polished rocks. *Journal of Geophysical Research,* 94, 17907–17915.

Olley, J.M., Caitcheon, G., & Murray A., 1998. The distribution of apparent dose as determined by optically stimulated luminescence in small aliquots of fluvial Quartz: implications for dating young sediments. *Quaternary Science Reviews,* 17, 1033–1040.

Olley, J.M., Caitcheon, G. and Roberts, R.G., 1999. The origin of dose distribution in fluvial sediments and the prospect of dating single grains from fluvial deposits using Optically Stimulated Luminescence. *Radiation Measurement,* 30, 207–217.

Phadtare, R. N. 2000, Sharp Decrease in summer monsoon strength 4000–3500 cal yr B.P. in the central higher himalaya of India based on pollen evidence from alpine peat. *Quaternary Research,* 53, 122–129.

Pratt, B., Burbank, D.W., Heimsath, A. and Ojha, T., 2002. Impulsive alleviation during early Holocene strengthened monsoons, central Nepal Himalaya. *Geology,* 30, 911–914.

Proszynska-Bordas, H., Stanska-Proszynska, W., and Proszynski, M., 1992. TL dating of River terraces with fossil soils in the Mediterranean region. *Quaternary Sciences Reviews,* 11, 53–60.

Quidelleur, X., Gillot, P.Y., Soler, V. and Lefevre, J.C., 2001. K/Ar dating extended into the last millennium: application to the youngest effusive episode of the Teide volcano (Spain). *Geophysical Research Letters,* 28, 3067–3070.

Rittenour, T., Goble, R. and Blum, M., 2003. An optical age chronology of the late Pleistocene fluvial deposits in the northern lower Mississippi valley. *Quaternary Science reviews*, 22, 1105–1110.

Roberts, H.M., Duller, G.A.T., 2004. Standardized Growth Curves for optical dating of Sediment using multiple-grain aliquots. *Radiation Measurement*, 38, 241–252.

Sangode, S.J., Suresh, N., Bagati, T.N., Bloemendal, J., Kumar, R. and Thakur, V.C., 2002. Discovery of an aborted reversal (geomagnetic excursion) in the late Pleistocene sediments of Pinjor Dun, NW Himalaya. *Current Science,* 82, 210–215.

Singh, I. B., Manoj K. Jaiswal, A. K. Singhvi and B. K. Singh, 2003, Rapid subsidence of western Ganga plain during late pleistocene : Evidence from optical dating of subsurface samples. *Current Science*, 84, 451–454.

Singhvi, A.K., Sharma Y.P. and Agrawal D.P. 1982. Thermoluminescence dating of sand dune in Rajasthan. *Nature,* 295, 313–315.

Singhvi, A. K., D. Banerjee, K. Pande, V. Gogte, K. S. Valdiya, 1994. Luminescence studies on Neotectonic Events in South-Central Kumaun Himalaya-A Feasibility Study. *Quaternary Science Reviews*, 13, 595–600.

Singhvi, A.K. and Banerjee, D., 2003. Luminescence dating in Earth and Planetary science- an appraisal. *Proceedings of the Fourth South Asia Geological Congress, New Delhi, India,(GEOSAS-IV)*, 11–25.

Someshwar Rao, M., Bisaria B.K. and Singhvi A.K., 1997. A feasibility study towards absolute dating of Indo-Gangetic alluvium using thermo-luminescence and Infrared stimulated luminescence techniques. *Current Science*, 72, 663–669.

Srivastava P., Juyal N., Singhvi A.K., Wasson R. J., Bateman M.D., 2001. Luminescence chronology of river adjustment and incision of Quaternary sediments in the Alluvial plain of Sabarmati river, north Gujarat, India. *Geomorphology,* 36, 217–229.

Srivastava P., Singh I.B., Sharma M., Singhvi A.K., 2003. Luminescence chronometry and late Quaternary geomorphic history of the Ganga plain, India. *Paleogeography, Paleoclimatology, Paleoecology*, 197, 15–41.

Stokes, S., 1994. The timing of OSL sensitivity changes in a natural Quartz. *Radiation Measurements*, 23, 601–605.

Stokes, S. and Singhvi, A.K.. Changes in natural OSL sensitivity during Single Aliquot Regeneration procedures and their implications to equivalent dose determination (Under preparation).

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac G., Vander, P.J. and Spurk, M., 1998. IntCal98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon*, 40, 1041–83.

Thomas, P.J., Jain, M., Juyal, N. and Singhvi, A.K., 2004. Comparison of single grain and single aliquot OSL dose estimation in <3000 years old river sediment from south India. *Radiation Measurement*, 39, 457–469.

Whipple, K.X. and Meade, B.J., 2004. Controls on the strength of coupling among climate, erosion and deformation in two-sided, frictional orogenic wedges at steady state. *Journal of Geophysical Research*, 109, 1–24.

Wohlfarth, B., 1996. The chronology of the last termination: a review of radiocarbon-dated, high-resolution terrestrial stratigraphies. *Quaternary Science Review*, 15, 267–284.

Zhang, J.F., Zhou, L.P. and Yue, S.Y., 2003. Dating fluvial sediments by Optically Stimulated Luminescence: selection of equivalent doses for age calculation. *Quaternary Science Reviews*, 22, 1123–1129.