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Luminescence dating and Quaternary Geology: The Indian Narrative

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This overview provides a review of the development of luminescence dating in India, recounts important contributions and their import on the chronology of the Indian Quaternary sequences. A brief outline of other applications and future outlook is also presented. Due to the nature of this review, the focus is largely towards applications, and the methodological aspects will be discussed elsewhere.

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1. Initial Developments

The earliest description of luminescence is ascribed to Robert Boyle, who famously observed and reported about a diamond that shines in the dark, '*I also brought it to some kind of glimmering light, by taking it into bed with me and holding it a good while upon a warm part of my naked body….*" (quoted from Aitken, 1985). Daniels *et al.* (1953) were the first to suggest the possible use of luminescence for radiation dosimetry and for age determinations. The subject has grown ever since. The first detection of luminescence from pottery was reported by Groegler *et al.* (1960) and by Kennedy and Knopf (1960). Shelkoplyas and his group were the first to apply thermally stimulated luminescence (TL) technique to date loess, buried soils, glacial and marine deposits in USSR (Shelkoplyas, 1971; Dreimanis *et al.,* 1978). However, these developments remained unknown due to lack of English translation and a limited understanding of the physical processes underlying the age determinations.

In the US, initial efforts to date pottery yielded grossly underestimated ages. These lead to a loss of faith in the method. However painstaking research at the Research Laboratory for Archeology and the History of Art (RLAHA), led by Martin Aitken identified the key unknown physics factors that resulted in such an underestimation. These included markedly varied difference in the efficiencies of α and β particles in producing luminescence, the athermal fading and supra-linear growth of luminescence and the estimation of dose rate and errors, besides others. Several doctoral theses from this laboratory examined various aspects of physics of luminescence in minerals and provided a foundation for the use of luminescence dating for reliable ages. By the late 70's, thermoluminescence was an established method for the dating of heated objects. Parallel efforts by the Risoe Group in Denmark, led by Vagn Mejdahl and Lars Boetter Jensen led to the development of automated TL readers and a more refined version of these now find routine use in numerous laboratories.

Further, the understanding of the physics of interaction of ionizing radiation in a mineral matrix and its variable impact on luminescence helped develop luminescence as a foolproof tool for authenticity of ancient ceramics and led to discovery of many fake objects. The reliability of TL in authenticity was such that luminescence based evidence was admissible in legal proceedings, (Fleming, 1975).

Wintle and Huntley (1979, 1982) used TL to date sediments by exploiting the fact that a significant fraction of TL signal is photo-bleachable and the rest, a minor fraction (typically 10-20%) was insensitive to light. By developing suitable protocols, they were able to date sediments that experienced sun-light during their transport. Singhvi *et al.* (1982a) demonstrated the dating of desert sands that paved way for the dating of deserts and associated processes and climates. Development of new application followed and the then contemporary methods, were reviewed by Singhvi and Mejdahl (1985).

A major disruptive innovation was the report of optically stimulated luminescence from quartz by Dave Huntley and his group at the Simon Fraser University (Huntley *et al.,* 1985). This group used green light to stimulate luminescence in quartz in the UV window. Use of an optical stimulation to probe optically sensitive photo-bleachable luminescence signal opened possibilities to date almost all types of quaternary sediments, which get exposed to daylight during the weathering of the parent rock and multiple episodes of transport (Aitken, 1998; Rhodes, 2011; Murray *et al.,* 2021). Hűtt *et al.* (1988) were the first to use infrared stimulation to stimulate luminescence from K-feldspars. Presently over 1000 papers based on optically stimulated luminescence (OSL) or optical dating are published annually and these account for an estimated over 70% of chronometric data for the recent earth history and the Quaternary studies. A comparison of OSL ages with ages from independent estimates has been provided by Murray et al. (2021) besides many others, and the robustness of available protocols has been adequately demonstrated. A biannual newsletter, Ancient TL provides a bibliography of publications of luminescence applications along with contributions on various methodological nitty-gritty and improvements in dating protocols. A triannual international meeting on Luminescence and Electron spin Resonance dating (LED) is held and the most recent being during September 2021 was the 16th in the series and about 400 participants attended this. The proceedings of these are published as special issues of Journals, *Radiation measurements* and *Quaternary Geochronology*.

In respect of applications, some of the benchmark publications are, *Thermoluminescence of Geological Materials* (McDougall *et al.,* 1968), *Progress of thermoluminescence research on Geological Materials* (Sankaran *et al.,* 1983), and *assessment of Natural Radiation Environment of India using TL dosimeters* (Nambi *et al.,* 1986), besides the special issues of *Radiation measurements*. Several regional meetings are also held annually and notable being the UK, Germany, New World luminescence meetings and more recently in India.

Apart from dating, optically and thermally stimulated luminescence (TL and OSL), now finds routine usage in radiation monitoring and medical therapy with real time measurement of radiation dose delivered to the organ of a patient for radiation therapy. The dating application to archeology, additionally provided a useful tool to estimate the fallout dose from nuclear tests and accidents. In this the radiation dose from fall out could be made using TL from building bricks, porcelain, whose age was known. For this the expected luminescence dose can be computed using the known age and the dose rate, and the difference between the measured and expected dose, is the fall out dose. TL and OSL also provide a useful tool to assess exposure to irradiated foods.

Luminescence is now routinely used in meteoritics for the determination of petrologic grades, the perihelion of their orbit, terrestrial ages and in the detection of their oriented entry (Sears *et al.,* 2013). Currently, effort to use luminescence for space dosimetry and for in situ optical dating of sedimentary processes on Martian sediments are awaiting implementation (Jain *et al.,* 2012).

In India, Bhabha Atomic Research Centre (BARC) established an internationally acclaimed school of luminescence dosimetry at the Health Physics division. This was led by Prof. A. K. Ganguly along with Drs. C.M. Sunta and K.S.V. Nambi. This group contributed to the physics of luminescence in solids, developed instruments and attempted ranging applications in radiation monitoring. A good overview is provided by Bhatt (2011). Other, important contributions to the physics of luminescence were by the groups at IIT Kharagpur, Universities of Nagpur, Raipur, Jabalpur, Imphal and Baroda.

As a logical extension of radiation dosimetry, BARC explored varied applications of luminescence including dating of archaeological pottery using samples from the Archaeological Survey of India (ASI). BARC also initiated the National symposium on TL and its application, the first one in 1979. The second meeting was at the Physical Research Laboratory (PRL), Ahmedabad in 1979 which attracted substantive international participation and its proceedings led to a special issue of Nuclear Tracks (now Radiation Measurements; Ed. Singhvi *et al.,* 1984). Efforts by Prof. K. S. V. Nambi, Prof. C. M. Sunta, and Dr. R. P. Rao led to the formation of Luminescence society of India that holds annual meeting of over few hundred participants since the late 1980's.

2. Relevance of luminescence dating

Willard Libby (1946) suggested that radiocarbon (^{14}C) in living matter is of near identical concentration. A year later, his group (Anderson *et al.,* 1947) demonstrated the possibility of dating of carbon containing materials, and this led to the radiocarbon dating revolution in archeology. India established the radiocarbon laboratory at Tata Institute of Fundamental Research (TIFR), Mumbai during early 60's and this laboratory served as a National facility for the radiocarbon chronology of Indian archaeological sites. During early 1990's this laboratory moved to the Physical Research Laboratory and has since been upgraded to AMS radiocarbon dating, (Bhushan *et al.,* 2019, Kusumgar and Yadava, 2002). National Geochronology Centre at IUAC also now provides AMS radiocarbon ages routinely on a pan India basis (Sharma *et al.,* 2020).

Despite the possibility of radiocarbon dating, several important archaeological sites remained undated due to paucity of uncontaminated material for dating and its limited dating range of 40 ka. Tropical, hot and humid environment of India results in poor preservation of organic matter needed for radiocarbon analysis. Thus e.g., much of the microlithic phase, the megalithic burials, archaeological hearths remained without chronologies and the limited range of radiocarbon dating implied that most of the paleolithic cultures, were beyond the reach of a numerical chronology. This gap is now being filled up by luminescence methods.

In respect of Quaternary sediments, a key difficulty in the use of radiocarbon has been in establishing the association of sample dated and the sediment horizon, as it could be likely that the organic matter was derived from older vegetation in the catchment and later altered through varied interaction with either modern or paleo-waters. These limited the applicability of radiocarbon and on this count most published radiocarbon ages on terrestrial archives, need a careful revisit for contamination and similar factors of reservoir effects (Mischke *et al.,* 2013). More recent advances in the component specific radiocarbon dating (e.g. Casanova *et al.,* 2020), has so far not been tried in the Indian sites.

In the Indian contexts, other dating methods such as paleomagnetic dating did not find much applications due to their poor resolution, and the requirement of an alternate time marker normally in the form of a volcanic tephra layer in their primary context and assumed a constant sedimentation rate. In terrestrial situations presence of tephra layer in their primary contexts is generally difficult and this leads to difficulties of their use as a chrono-stratigraphic marker. Likewise, U-series dating of calcretes require pure, unaltered carbonates, which are rare in terrestrial settings. Cosmogenic radionuclides offer lower resolution for samples till the last glacial cycle and an intrinsic problem is caused by inherited signal; however, some important results on the paleolithic have been reported (Pappu *et al.,* 2011). Methods like amino acids racemization did not find much application as the rates of racemization are critically dependent on temperature. Poor preservation and large amplitude of changes in seasonal temperatures precluded this application to Indian Sites. Use of cosmogenic isotopes, the concept of which was developed in India has largely been made in the dating of glacial deposits and more recent efforts at Interuniversity Accelerator Centre and PRL show promise for future growth of this methods, (Bhushan *et al.,* 2019; Lal, 1988).

Methods like electron spin resonance also found very limited use through the joint effort by Dr. T.K. Gundurao of IIT Bombay and the Physical Research Laboratory. The studies were in the context of dating climate sensitive minerals like calcretes and gypsum (Kailath *et al.,*2000; Nagar *et al.,* 2010) and on Feldspar and Diamonds with the help of Dr. M.D. Sastry of BARC and the Gemological Institute (Sastry *et al.,* 2007, 2011). Despite the potential to date a variety of geological materials, no dedicated effort is yet underway to develop ESR applications in geosciences, in India.

Difficulties caused on account of absence of datable samples, methodological needs and practical aspects of sample preservation, made luminescence dating an attractive choice for chronology of Quaternary sediments and archeology. Its applicability to minerals comprising the sediments (thereby removing the ambiguity of correlation between sample and its host sediment and a continuous dating range from a few years to few hundred ka (possibly a Ma) makes it an ideal choice for both the chronology and calibration of proxies for climate reconstruction. The current limit of dating using quartz OSL is ~ – 200 ka, determined by saturation of OSL signal with dose and the dose rate. For feldspar, the dating limit is ~500 ka for low dose environment and with some methodological innovations it is soon expected to reach a range of a million years.

3. The Indian Scene

Direct applicability of luminescence for the dating of archaeological artifacts (pottery, bricks, debitage, sediments), their thermal history and a potential dating range of a million years provided the requisite incentive to explore the use of luminescence dating.

Therefore, in 1977, PRL initiated a dedicated effort to develop dating application of luminescence in India. This endeavor derived multifarious help from the Health Physics group at BARC; the Research Laboratory for Archaeology and the History of Art and the financial support from the Ford foundation. The first results were on an important archaeological Site at Sringaverapura, near Allahabad with the samples collected with the help Prof. B.B. Lal of the Archaeological Survey of India (Agarwal *et al*, 1981). Most measurements were carried out using indigenously developed TL reader (Devgan *et al.,* 1980) and it was only after two decades, in the late 1997-98 a commercial, automated reader could be purchased through support from Department of Science and Technology. Over the years, PRL helped many institutions in establishing several laboratories across India. Table 1 provides the current scenario of luminescence laboratories, their programs.

Thanks to initiative by P. Morthekai of the Birbal Sahni Institute of Palaeosciences and Devendra Kumar of National Geophysical Research Institute, scientists from different Indian luminescence dating laboratories now meet annually and discuss various developments. These meetings attract over 100 participants of varied backgrounds and include invited international workers for lectures and interactions. A dating hand book is currently being prepared and will be available as a guide for non-specialists.

4. Luminescence Dating

4a. Basic Premise:

The basic principle used in any of the dating programs is outlined in Fig. 1a. Luminescence dating is radiation dosimetry of natural radiation environment using natural minerals like quartz and feldspars as sensitive and reliable dosimeters. Decay of naturally occurring radionuclides viz. ^{238}U, ^{232}Th, ^{40}K and ^{87}Rb produces a constant flux of ionizing radiation comprising α, β, γ rays. Large half-lives of these radionuclides imply that on a million-year time scale the radiation dose remains constant. In addition, near surface sediments are exposed to cosmic rays.

Ubiquitous, weathering resistant minerals like quartz and feldspars have the ability of faithfully recording the cumulative amount of irradiation received by them through a complex process of ionization and trapping of charges at lattice defects. The stability of some of trapped charges exceeds millions of years at environmental temperature of around 30°C are used for dating applications.

Their detection occurs through excitation of trapped charges and their radiative recombination with charges of opposite type (electrons or holes). The intensity of light (luminescence, measured as number of photons/sec) bears a proportional relationship with radiation dose (measured in Gray/ka or Gy/ka) up to a saturation level, whence all traps are filled or reach an equilibrium level (a stage when the net loss and gain of trapped charges balance out; Fig. 1b). The luminescence behavior of grain is determined by the physico-chemical environment at the time of mineral formation and later radiation/thermal/optical history. This implies that luminescence properties of each sample/ grain used for dating analysis have to be determined in a self-consistent manner. A typical dating analysis including sample preparation may consume anywhere from up to 8–10 days depending on the sample state, grainsize to be used, sensitivity, degree of bleaching, age of sample (paleodose), dose rate measurements with dedicated instrument time. This makes the methods cost, labor and time intensive, but at the same time permits the method to be self-consistent, without the need for any dating standards.

The dating applications rely on a premise of an initial zero level of trapped charge concentration, a constant environmental dose that results in an increase in trapped charge concentration at a constant rate. Therefore, at any given time, the concentration of trapped charge can be converted into time as their production rate can be computed by measuring the environmental dose. In practice the sample is stimulated thermally or optically. The measured luminescence (with appropriate laboratory calibration through calibrated beta irradiation source) is converted into equivalent radiation exposure (termed as equivalent dose or paleo-dose, D_e). Measurement of environmental radionuclide

Table 1. List of Indian OSL/dating labs.

S.N.	Laboratory	Originators	Current in charge	Areas of research	Facilities for dating
1	Bhabha Atomic Research Centre, Mumbai	Dr. C.M. Sunta/ Dr. K.S. V. Nambi	Dr. Devesh Mishra / Dr. Anuj Soni devesh22@gmail.com; anujsoni.phy@gmail.com	Medical Dosimetry, Retrospective dosimetry, Physics and modeling, Phosphor development and instrumentation	Multiple TL reader, Riso reader, In-house developed automated reader, gamma ray spectrometers.
2	Physical Research Laboratory, Navarangpura, Ahmedabad	Dr. A.K. Singhvi	Dr. N. Chauhan naveenchauhan1983@gmail.com	Methodological Aspects, Applications to sediments of all types, Archeology, Meteoritics, Space dosimetry, Modeling of natural radiation environment	Riso systems with options Red, violet and radioluminescence, IRPL, imaging system, gamma spectroscopy system
3	Physical Research Laboratory Thaltej Campus, Ahmedabad	Dr. D. Banerjee	Dr. D. Banerjee deba@prl.res.in	Space dosimetry, Dating of terrestrial sediments	Riso system, gamma spectroscopy system
4.	Wadia Institute of Himalayan Geology, Dehradun	Dr. N. Suresh/ Dr. Pradeep Srivastava*	Dr. Anil Kumar akumar@wihg.res.in	Dating of sediments across Himalaya, Ganga plains, Paleo-tectonics and paleo seismology	Riso systems; ICPMS, XRF systems
5.	National Geophysical Research Institute, Hyderabad	Dr. B. S. Sukhija	Dr. Devender Kumar devngri@gmail.com	Paleo seismology, Aeolian Processes, Relic fluvial archives	Riso system, NaI gamma counting system
6.	Geological Survey of India, Faridabad Campus	Dr. H.S. Saini/ S.A.I. Mujtaba	Dr. R.V. Chunchenkar Chunchenkar.radhakrishna@gmail.com; Dr. M. Atif Raza, Atif.du@ gmail.com	Dating of Quaternary sediments	Riso systems. ICPMS, XRF
7	Institute of Seismological Research, Gandhinagar	Dr. B.K. Rastogi/ Dr. M.S. Gadhvi	Dr. S.Prizomwala Prizomwalasiddharth @gmail.com	Paleo-seismology, dating of sediments	Riso systems. ICPMS
8.	Indian Institute for Science, Education and Research	Dr. Manoj Jaiswal	Dr. Manoj Jaiswal mjkosl@gmail.com	Fluvial systems, loess and paleoclimate, tectonic geomorphology	Lexyg systems, ICPMS, XRF, uDose system
9.	Birbal Sahni Institute of Palaeosciences, Lucknow	Dr. P. Morthekai	Dr. P. Morthekai morthekai@gmail.com	Methodological Aspects, dating of quaternary sediments including diatoms, Comparative geochronology	Riso system, HPGe gamma ray counting system
10.	Indian Institute of Technology, Kanpur	Dr. J.N. Malik	Prof. J. N. Malik, javedmalik77@gmail.com Dr. R.H Biswas biswasrabiul@gmail.com	Paleo seismology, Thermochronology, rock surface erosion, surface paleo-thermometry, dating of sediments	Riso system, HPGe Gamma ray counting system
11	Jawahar Lal Nehru University, Delhi	Dr. Milap Sharma	Prof. Milap Sharma milap@mail.jnu.ac.in	Chronologies of past glaciations-CRN intercomparison	Lexyg system
12	Delhi University, Delhi	Dr. Vimal Singh	Dr. Vimal Singh vimalgeo@gmail.com	Tectonic geomorphology, Processes in the critical Zone	Lexyg System
13	Manipur University, Imphal	Dr. R.K. Gartia	Dr. Dorendrajit Singh dorendrajit@yahoo.com	Chronology for fluvial processes	Riso System
14	M.P. Council of Science and Technology, Bhopal	Dr. M.K. Rathore	Dr. Manoj K Rathore mkrathore1@gmail.com	Sediment Dating, Quaternary Science	Lexyg System

* Now at IIT Roorkee, Roorkee

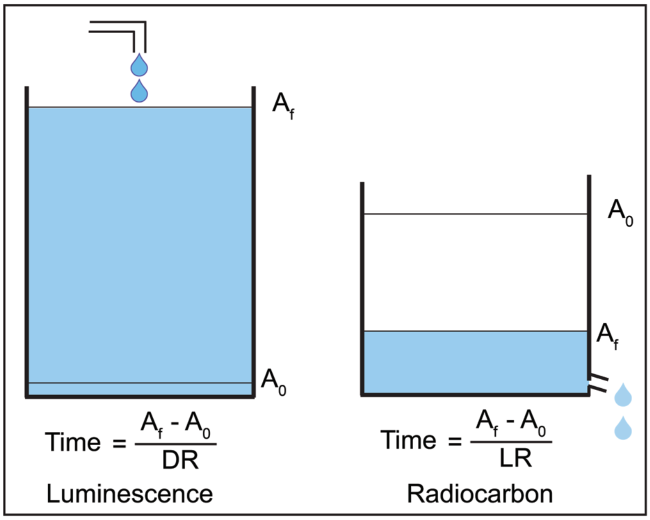

Fig.1a Basic generalized principle for numerical chronology. This is akin to a beaker being filled or emptied at a known drop rate (DR) or leak rate (LR). In both the cases the time taken to fill or empty the beaker requires knowledge of initial level A_0, the final level A_f and of LR or DR. In addition, the measurments should ensure that no unknown inputs or leaks occurred during the time the level changed from A_0 to A_f, i.e. the system remained a closed system. The filling of a beaker can be compared with luminescence dating, where A_0 is assumed to be close to zero or zero due to either heating or daylight bleaching prior to deposition and A_f is the present level of luminescence. Drop rate DR is the annual radiation dose and it is noteworthy that signal increases with time, till the beaker gets filled up due to saturation of charge traps.
The leakey beaker is analogus to radiocarbon dating, where every living matter exchanging with atmosphere gets labelled with modern carbon and upon death, no new supply occurs and the radiocarbon in the organism decays as per its expoential decay rate (half life 5730 years). Here also the requirement of closed system has to be met for each case. Decrease of signal with time, limits the dating range of radiocarbon to 40 ka. This logic of beakers being filled or emptied can be extended to all methods for dating.

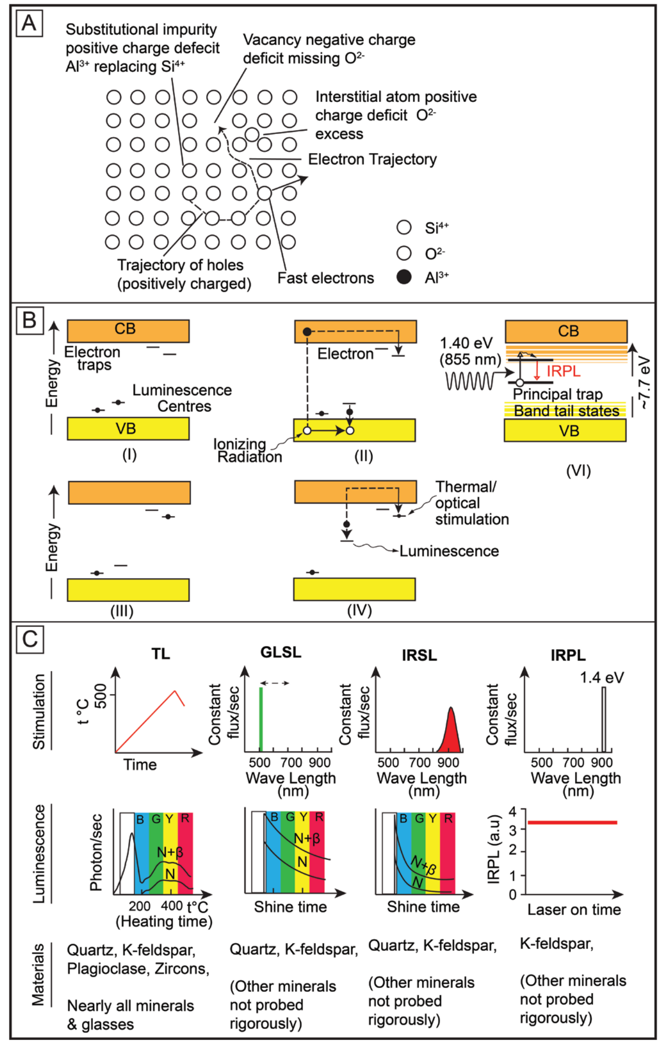

Fig. 1b. (A) Schematic of typical crystal structure showing crystallographic sites or vacancies. (B) Energy level diagram with illustration of luminescence process; the band structure of a crystal, irradiation, charge trapping, and charge detrapping and recombination, hence the production of luminescence; in (VI) band diagram showing the mechanism of Infra-red Photoluminescence (IRPL) generation in feldspar. (C) Schematic representation of different stimulation modes and their respective luminescence. In case of IRPL, stimulation is at 830 nm and observation is at 885nm/930nm. TL-Thermal luminescence, GLSL-Green light stimulated luminescence, IRSL- Infra-red stimulated luminesce, N-natural (This figure is based on numerous illustrations on these methods and processes).

concentrations (using either of alpha counting, gamma ray spectrometry or chemical analytical methods), and the use of infinite matrix assumptions, then enables computation of annual radiation dose (D). The ratio of paleo-dose and annual dose rate provides age.

Fig. 1 provides a schematic of principles used in dating (1a) and the luminescence process (1b).

The age equation is as follows-

$$Age = \frac{(Luminescence)}{luminescence/year} = \frac{Paleodose}{dose/year} = \frac{De}{aD_\alpha + D_\beta + D_\gamma + D_c}$$

Where D's (mGy/year or Gy/ka) are the component of annual radiation dose from specific particles and rays emanating during the decay of U, Th and K. D_c is the component of dose from the cosmic ray dose and accounts for up to a few % of the total doses. Cosmic ray flux that varies with location and altitude is attenuated with the depth of sediment/water. This, leads to varied shielding and generally a mean depth is used for computation of this dose using relations provided by Prescott and Hutton (1994).

Factor *a* is a grain dependent alpha efficiency factor that accounts for differences in luminescence induction efficiency of α-particles as compared to β's and this is typically 0.03-0.06 for quartz and o.06-0.08 for feldspars. The range of alpha particles is typically 20 µm and therefore is relevant when the mean grain size used is fine silt (4-11 µm). For larger grains, the outer α-irradiated skin is etched off and the interior is analyzed with a robust assumption that it did not receive any α- dose. The dose rate also depends on the average water content. Water does not carry any radioactivity, but attenuates the radiation flux through it and therefore dilutes the net dose rate. Typically, 10% water content results in ~10% attenuation of dose and hence a ~10% change in the age. We refer to Aitken (1985, 1998) for more detailed discussions. We refer to several books/reviews that deal with the basic concepts of methods viz., (Wagner, 1995; Rhodes, 2011; Liritizis *et al.,* 2013; Batemen, 2019; Murray *et al.,* 2021).

4b. Types of Events Dated

Three types of events ensure that the initial trapped charge concentration with in minerals are reduced to zero or near zero level. The events that can be dated are:

a) a heating event (> 400°C) that evicts all the trapped charges through thermal excitation. Such events include e.g. the firing of pottery, heating of a kiln brick, contact heating of a sediment due to flow of lava on it or forest fires, frictional heating during the formation of fault gouges and injection of sediment as a dike. On cooling re-accumulation of luminescence is initiated and therefore the trapped charge concentration reflects the time elapsed since heating.

b) a day light bleaching event that photo-bleaches the luminescence of mineral grains to a near zero value and on burial the grains get shielded from further daylight exposure. Consequently, a re-accumulation is initiated and this continues till excavation and measurements. Thus, the event dated here is the most recent daylight exposure and the burial event. The daylight exposure of sediments occurs during their detachment from the parent rock and multiple cycles of transportation; therefore almost all types of sediments, viz., aeolian, fluvial, lacustrine, glacial and glaciofluvial and soils, can be dated. More recently it is demonstrated that rock surfaces exposed to daylight can also be dated based on the bleaching of rock luminescence with depth by daylight.

c) mineral formation events where trapped charge concentration at the time of formation of mineral is *ab initio* zero. Thus, chemical precipitates like gypsum, barites, carbonates can be dated directly or through included mineral grains that can be assumed to have been bleached prior to entrapment in the chemically precipitated matrix. The formation event is therefore, dated.

4c. Methodological Aspects

Spatial Distribution of radiation dose: Despite obvious conceptual simplicity of the method, in practice measurement of luminescence age is non-trivial due to a variety of complicating factors. While, given automated systems, some numbers (supposedly ages) can be obtained, but for them to qualify as age, a proper understanding of underlying physics and the depositional environment is critical for their accuracy and reliability.

A key aspect that arises due to the varied ranges of ionizing radiations, i.e., 20 µm for α's to a few mm for β's to tens of cm for γ's. These imply that, the decay of same radionuclide provides a spatially heterogenous radiation dose from these components, and this fact needs to be accounted for in the analysis of age using infinite matrix assumption (see e.g., Murray *et al.,* 2021). Some simplification is achieved by using a limited range of grain sizes for analysis. Thus, for example fine silt size grains receive full quantum of α-dose and sand grains from the same environment receive α-dose only on their skin. This skin when etched, provides the interior devoid of alpha dose and simplifies the age determination.

Instruments now permit automated analysis of luminescence from individual grains. However, at a single grain level, variable spatial distribution of β-dose occurs. Feldspar grains that carry up to 11-14% stoichiometric potassium serve as hot spots and provide most of the beta dose. For a typical concentration of 1% such hotspots are few and randomly distributed. Given that beta dose gets attenuates rapidly over sub-mm level, it implies that dose received by a quartz grain depends on the distance of a particular grain of quartz from feldspar grains serving as a hotspot. This leads to a distribution of beta dose and this has to be factored in calculation, (Mayya et. al., 2006). Expectedly, the heterogeneity is larger for smaller concentration of feldspars and diminishes to a uniform value for sediments with >2.5% potassium.

Further, the dose delivered by a laboratory beta source depends on the grain size, mineral type and the metal used to make the substrate disc and this calls for calibration of the laboratory beta source for each measurement condition, each grain sizes and each mineral type. If not taken care of, this may lead to systematic age offsets of up to 20-30%

Stability of luminescence signal: Stability of luminescence signal over geological storage times depends on the configuration of defect centers that participate in luminescence process. For quartz, fortunately the stability is seemingly robust, but for feldspars a spatial configuration of defect states, leads to anomalous loss of charges from deep traps, that normally would need higher stimulation energies for eviction. This is variously called as anomalous, athermal or quantum mechanical fading and if not corrected for, leads to underestimation of D_e. Correction procedures based on laboratory based time lapse measurements are used to estimate such a loss and currently this is an active topic of research for further refinement in procedures (Huntley and Lamothe, 2001; Kars and Wallinga, 2009; Morthekai *et al.,* 2015).

Changes in luminescence sensitivity: The luminescence sensitivity of a grain depends physico-chemical environment of mineral formation and on its thermal, optical and radiation history. A discussion on this is beyond the scope of this contribution, but unaccounted changes in sensitivity can cause systematic offsets in ages. These need additional experiments and analytical care, (Singhvi *et al.,* 2011; Chauhan and Singhvi, 2019; Singhvi *et al.,* 2021).

Sharma *et al.* (2017) used IR spectroscopy and photoluminescence to suggest that ten orders of change of luminescence sensitivity of quartz could be explained by the changes in OH radical in the lattice. This work opens up ways to firmly establish the provenance of sediments and in this context, the reader is referred to Sawakuchi et al. (2011, 2018).

Heterogeneity in photobleaching: Normally photobleaching is an efficient process and a few minutes of daylight or even equivalent moonlight exposure is sufficient to bleach the pre-existing luminescence to a residual, near zero level. Key determinants for bleaching are the energy of light flux and flux. Thus, for aeolian sediments that are transported sub-aerially, a total bleaching (i.e., bleaching to the extent possible), can be reasonably assumed. However, for fluvial sediments transported under high sediment load, the net daylight flux available to them is attenuated both in respect of spectral features of day light and its flux due to attenuation through water depth and sediment load that affects the net transparency.

Therefore, in general bleaching can be both partial and heterogenous. Such samples are dealt with various statistical protocols and appropriately reported. One of the often used practice is the analysis of a modern samples with an implicit zero age deposited at the same place and under similar depositional environment and use the results on such sample to interpret/correct ages on older samples. The other approach is to obtain a distribution of ages on a large number of grains and then use statistical procedures to compute ages based on most bleached grains (Galbraith and Roberts, 2012 and reference therein).

Gleying of samples is an issue for consideration, as the coating of iron oxides attenuate the flux of daylight into the grain volume and this impedes the bleaching process. It therefore becomes essential to ascertain if the gleying occurred pre deposition and post deposition to obtain a meaningful age. Several criteria, such as the presence/absence of well-formed clay minerals, are used to establish the implication of gleying. A minor but noteworthy factor is co-precipitation of U with Fe and its import on radiation flux, (Singhvi et al. 1986).

4d. Interpretation of Luminescence Ages

Numerical ages from any of the methods are merely numbers that provide a quantitative measure of the changes in a physical, chemical or biological attribute of a given sample. That they relate to the age of sedimentation, needs to be established *a priori* by establishing the relationship (syn-sedimentation) of the parameter/sample being measured, with the sedimentation process. This is generally non-trivial. In radiocarbon the age of sediment is inferred from the organic matter (of unknown/mixed provenance) associated with it with the assumption that the organic matter embedded in it was contemporary. It is now known that this assumption may not hold always. On the other hand, luminescence dating is the only method that provides direct dating of sediments. It dates the burial event of sediments using the very grains that constitute it. The event dated is the combined event of, deposition and preservation, as it is the preserved sediment that becomes available at this time for dating.

Creation of sediment record on land is a complex process as it combines a sequence of sediment creation, its transport and the transport capacity of the medium, and eventual preservation (Kocurek, 1998; Kocurek and Lancaster, 1999). What is dated is the preserved record and this event may occur several ka after the creation of sediment and presence at the present site after multiple cycles of transport - burial - preservation - excavation - transport and burial. Given the efficiency of bleaching of luminescence, only the most recent cycle is dated.

While sediments could be generated in a given climatic setting, its transport (sediment supply and carrying capacity of medium) and preservation are governed by both ambient climates, shift in climate variables and other factors such as vegetation. For example, in the case of aeolian sands of the Thar Desert, the preserved sediment reflects a transitional climate from arid to semi-arid to semi humid. This aspect of preservation implies that, *sensu stricto,* any effort to establish a direct correlation between similar landforms in different region with different preservation potential and sediment supply may not be tenable as will be elucidated later (Kocurek *et al.,* 2003; Singhvi and Porat, 2008).

Similarly, the interpretation of a soils with A, B or C horizons requires cognizance of in-situ pedoturbation of A horizon as the soil formation process may continue for several ka post sedimentation. Thus, the age of an A-horizon may be several ka younger than the underlying B or C horizon, (Bateman *et al.,* 2003; Singhvi *et al.,* 1987). In the case of loessic sediment, slumping is a common occurrence and this if not taken in to account in the field, may lead to erroneous ages and inversions of age vs. depth. Techniques such as soil micromorphology in such cases can provide useful safeguards for secure sampling. It is worth recalling Ager (1973) that '*the stratigraphic record has lot of Holes. It's like a net tied together with Sediment…*' and luminescence dating of terrestrial sediments has confirmed this suggestion, over and again, with their implication for geological correlation over the time scales of its applicability.

4e. Varied Luminescence dating approaches and their interrelationships

Thermally stimulated luminescence (also called Thermoluminescence) is exhibited by both quartz and feldspars besides others (Sankaran *et al.,* 1983). This excitation leads to signals from both thermally and optically sensitive traps and for their use for the dating of sediments, appropriate correction is needed to get the signal from optically stimulated traps. No such correction is needed for samples that are heated but the analysis needs to take into account the supralinear growth of TL at lower doses.

By definition, OSL originates from photo sensitive traps and therefore no correction is needed for samples—either heated or unheated (daylight bleached) samples. Many variants of optically stimulated luminescence are used and classified based on the stimulation light (Fig. 1D). Thus, terms like GLSL, BLSL, VSL are common and imply stimulation through green, blue and violet light emitting diodes/lasers/filtered Xenon lamps, respectively. For feldspars, specific combination of defects additionally permits the use of Infrared light to stimulate luminescence and therefor the term IRSL is used. A recent variant is IR photoluminescence that deals with special mode of stimulation and observations on feldspar (Huntley *et al.,* 1985; Hutt *et al.,* 1988; Jain *et al.,* 2020).

Improvements in technology and in the understanding of the basic luminescence process helped develop several approaches for analysis so as to improve the precision and accuracy of ages. The first development was from the dosimetric stand point and the development of *fine grain* and *coarse grain technique*s. In the fine grain method, fine silt fraction (4 – 11 μm) are extracted and used and then it is assumed that they receive the full α-dose (Zimmerman, 1972). In the coarse grains >100 μm mineral grains are used with a narrow range of sizes due to dosimetric consideration, as the dose absorbed is dependent on grainsize (Fleming, 1970; Mejdahl, 1979). Most used grain-size ranges are 100 – 125 μm or 150 μm or 150 – 180 μm or 200 – 250 μm for single grains. For these grains, the outer 20 μm of α- exposed skin is etched and the interior is used with a reasonable premise that it received only the beta, gamma and cosmic ray doses. More recently, a proposal has been made to use large grain size such that both the α and β irradiated regions can be removed to get only the gamma irradiated central portion. The feasibility has been established but a routine use has not yet been published (Chauhan *et al.,* 2009).

In the fine grains, mineral separation is not easy and a composite signal from all the luminescing phases of quartz and feldspars is used, though some separation using combination of spectral/stimulation are often attempted. More refined efforts are used to isolate signals from individual phases by etching of feldspar fraction using extended treatment with silica saturated hydro-flouro-silicic acid or through prebleach of feldspar OSL using IR stimulation and then working with Quartz rich OSL (Jain *et al.,* 2001)

For the luminescence measurement it is possible to use either of, a) multiple aliquots to get a single age, b) several single aliquots or single grains to obtain a large ensemble of ages (one age each from an aliquot with few tens to few hundred grains or a single grain). The data from them are then analyzed using appropriate statistical protocols, (Galbraith and Roberts, 2012). Each of these approaches have their merits and demerits and lead to slightly variable precision. The choice of the most appropriate protocol depends on the sample, the depositional environment, sensitivity of the samples and the level of instrumentation. None the less, given the overall signal is the same, similar ages are to be expected from varied OSL protocols and with TL within the bounds provided by behavior of luminescence behavior. Statements to the contrary are not based on sound physics. In general, all of OSL and TL ages should be reasonably concordant and reliable within the precision they offer and any discrepancy should relate to a physical process.

It is eminently desirable to have a combination of a dating expert (normally a physicist) and the end user (the geologist), who together can decide on the protocol based on the field evidence and stratigraphical data of the samples. Likewise, interpretation of data needs a combined expertise.

The precision of a luminescence age depends on a combination of random and systematic errors and formal protocols are used to compute them. Random errors are sample dependent and comprise factors such as photon counting statistics in luminescence and radioactivity measurements. Systematic errors comprise errors in source calibration and the like. Aitken (1976), and Aitken and Alldred (1972) elucidate possible errors in luminescence ages and their treatment. Typical errors in luminescence ages are in the range of 5 – 10%. Marginally better than 5% can be aimed in some cases but these are the expense of significantly more measurement time. Typically, it takes a man week to measure one age and this calls for several systems to provide a reasonable dataset for interpretations. The foregoing may seem to suggest that precision of luminescence ages may be an issue but this is not so. For example, at 5% error level, the error in a 2020 ka sample would be 1 ka. This is to be compared with a high precision radiocarbon measurement of say 20±0.2 ka when taken through the calibration process that would lead to age range of 22671 - 21494, that is a net error margin of ~5%.

Ages are based on the year of measurement and as on date, there is no '*agreed to*' baseline date in reporting the ages, as in radiocarbon with 1950 as the base year. Thus, for a luminescence age measured in 2022, a systematic offset of 70 years is to be included for comparison with a calibrated radiocarbon age.

5. Luminescence dating in India

Luminescence dating of terrestrial sediments in India began within a few years to other initial efforts in the western world, notably with the pioneering work at the Simon Fraser University, the RLAHA in Oxford and the Risoe National Laboratory in Denmark. Those initial years of development of methods provided challenges (and thence opportunities), in terms of development and verification of protocols and of procedures to handle samples, to extraction of pure grains, to their pretreatment, to the measurement and calibration of luminescence. Several methodological developments were therefore attempted to deal with a variety of sediments and sedimentary contexts. Some of the noteworthy and contributions were in the realm of novel application, and methodological development. Ancient TL as a newsletter served as a medium to share such methodological observations with reasonable speed, without compromising on the scientific rigor of a peer review process.

In the realm of geomorphology, the dating of: desert sands, reddened *teri*-sands, dust from glacier and Antarctic ice, chemical precipitates (barites and gypsum, pedogenic carbonates, coastal carbonates), fulgurites, volcanic ashes, frost wedges and loess paleosol deposits were first developed at PRL. Many of these eventually led to conceptual changes in the interpretation of terrestrial records reminding of issues of threshold, response times, causality and correlation between records, and in regional geological correlations.

In terms of analysis methodologies, identification of luminescence providing minerals in archaeological pottery and sediments (Singhvi and Zimmerman 1979; Sutton and Singhvi, 1983), development of the total bleach method and ultimate partial bleach protocol, component specific normalization methods, procedure to deal with red sand deposits, protocol for correction for changes in luminescence sensitivity both for multi grain and single grains, modeling of heterogeneous distribution of beta dose and development of optimum analysis strategies for multiple aliquots, use of large grains, optical isolation of feldspar signal were important contribution made by PRL. Important contribution on feldspar dating methodologies were developed at BSIP and large scale applications programs across India are being carried out at WIHG, IISER Kolkata, GSI Faridabad, PRL, ISR and NGRI.

The following narration presents a broad brush overview of luminescence studies in India and their overall impact on understanding the evolution of Indian landscape such that chronology of sedimentary record of past 200 ka at many places across India is now available (Fig. 2). At places the record extends to almost 400 ka. The dated records now need

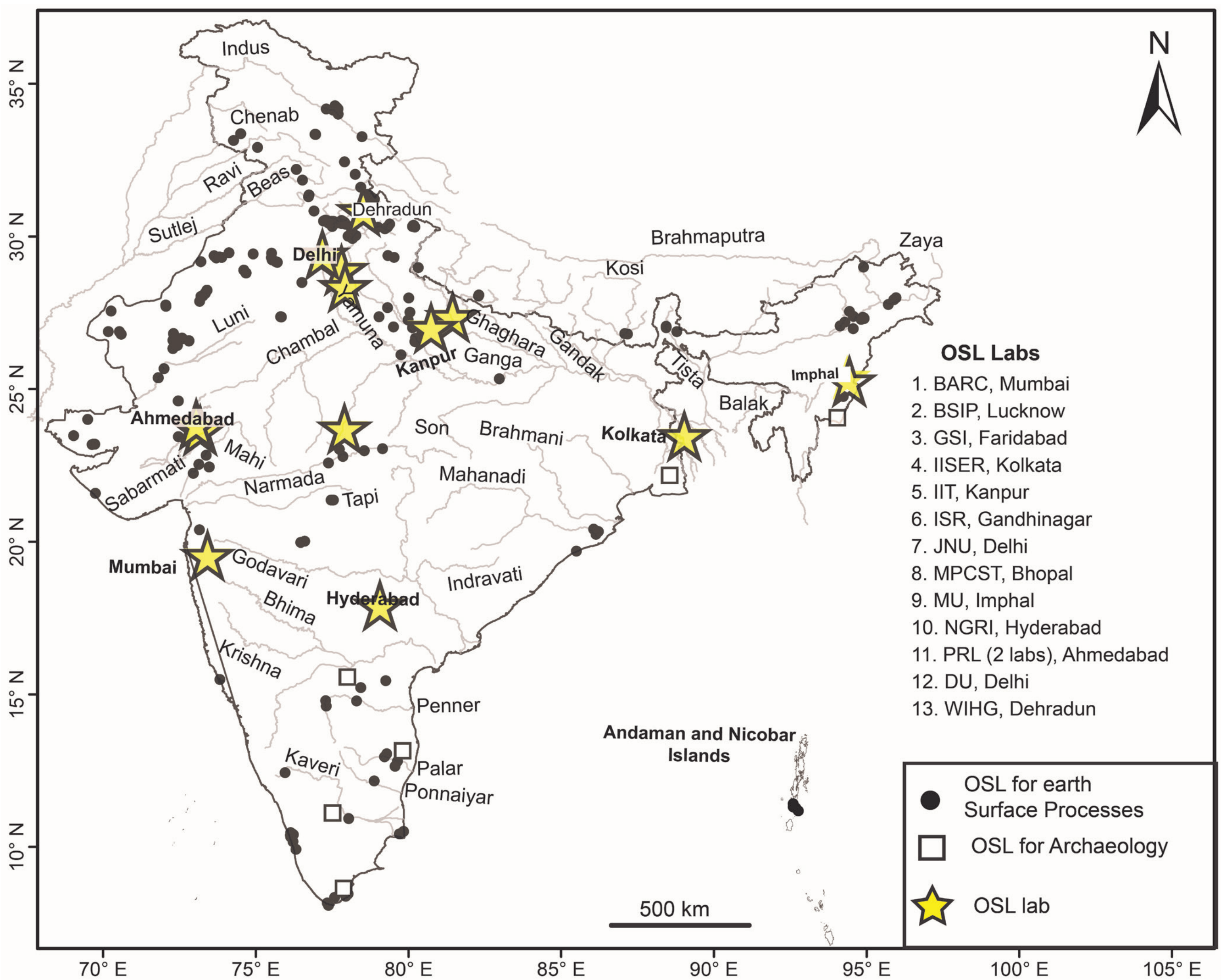

Fig. 2. Location of sites in India dated using luminescence. Location of OSL laboratories is also provided. An attempt is made to include data from all sources and any omission is inadvertent. This figure aims to provide an overview of the extent of luminescence dating facilities and applications across the country.

further enquiry in terms of sedimentary processes including sediment creation, transport and preservation, to deduce lags and leads in their deposition and preservation and thereafter in regional gradients in precipitation/temperature through time. These, when done rigorously, should inform the current monsoon modeling efforts and the relationship of foraminiferal proxies of monsoon winds in oceanic cores with regional and temporal variability of monsoon over land. In the following sections a brief, synoptic flavor of the dated records, their lengths and key events in them are presented for an appraisal of the evolution style of the Indian surface through time. No attempts to include every single data to achieve completeness, has been made as this is beyond the scope of the present contribution. Some future possibilities are also outlined.

5a. Aeolian Deposits: Desert Sands

Dating of aeolian deposits of the Thar desert provided a way to directly date the Desert sequences and to-date luminescence remains the only direct dating method. The method was established with the help of TL ages on dunes with archaeological contexts, that provided age controls (Singhvi *et al.,* 1982a). The initial results used fine grains and thereafter were confirmed using coarse grain, suggesting that the fine grains do not move downwards in a dune matrix.

There after a major fraction of work arose from an intensified high priority research area program (IRPHA) on Thar Desert funded by the Department of Science Technology, Govt. of India. This multi-institutional program comprised varied disciplinary experts from Deccan College, Pune University, University of Delhi, Central Arid Zone Research Institute (CAZRI), Bhabha Atomic Research Centre, the Geological Survey of India western region and PRL. This group focused on the antiquity of the Thar Desert in the context of its suggested spread towards Delhi during the recent times; chronology of dune building phases; past extent of the Thar Desert; and its relationship to climate. This study provided first results on the long-term evolution of the Thar and the results are summarized in a special issue of the Journal of Earth System Science, (Singhvi (Ed.), 2004;

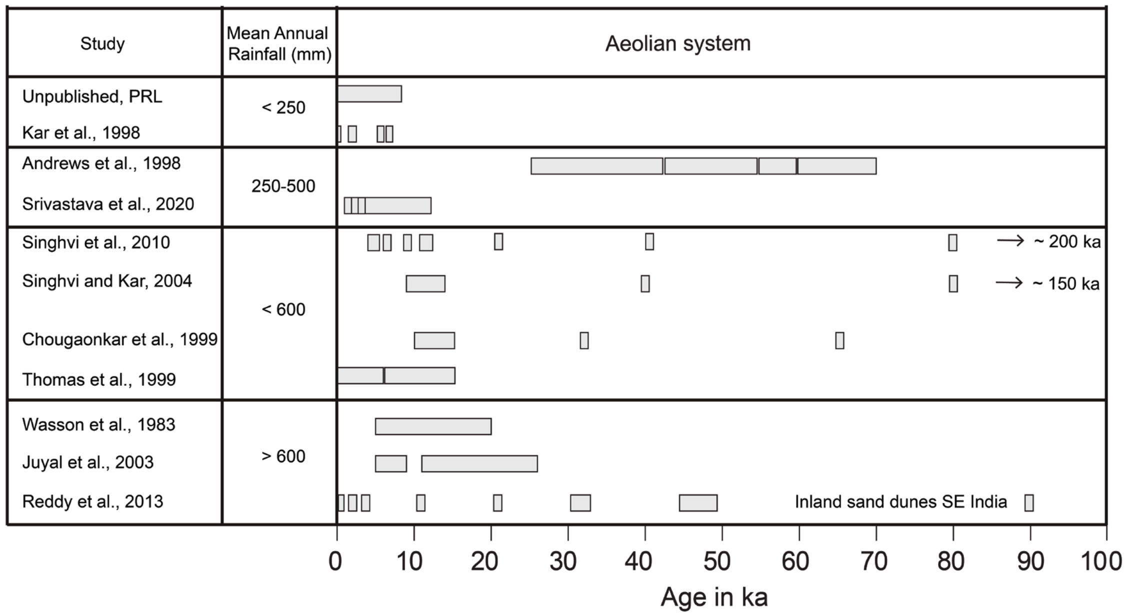

Fig. 3. Chronology of aeolian sand records across India. Notice the fragmented nature of the record that suggests regionally variable controls on sediment accretion and preservation mostly during the transition from drier to wetter phases

Fig. 3). More recent work by the Oxford and PRL groups provides data on the western Thar, a region that was inaccessible during the late 1990s. The aeolian records reveal following important inferences:

1. Thar desert is of geological origin and the suggestion of its being of anthropogenic nature is untenable. This is based on ages of >150 ka on dune sands (Singhvi *et al.,* 2004, 2010). Thar provides amongst the oldest dune record, anywhere and is perhaps due to its being at the eastern end of Saharo-Arabian desertic belt, offering perhaps higher preservation of dunal sediments.
2. The dune accretion in the Thar was episodic and peaked during a transitional climate from glacial to interglacial. The episodes of sand accretion occurred broadly at ca. 190, 130, 80, 40, 13 ka. The window of opportunity for dune accretion was of a short duration and typically should have spanned 10% of time. At most other times, no net accretion occurred and numerous episodes of landscape stability led to soil formation/carbonate leaching.
3. A window of optimum conditions for sand transport, accretion and preservation occurred during ca. 13 ka, when an optimum a combination of sediment supply, winds (associated with the monsoon that was re-established around 13 ka), and preservation through minimal but finite vegetation cover. At other times, stronger winds or higher vegetation impeded sand mobility, accretion and preservation.
4. Thus, in terms of creation of sedimentary record, for most of the time including the last glacial maximum. Thar was geomorphologically dormant in respect of dune accretion. At other times, winds were either too high to permit their accretion/ preservation, or the vegetation was too high to permit sand deflation. An alternative possibility could have been low winds and low vegetation cover. This observation implies the presence of geomorphic response time and thresholds, and that the process acceleration occurs during transitional climate and a phase lag of several ka from peak aridity phase at the last glacial maximum. This was an inference that contrasted with conventional wisdom of associating sand with peak aridity.
5. Average time interval between successive accumulation and preservation episodes was 19 ka, suggesting precessional influence on dune construction activity. If the interpretation of the association with monsoon is correct, the dune construction episodes suggest that wind/vegetation condition at the earlier time periods of dune construction were similar to that at 13 ka leading to a potential use of dune chronology for paleomonsoon reconstruction. This climate specificity of dune construction is also seen by the stable isotopes analysis of traces of organic matter from within the dunes (Singhvi *et al.,* 2010).
6. Asynchronous dune construction activity in the Thar and in other deserts also implies that albedo changes due to expansion and contraction of deserts was more complicated- both in respect of spatial extent and timing, and was possibly smaller than assumed so far, (Singhvi and Porat, 2008).
7. During the Holocene, short duration dune preservation record occurred at 7, 5, 3.5 and 2 ka (Srivastava *et al.,* 2019, 2020; Durcan *et al.,* 2019; Thomas *et al*. 1999).
8. A phase of dune accumulation on NE Thar margin during 18-12 ka (Saini and Mujtaba, 2012).
9. The Thar is currently in a contracted state and that its past extension during 14 ka and 6 ka were higher. Luminescence dates permit delineating of past extensions of Thar desert, (Juyal *et al*., 2003).
10. The dune migration rates accelerated up to ten folds in areas of human activity compared to geological past, largely due to the removal of vegetation cover; (Kar *et al*., 1998).

11. In the peninsular India, Reddy *et al*. (2013) dated sand dunes of aeolian origin in the Andhra Pradesh (SE India) with sands are locally derived from the Nellore schist belt. The physiography and wind pattern in this area promoted the dune aggradation from present to ~50 ka with 9 age clusters, indicating long phases of dune building, reworking of sand grains and a fluctuating climate
12. Studies by Lancaster *et al*. (2002), Glennie and Singhvi (2002) used remote sensing and dune chronology measured at PRL to establish long term surface wind patterns in Arabia and Western Sahara. Such studies in Thar have so far not been conducted but general dune trends based on surface features suggest a constancy of wind regimes. Processes leading to multiple dune types in Thar however, do need further elucidation.
13. Dating of fulgurites and stable isotopes of microliters of gases trapped in glass matrix, permitted its use for quantitative paleo-ecological tool and is currently being explored in Sahara (Navarro-Gonzalez *et al.,* 2007).

5b. Aeolian Deposits: Loess-Paleosol sequences

Loess – paleosol sequences are considered to be the most complete terrestrial records of climate change that can be compared with oceanic and ice core records and a large effort has been made to deduce their chronology based on proxy correlations. *Ipso-facto* these correlations have implicitly assumed that the deposition of loess was as continuous as sediments in the ocean. Presence of paleosols however imply phases of landscape stability for soils to develop.

1. Detailed analysis of luminescence chronology on a global basis, indicated that loess accumulation was episodic, postdated glacial epochs, and regional gradients in the depositional patterns, did exist, (Singhvi *et al.,* 2001). Large time gaps of several 10's of ka between successive accumulation events exist and variability of sediment supply by an order of magnitude was also inferred. This led to a major question of land-sea correlation that have been attempted and inferred in countless publications.
2. In the context of loess in Himalaya, extensive paleopedological work on loess paleosol sequences of Kashmir by Bronger *et al.,* (1987), supported by TL chronology Singhvi *et al.,* (1987), suggested that the loess accumulation was at least 4 interglacial cycles old. This was based on the interglacial age of the first pedo-complex with well-developed Bt soil complex and the presence of four such complexes.
3. This work also indicated that most radiocarbon ages on bulk samples were grossly underestimated by a factor of two or three and cannot be relied upon. Other similar studies in Carpathian basin of central Europe, led to a revision of several stratigraphic *leitsatze* and interpretations (Singhvi *et al.*, 1988).
4. In Kashmir, subsequent studies by Babeesh *et al.,* 2017 and Shah *et al.,* 2021 provide ages of ~15 ka for the upper part of loess paleosol deposits of Kashmir.
5. In the upper Ganga catchment, central Himalaya, variability of ISM in last 20 ka resulted in three phases of loess deposition and followed by pedogenesis (Pant *et al.,* 2005).
6. In Ladakh Kumar *et al*. (2017) dated Aeolian sand ramps and suggested aridity and aeolian activity in Ladakh during 25–17 ka and <12–8 ka.

5c. Frost Wedges in loessic contexts

In a linked study (Porter *et al.,* 2001), frost wedges deposits in Tibet were dated using bounding loess deposits – the silt in which the frost wedges developed and the silts deposited inside the wedge. These permitted the dating of wedge forming event. Given that such frost wedges form underground temperatures of -8°C, it implied that at ~ 15 ka, the ground temperatures were a 4°C lower than the present, making luminescence as a tool for quantitative paleo-thermometry via frost wedges.

5d. Fluvial Sequences

River systems sustain civilizations serving as a lifeline to billions. This is possible through distribution of materials from source regions to downstream buffers and sinks, thus creating and modifying landscapes. Preserved fluvial sections are slices of time that inform about environments in the past including extreme events. In India a good volume of data on chronology of fluvial deposits are available. An estimated ~1000+ luminescence ages across the country exist and their broad import is discussed below. For ease of discussions, rivers in Himalaya are separated from those in other regions.

Rivers – Himalaya

The Himalaya hosts several rivers, viz. the Indus, Sutlej, Yamuna, Ganga, Ghaghara, Gandak, Kosi, Tista, Kameng, and Brahmaputra being the larger systems. These rivers are fed by the southwest monsoon, westerlies, and glacier melt. The annual rainfall across the Himalaya varies from few hundred mm (in the rain shadow zones north of the Higher Himalaya) to >1500 mm in the windward side of the topographic divides along the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT). Parts of northwestern and eastern Himalaya experience annual rainfall of >3.5 m (Bookhagen and Burbank, 2006). In general, the mean annual rainfall increases from the west to the east. Apart from climate, tectonics sculpts the landscape in the Himalaya. Frequent landslides and other mass wasting processes serve as a large sediment source zones and the sediments transported by the rivers are buffered as valley-fill deposits, fans, surfaces in the mountainous part, and are distributed in the foreland plains before reaching the seas. Sediment movement occurs through multiple cycles of deposition and erosion, determined by sediment supply and stream power. Luminescence ages, facies analysis, and geochemical proxies helped elucidate phases of aggradation, incision, fan building, damming and failures, intensification of mass wasting processes (Fig. 4). These events have been variously related to intensification / weakening of weather systems, viz. the summer monsoon and the westerlies along with changes in glacial melts and tectonics.

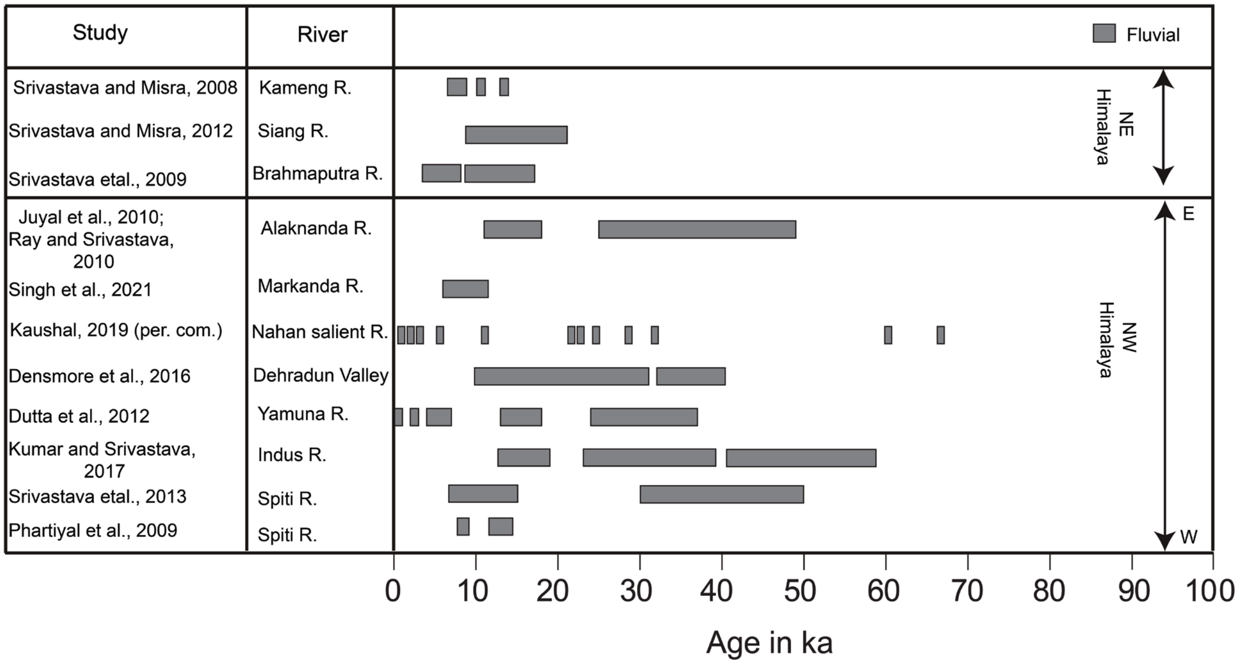

Fig. 4. Chronology of fluvial sediments from different rivers in the Himalaya. Post 10-8 ka incision is suggested by some authors (e.g. Ray and Srivastava, 2010; Srivastava *et al*., 2009) due to increased rainfall resulting in both erosion and evacuation from the hinterland areas. Alternatively, works (Juyal *et al*., 2010) correlate incision in the central Himalaya with reduced rainfall post 8 ka. Process wise both the suggestion can be reconciled to represent two time slices where amplified changes in sediment generation and their subsequent deposition/ transport/ evacuation depending on the hydrological efficiency of fluvial systems. In addition, other studies (Kaushal, 2019, PhD Thesis; Srivastava and Mishra, 2008, 2012) have attributed tectonic control over incision and deposition in the hinterland that has formed different levels of terraces.

1. OSL dating of sediments in the trans Himalayan river valleys viz. Indus, Zanskar, Spiti and Baspa river valley sections provide sedimentary records of past 50 ka. During this period, increased sedimentation and aggradation between 50 to 20 ka period occurred, (Srivastava *et al.,* 2013b; Bloethe *et al.,* 2014; Phartiyal *et al.,* 2015; Kumar and Srivastava, 2017; Dutta *et al.,* 2018; Jonell *et al.,* 2018; Chahal et al., 2019; Fig. 4). In the Indus River phases of sediment aggradation occurred during 79-46 ka and in pulses during ~52, ~28, and ~16 ka (Kumar and Srivastava, 2017; Mujtaba *et al.,* 2017; Lal *et al.,* 2018). Further, using OSL chronology of fault gouges and deformed sedimentary units in Ladakh, a model of neotectonic deformation of Himalayan hinterland is proposed (Kumar *et al.,* 2020).
2. Cosmogenic ages of >200ka for terraces and moraines of in the upper Indus valley have been reported and a net incision between ~200 – ~50 ka has been suggested, (Owen *et al.,* 2006; Blothe *et al.,* 2014). Sequences from Leh and Spiti regions formed through impoundments and lake formations, provide sedimentation history from ~177 ka to 6 ka with aggradation phases at ~177 ka – ~72 ka, 50 – 30 ka and 14 – 6 (Phartiyal *et al.,* 2009 a, b; Blothe *et al.,* 2014).
3. In the upper Ganga valley, sedimentation history of past 50 ka is recorded as valley fill sequences. Phases of sedimentation during the 49 – 25 ka and 18 – 11 ka have been used to suggest stronger monsoon (Srivastava *et al.,* 2008; Ray and Srivastava, 2010; Juyal *et al.,* 2010) coupled to an increase in sediment supply post deglaciations along with changes in the hydraulic efficiency.
4. OSL chronology from Yamuna valley and its tributary in the sub-Himalaya witnessed two phases of aggradation between >37 to 12 ka (Dutta *et al.,* 2012). Both the Ganga and the Yamuna basins provide evidence of aggradation during the transition from a glacial climate to warmer regime and incision of valley fill at ~11 ka due to reestablishment of monsoon by 13 ka onwards.
5. The intermontane valleys (dun) in the Himalaya have a sediment record of 100 ka with alternating phases of aggradation and incision. In the Kashmir valley, Jaiswal *et al.,* 2009b, dated tectonically created terraces to between 100 – 11 ka. In Pinjaur dun phases of fan aggradation occurred between <96 – 24.5 ka and their incision around ~74 and 20 ka (Suresh *et al.,* 2007); in Dehra Dun, fan deposits were dated between 43 –11 ka and at 3 – 2 ka (Singh *et al.,* 2001; Densmore *et al.,* 2016; Sinha and Sinha, 2016; Fig. 4). In the central Himalaya at Chitwan dun, fan aggradation during >112 ka – 25 ka, and at <18 ka has been reported (Divyadarshini *et al.,* 2020). Aggradation phases in the duns were followed by phases of incision and non-deposition at times were marked through soil formation.
6. In the eastern Himalaya, terraces between Mal and Murti rivers preserved a history of >170 ka (Singh *et al.,* 2016). The oldest aggradation phase occurred between 171 to 72 ka, followed by phases between 59 – 6 ka. Similarly, along the Tista River three paired terraces formed between 44 ka to the present (Singh *et al.,* 2017). Along the rivers from the NE and eastern part of Himalaya (Brahmaputra, Tista, Kameng, Kali and Siyom rivers) incision after ~7 ka is taken to suggest strengthening of monsoon, (Mukul *et al.,* 2007; Srivastava and Misra, 2008; Srivastava *et al.,* 2009).

7. Kar *et al*. (2014) investigated the Maitali fan, one of the coarse-grained mountain-attached fans at the foothills of the Darjeeling Himalaya that was initiated around 34 ka, then abandoned and incised during the 24-18 ka followed by a renewed terrace aggradation around 15 – 5 ka.

Rivers- Peninsular India

1. In the peninsular India, both the east and west flowing rivers form coastal plains, Gujarat plains and badlands in the central part of India. These rivers are fed from the summer monsoon and in the absence of significant tectonic forcing (with some exceptions, Bhattacharjee *et al.,* 2016) becomes the key determinant for the evolution of landscape. In the Thar desert, dated sequence spans 400 ka along the Luni River and detailed facies analysis, isotopic studies, geochemistry unravel phases of arid and humid climates with aggradations between 50 – 30 ka (Kar *et al.,* 2001; Jain and Tandon, 2003; Fig. 5), followed by dormant / arid phase that ended ~14 ka ago. The Holocene witnessed increased fluvial activities and minor phases of aeolian aggradation, (Kar *et al.,* 2001; Jain *et al.,* 2005).
2. In the central Thar, at the Nal Quarry site, signature of fluvial activity around 172-174, 140-150, 79-95, and 26 ka, suggest dynamic fluvial landscape and its implication of modern human dispersal from Africa to Asia during the late Middle Pleistocene and early Late Pleistocene (Blinkhorn *et al.,* 2020).
3. In the southern Thar, in the Sabarmati river basin, Tandon *et al*. (1997) reported a sequence of gravel, sand, sediment deposits of > 300 ka age with pedogenesis at 58 – 39 ka. In the adjoining Mahi and Sabarmati rivers, Juyal *et al.* (2000) and Srivastava *et al.* (2001) recorded aggradation between 50 – 30 ka. Incision events due to tectonic activities are recorded in the form of scroll bars during 12 – 5 ka (Srivastava *et al.,* 2001). In the Banas and Saraswati river basins, aggradation between 18 to >12 ka, followed by phases of incision in the Holocene have been related to monsoon (Bhattacharya *et al.,* 2017).
4. Along the Par river in the western India, formation of a chute canyon was investigated by Patil *et al.,* 2021. The sediments from the older chute cut-off were dated ~20 ka, indicating the present day chute canyon formed in later period. Studies around the buried Saraswati paleochannel reveal major phase of fluvial aggradation in this area has occurred during >28 ka (Saini and Mujtaba, 2012). Further, post-LGM period in this region is marked by intermittent phases of wet and dry periods (Saini and Mujtaba, 2010). A channel of Sutlej feeding palaeo -Saraswati dried up 8 ka near its confluence with Ghagghar-Hakara, while the Saraswati itself dried up about 12 ka near Kalibanga (Singh *et al.,* 2016; Tiwari *et al.,* 2021).
5. Based on OSL ages samples from deep river bed in the Chautang river basin, Dave *et al.,* 2019, disproved the link between large settlements and large rivers by conclusively establishing that major fluvial systems in this basin ceased to exist around 40 – 45 ka and the transition to present ephemeral state occurred around 24 ka and with the exception of dune activity, the landscape has not materially changed. The Harrapan cultures are dated for ca 5 ka BC and therefore the entire debate on R. Saraswati and its association with cultures, is on misplaced associations and interpretations.
6. In the Ganga plains, periodic aggradation in the Ganga-Yamuna interfluve area between 90 – 20 ka, and incision during past 20 ka have been reported (Srivastava *et al.,* 2003a, b; Gibling *et al.,* 2005, 2008; Fig. 5). A

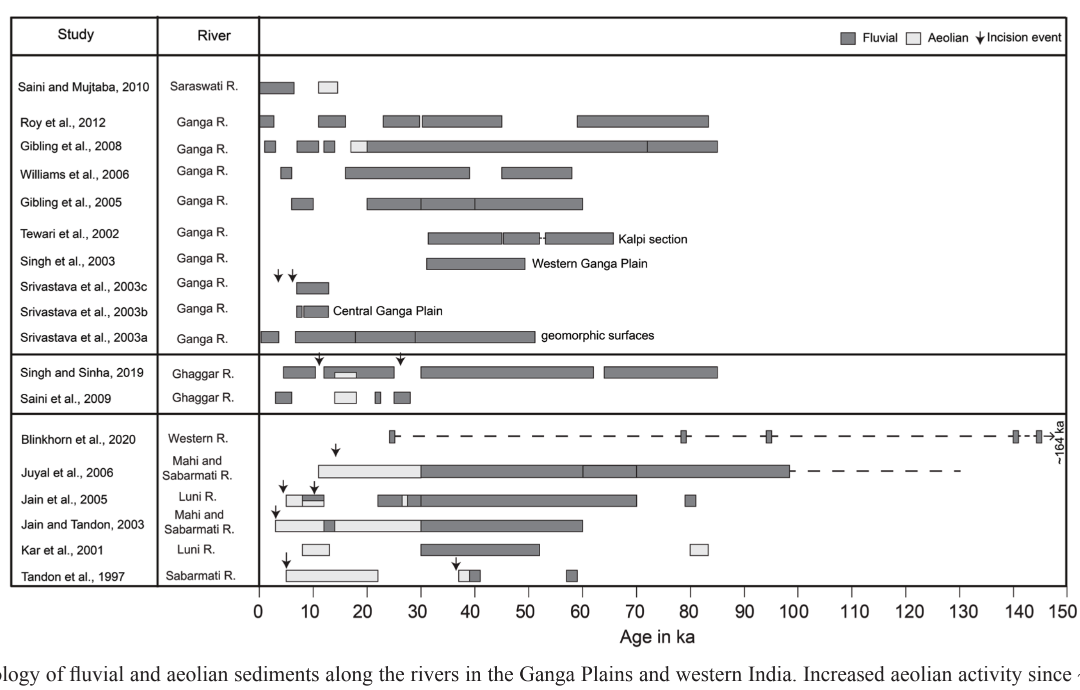

Fig. 5. Chronology of fluvial and aeolian sediments along the rivers in the Ganga Plains and western India. Increased aeolian activity since ~30 ka suggest transition from humid to more arid phase. Further, a shift of few ka in the preserved sediment record between western India (~30 ka) and Ganga Plains (~25 ka) suggests regional controls in preservation. It will be of interest to see older record from Ganga plains but this may not be easy, given the evidence of rapid syndepositional subsidence of Ganga basin during 50-10 ka (Singh *et al*., 2003).

thin reworked gravel layer indicative of reduced river discharge and increased gully erosion was suggested to mark the conditions during the last glacial maximum. Luminescence ages by Sinha *et al.,* 2007, suggest southward migration of the Ganga River during 11 – 6 ka near Kanpur. An incision is seen across the Ganga plain around 8 – 7 ka (Shukla *et al.,* 2012). This is ~3 ka later as compared to that in the Himalaya (Ray and Srivastava, 2010) and implications of such differences in incision need further studies.

7. In the marginal Ganga plain, badlands formed along Yamuna and its tributaries preserve sedimentation records older than 110 ka. Several sections investigated by Ghosh *et al*. (2018, 2019) and Sinha *et al*. (2009) along the Yamuna and its tributary river Betwa reveal three phases of deposition. The oldest phase deposited at >110 ka, followed by a ~30 ka of hiatus, and a middle phase at around 80 – 54 ka. The last phase of deposition occurred during 54 – 14 ka (Ghosh *et al.,* 2018, 2019). Incision and ravine formation postdates the last phase of deposition.
8. In the Palar river basin of south India, Resmi *et al*. (2017a, b) identified two phases of channel migration between 5 – 2 ka due to climatic and tectonic forcings (Fig. 6).
9. Sediments eroded from the continents are destined to reach the sea in various time interval. Stratigraphic records from river deltas formed because of sedimentation near the river mouth not only reveal activities related to tectonics and climate in the hinterland, but also sea level changes. A sediment core investigated by Goswami *et al.,* 2019b reveals >150 ka of integrated history of the Kaveri delta in the southern part of east coast India. Eight phases of sedimentation identified by them correlates with interglacial periods and sea-level high stands.

5e. Palaeoflood Deposits

Dating of slack water deposits (SWDs) and flood out deposits (FODs), helped re-construct paleohydrology of extreme events across India (Cornwell, 1998; Kale *et al.,* 2003; Ray and Srivastava, 2010; Juyal *et al.,* 2010; Wasson *et al.,* 2013; Kale *et al.,* 2014 Srivastava *et al.,* 2017). Fig. 7 provides a synoptic view for the OSL ages of slack water deposit in different areas and suggest that the hydrological regime was different from that of the present. Synthesis by Kale *et al*. (2003) and Srivastava *et al*. (2017) suggest that changes in monsoon intensity determined the hydrological characteristics of the rivers.

Key inferences are:

1. Major flood events at ~37 ka and ~43 ka in the Chenab River were reported by Coxon *et al*. (1996). The Indus river at the Indus-Zanskar confluence, Ladakh, exhibits at least 14 large paleofloods during 14-10 ka 11-10 ka. (Srivastava *et al.,* 2017; Sharma *et al*., 2022; Chahal *et al*., 2020).
2. In the Garhwal Himalaya, floods events occur due to glacial or landslides lake outburst. The important paleo–flood records from the Alaknanda-Mandakini River indicate four flood events between ~5.4 to 1.4 ka, suggesting a wet and warm Climate. (Srivastava *et al.,* 2017). It is noteworthy that during more recent times, flash floods events have increased in the Upper Ganga basin (Wasson *et al.,* 2013).
3. The Alaknanada experienced the 1970 mega flood. This flood led to the famed *Chipko* movement that implicated deforestation of lower Himalaya being the cause for floods. Using Sm/Nd systematics and optical ages, it was shown that 1970 flood carried more sediment from higher Himalaya compared to lower and a similar event occurred some 800 years ago. This observation put to question, the scientific foundation of Chipko movement, and provide a caution of such mega floods being of geological origin, and being once in a millennia event (Wasson *et al.,* 2008).
4. In the NE Himalaya, the Brahmaputra River experienced mega floods between 8 and 1 ka. (Panda *et al*., 2020; Srivastava *et al*., 2017). In the Namche Barwa massif five mega flood along the Siang valley at 14.5 ka, 7 ka, 3.5 ka, and 2.2 ka occurred due to lake failures (Borgohain *et al.,* 2020). This work suggests that catastrophic flood events more likely helped in exhumation of the Namche Barwa along with tectonics as discussed later.
5. In the Sub-Himalaya, the Ghaggar-Hakra paleochannel in the upper reaches (Markanda River) witnessed flooding during ~4.6-3.9 ka (Singh *et al.,* 2021). These flood deposits helped to estimate the paleogeometry and paleohyrology of the Markanda River.
6. In Western Gujarat, floods in the past due to sudden extreme rainfall events at 9.2 ka with flood events at 500 a and 288 a are reported (Sridhar *et al.,* 2013).

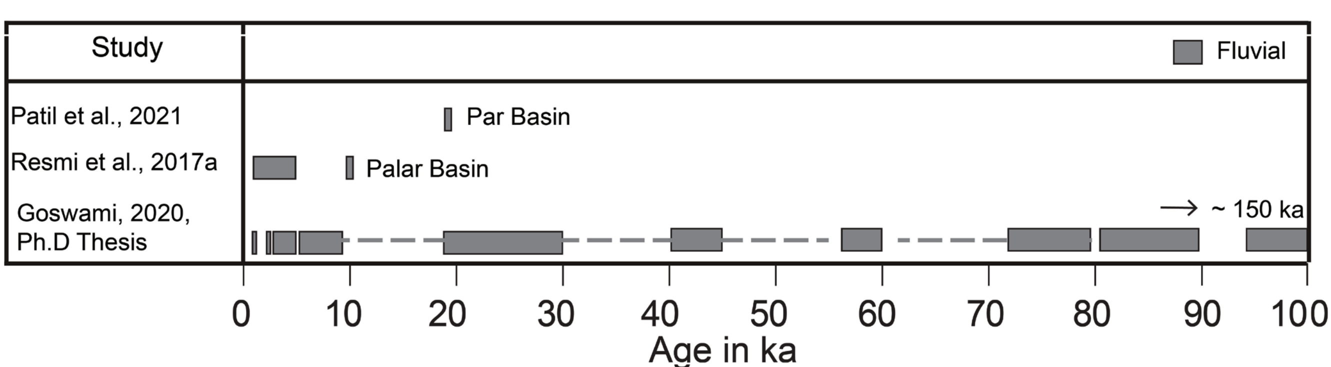

Fig. 6. Chronology of fluvial sediments along the peninsular rivers. Goswami (2020, PhD thesis) has found intermittent records of sedimentation in the Kaveri delta region since last ~150 ka. The phases of deposition seem to correlate with higher sea level stands.

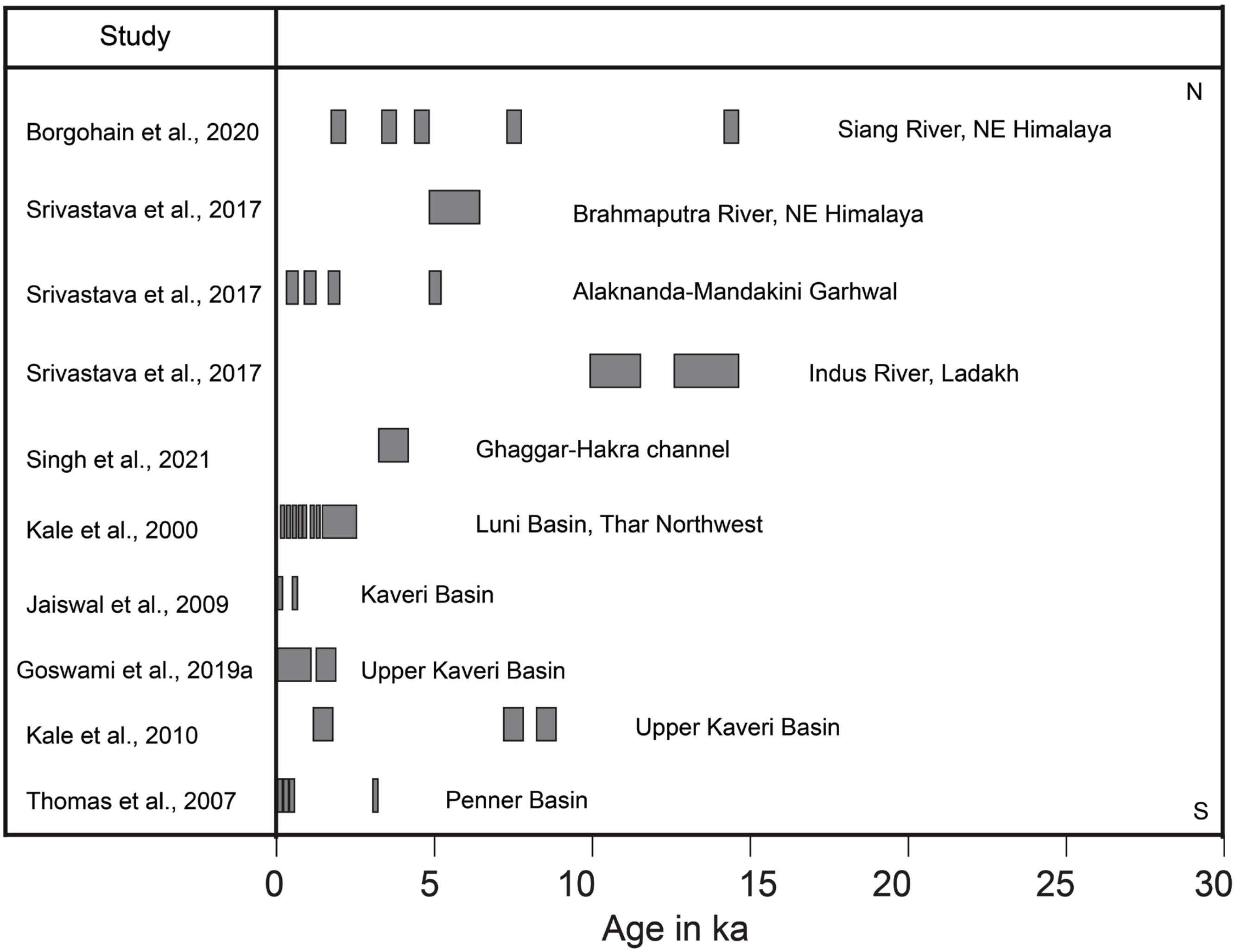

Fig. 7. Summary of dates on slack water deposits along the different rivers. This record suggests asynchronous phases of higher rainfall across India.

7. The River Luni of the Thar Desert experienced 17 extreme floods during the past millennium (~800 years, Kale *et al.,* 2000). Three major incision events occurred around 14 ka, 11-9 ka and 3-1 ka as monsoon intensified and rivers were dynamic during 14-11 ka. Luni river had also experienced sheet flood deposits around ~70 ka (Jain *et al.,* 2005).
8. The Peninsular rivers in cratonic southern India mark continuing denudation processes. It is suggested that all the major peninsular rivers (Narmda, Tapi, Godavari, Krishna, Penner and Kaveri) have bedrock gorges and canyons that store fluvial deposits. OSL dating of paleoflood sediments in the Upper Kaveri River shows six discrete sand-slit couplets dated to ~8 ka -2 ka (Kale *et al.,* 2010) and distinctly resolved flood cluster during the past two ka at 2380, 2370, 2190, 700, 190,170, 160, 90, 60, 50 years (Goswami *et al.,* 2019a). Such a clustering around 2.2 ka, 700 a, 170 a and <100 a, indicates towards meteorological explanation.
9. The upper Penner River exhibits paleoflood sequences around 3-2 ka and low or no floods between 2-1 ka indicating reduced rainfall activity (Thomas *et al.,* 2007). Floods records between 1 ka and 0.6 ka suggests stronger monsoon. This study suggests possible changes in rainfall during these periods, leading to enhanced hydrological activity in this basin (Thomas *et al.,* 2007).
10. In SE part of the Peninsular India (near Puducherry, Tamilnadu), flood events during 800-750, 300-280, 200-180, 120-100, and 50-60 years are recorded in the lower Kaveri, Paller, Gingee, Vellar basins (Mahadev *et al.,* 2019). Regional implication of these records needs further elucidation.

5f. Glaciers and Glacial deposits

Considerable efforts on dating of moraines using OSL techniques has been made. Issues related to bleaching of OSL signal exist, but higher UV radiation at high altitude, more transparent atmosphere and ice provide some assurance of adequate bleaching. Sampling of moraines is normally carried out from sand lenses within the moraines to simplify dose rate calculations. OSL dating of glacial deposits in Himalaya offer prospects of delineation of relative roles of ISM and mid-latitude westerlies in glacier advances/retreats. Glaciers can be dated directly through dust trapped in ice or indirectly through the moraines left by their retreat. The later has been explored and should inform on changes in the equilibrium line altitudes on a regional basis.

Direct dating of the glaciers was reported by Bhandari *et al*. (1983) on the premise that, i) during its fall, the snow traps traces of airborne due with it (< few mg/lit), ii) being airborne the dust sees sufficient light such that the luminescence of these grains is fully bleached; iii) on deposition the reflectivity of snow and then ice are high enough that the interior of glacier is dark beyond a meter depth (as confirmed by light attenuation experiments) and thereafter, iv) the grain accumulate dose from cosmic ray at high altitude, with no irradiation from an inert ice matrix.

Initial studies from Nehnar glacier gave ages in the range of 600 years, consistent with their depth and other estimates. This work did not progress further, as in those days, TL was the only method and the detection capabilities needed a few mg. of sample. However, with the possibility of using single grains for analysis this issue can be overcome and in principle a non-destructive analysis of OSL from dust grains in ice core should be a possibility. An area of concern will the estimation of cosmic ray dose that gets attenuated with ice over burden and with depth, when the ice moves downslope. While difficult, this work along with the use of in-situ produced radiocarbon dating of ice layers, could open up new avenues of research on long term behavior of ice sheets and glaciers.

Recent studies on lake and glacial sediments in the Himalaya, have used variously to infer the glacier sensitivity to the local, regional, and synoptic-scale climate records, as also understand the reason for discrepancies between the ages based on cosmogenic radioisotopes and OSL ages, (Ali *et al.,* 2013; Sharma and Shukla, 2018; Shukla *et al.,* 2020 and references therein).

Key inferences are:

1. Evidence of Glacial advances in the NW Himalaya occurred during 31-24 ka in Puche valley, southern Ladakh (Shukla *et al.,* 2020), during ~80-70 ka, ~22-19 ka, ~16-14 ka and ~6 ka in the southern Zanskar valley. Glacial stages of Suru basin are also dated (Kumar *et al*., 2021). These episodes of glacial advances were related to enhanced westerlies with decreasing magnitude (Sharma and Shukla, 2018).
2. In the Garhwal Himalaya glacial stages are established using OSL dated moraine stratigraphy. In Chorabari glacier (Mehta *et al*., 2012); Dokriani of Gangotri group of glacier (Shukla *et al.,* 2018); Tons valley (Mehta *et al.,* 2014); Dunagiri (Kumar *et al*., 2020b) stratigraphy of glacial advances is established. In the, Goriganga valley of the central Himalaya two outwash gravels were dated to 16-12 ka and 10-8 ka and taken as suggestive of a strengthened summer monsoon (Ali *et al.,* 2013 and references therein).
3. In the Spiti valley, relict lacustrine deposits formed due to landslide driven damming of the river in the upper-lower reaches were dated to 50-30 ka and 14-6 ka (Phartiyal *et al.,* 2009a). In the lower reaches, lacustrine deposits on the uplifted bedrock strath have been used to infer tectonic activity along the Kaurick Chango fault.
4. Inter-comparison of IRSL ages with radiocarbon ages of bulk organic carbon at Goting and Garbyang paleolake deposits, suggested that most radiocarbon ages in lime rich terrains were afflicted by hard water effect (Juyal *et al.,* 2004). Comparison of radiocarbon and IRSL was used to determine the contamination needed to produce stratigraphically inconsistent radiocarbon ages. The computed amount of contamination carried a clear climate signal (Beukema *et al.,* 2011).
5. IRSL dating at the Goting and Burfu-lakes in higher central Himalaya (Juyal *et al.,* 2009) along mineral magnetic and geochemical (total organic carbon and nitrogen) analysis suggested phases of stronger precipitation around 25 ka, 23.5-22.5 ka, 22-18 ka, 17-16.5 k, 14.5-13 ka (Juyal *et al.,* 2009).
6. Sediments from Burfu in the Goriganga Basin of central Himalaya indicate that lake was fed by glaciers during ~15.5-14.5 ka followed by warming phase between ~13.2 -12.5 ka, ~11.3 ka (Beukema *et al.,* 2011).
7. Lacustrine deposits at Malari near the Goting lake were dated to ~11.5 ka, ~11-10.5 ka, ~10-9 ka, and ~8-7 ka indicating the phases of stronger monsoon (Srivastava *et al.,* 2013a).
8. A phase of high frequency seismic events was inferred from deformed lake sediments dated to 20-13 ka and Juyal *et al*. (2009) suggested these to be indicative of tectonic activity along the Trans-Himadari fault (THF).
9. Pattanaik *et al.,* 2022 identified lacustrine sedimentations with intermittent fluvial deposits between ~22 – 10 ka in the upper Alaknanda Basin.

Overall, these data suggest that dating of glacial, relict lakes and fluvio-lacustrine sediments help to infer past regional climate triggers and forcing factors as well as provide ages of past seismic events. Sufficient body of data now exists, and there is a need synthesize them into synoptic level, regional changes in the ELA and their connection with climate - the monsoon and the westerlies. Furthermore, these findings suggest that the use of radiocarbon ages in limestone terrain need caution.

5g. Soils and Palaeo-seismology Earthquakes, tectonics and erosion/fluxes

Soils of the Indo-Gangetic Plains

Soils sustain human life and are an important component of the critical zone of the Earth. Soils across the India have been used to understand the pedogenic responses to climate change and tectonics. Previous studies (Srivastava *et al.,* 1994; Kumar *et al.,* 1996; Singh *et al.,* 1998) suggested that tectonics have played role in the development of soils and geomorphology of the Indo-Gangetic plains. As these plain areas have several faults and tectonic blocks, the dating of soil geomorphic units helped constrain tectonic events over the last ~10 ka. Kumar et al. (1996) showed contrasting soil development on either side of faults that suggested neotectonic activities. Pedogenic processes accentuated with increase in the tectonic movements of the fault bounded blocks, as uplift reduces sedimentation and promotes the pedogenic activity as the river flow diminishes.

Key inferences are:

1. TL dating by Vohra (1987) on fluvial sediment along the Solani River in Roorkee shows a development of two unpaired terraces around ~2.3 ka-1.6 ka. These unpaired terraces were generated due to fault activity during the past ~1.5 ka.
2. Development of soil and geomorphic units in the western part of Ghagghar, upland interfluves of the Yamuna-Ganga, Ganga-Ghaghara, Ghaghara-Rapti interfluves and some upland areas of deltaic plains (Kumar *et al.,* 1996; Singh *et al.,* 1998; Srivastava *et al.,* 2015 and references therein) were dated to suggest that faults in the Ganga basin were active at ~2.5 ka and at ~500 years. These caused the titling of Ganga-Ramganga Block to the SW (Kumar *et al.,* 1996). Formation of pedogenic calcite between the 10ka and 6.5 ka cal ^{14}C BP periods and luminescence age on calcretes in 11-9 ka soils, have been used to suggest to a drier climate. (Srivastava *et al.,* 1994). When compared with the record of Thar Desert lakes, these suggest an out of phase relationship in regional precipitation and such observations needs to be explored, further.

5h. Palaeo-seismology and Tectonics

In the Himalaya, one of the important geomorphic landforms is fluvial terrace that help understand uplift and convergence rate along the mountain front and tectonic evolution of fold-and-thrust belt (Wesnousky *et al.,* 1999; Lave and Avouac, 2000, 2001; Kumar *et al.,* 2006; Singh *et al.,* 2008; Thakur *et al.,* 2014; Kaushal *et al.,* 2018; Dey *et al.,* 2020). The key results based on luminescence age of displaced sediments are:

1. Methodological aspects of luminescence dating of past tectonic events through direct dating of faults were first established in the Himalaya on the premise that at time of faulting, grains experience heat and pressure due to movement along a fault (as two opposing rock blocks move past one another). During this process, high shear stresses cause frictional heating because of grinding and movement of the mineral grains. Assuming that both heating and deformation can reset luminescence signal to overall zeroing (Aitken, 1985; Fukuchi, 1992; Singhvi *et al.,* 1994a; Banerjee *et al.,* 1997; Porat *et al.,* 2007), dating of fault gauge in the Almora thrust suggested a major faulting event around 45 ka. Possibly this event led to the formation of lakes in that region (Nainital and adjoining areas).
2. Dating of fault gouges from the Tista River basin in which several faults had surface exposure provided fault movement age around ~45 ka, ~42 ka, and ~20 ka respectively for the Main Frontal thrust (MFT) zone, South Kalijhora thrust (SKT) zone and fault splay respectively (Mukul *et al.,* 2007). Dating of Strath terrace ages of the Tista River valley along with MFT fault zone age also indicated that MFT was active ~40 ka, and out-of-sequence deformation on splays to the north of the MFT started ~20 ka in the Darjiling Sub-Himalaya region (Mukul *et al.,* 2007).
3. A neotectonic activity is inferred at ~- 56 ka along the Jhajra thrust in the southeastern part of the Pinjaur Dun by dating geomorphic surface (Singh *et al.,* 2008).
4. Through the luminescence dating of alluvial cover on uplifted strath terraces in the Kangra valley, Thakur *et al*. (2014) estimated shortening rates of ~14 mm/yr across various active structures in the Sub-Himalaya, averaged over ~40-30 ka.
5. Mathew *et al*. (2006) inferred seismic activity along the Kachchh Mainland Fault (KMF). OSL age of tectonically incised fluvial terraces of Khari River is ~12 to 4.3 ka that provided average uplift rate of ~10mm/yr along the KMF.
6. Kundu *et al*. (2010) dated deformed fluvial terraces in the Khari River and reported that Katrol Hill Fault (KHF) was active during the past ~30 ka with average slip rate of >0.23 mm/yr.
7. Chronology of seismic events were also attempted using the dating of soft sediment deformations structures or samples from Sumdo area near Kaurik-Chango fault in the Spiti valley, NW Himalaya (Banerjee *et al.,* 1997). Luminescence dating helped delineate four major seismic events between 90-26 ka suggesting activation of Kaurik-Chango fault.
8. Juyal *et al*. (2004, 2009) and Rana *et al*. (2013) used seismites in the Dhauli Ganga, Gori Ganga and Kali Ganga river basins of Central Himalaya to suggested that the South Tibetan Detachment System (STDS) was active during 20-11 ka. This dispelled the notion that region has been tectonically dormant.
9. Direct dating of scroll bars in the Sabarmati River suggested incision due to tectonics between 12 and 4.5 ka with an evidence of increased fluvial efficiency. The timing of tectonic activity at Mahudi basin that led to shifting of River Sabarmati, was placed at ~3 and 0.3 ka (Srivastava *et al.,* 2001).
10. Incision and channel pattern changes in the Ganga River led Srivastava *et al*. (2003b) to infer phases of incision at about <6 and 4 ka. Different ages of the terraces indicated a differential erosion of surfaces, due to tectonic unwarping of the region.
11. Namche Barwa massif in the Eastern Himalayan syntaxis has records of mega floods that changed landscape morphology within very short times. Borgohain *et al.* (2020) investigated the impact of catastrophic floods in the Siang valley and identified, five major floods events at 14.5 ka, 7 ka, 3.5 ka, and 2.2 ka due to lake failures. Based on multiple evidences, it was inferred that floods at 7 ka and 3.5 eroded 71 m and 24 m rock mass from the Namche Barwa massif and the estimated denudation rate translated to 9 mm/yr. This is three orders of magnitude higher than the denudation rates average over million years (Borgohain *et al.,* 2020). This study pointed out that catastrophic flood events and tectonics both led to rapid exhumation of the Namche Barwa massif in the Eastern Himalayan syntaxis.
12. OSL ages have constrained seismic events at various parts of western foothills of the Himalaya such as 1.3-1.4 ka (Chandigarh), 9.5 - 1.6 ka (Hajipur), 2.4 - 2.5 ka (Ramnagar), 4.5 - 2.9 ka (Kangra) and >6800-4450 years in the Kachchh and ~1100 year - 800 year (south Andaman), 1.8 ka (Car Nicobar), 1.7 ka-1.8 ka (Arakan coast) in the Andaman area (Malik *et al.,* 2008, 2010, 2015a, 2015b, 2017, 2019). These have implied (i) recurrence interval of 1100 year for Hajipur events -

four paleo earthquake along the KVF fault in Kangra valley; (ii) three earthquakes across the South Wagad Fault (SWF); (iii) three earthquakes associated with tsunamigenic events occurred during past ~1000 years in Andman Island.

13. Jayangondaperumal *et al.,* 2017 dated an earthquake event at the back of the Janauri anticline in NW Himalaya, to 0.8 ka using displacement of the recent sediments.
14. Dating of sand dykes was developed on the premise that during their viscous flow during the injection of sediments as dyke, inter-grain friction heating occurs and is sufficient to reset OSL (Murari *et al.,* 2009; Singh *et al.,* 2009; Tyagi, 2007, PhD Thesis). These were supported by theoretical consideration and laboratory measurements for estimation of temperatures seen by the dyke sediments through the Predose sensitization of dyke. The ages ranged from 1.5 ka to 0.1 ka.

5i. Volcanic Ash

Volcanic tephra was amongst the first few materials for which luminescence dating was attempted; however, a major difficulty was their poor luminescence response due to low range of crystalline order of volcanic glass, athermal fading and the absence of sound theoretical understanding to correct for fading. With time, improvements of detection methods and new signals (in the red spectral region), permitted the application to directly date volcanic ashes. Use of elevated temperature post IR- IRSL studies on volcanic ash deposits from Toba ash deposits and optimizations of detections led to secure dating of Toba ash layers- identified using geochemical associations. Interestingly through geochemically identified as Toba ash, it was seen that only few ages were consistent with an age of 74 ka whilst others were lower at 24 ka and 37 ka, suggesting that ash here was reworked. These implied caution in the use of ash layer on land for regional stratigraphic correlations. It was also concluded that this signal would enable dating of volcanic event to up to 150 ka (Biswas *et al.,* 2013).

An alternative way was to date the bounding sediments to bracket the age as 77 ka and 74 ka of ash layer as was done by Petraglia *et al*. (2007, 2012) and Haslam *et al.,* 2010 at the Jwalapuram, archaeological sites for tephra deposits in Kurnool District. In addition, Ash deposits are also dated from 67 to 0.35 ka in the Sagileru and Gundlakamma valley, southern India (Geethanjali *et al*., 2019). These do not correspond with the timing of volcanic eruption ~74 ka as suggested by Petraglia *et al*. (2007). These ash deposits have also been discovered alongside Middle Paleolithic artefacts and a possible fluvial reworking cannot be ruled out. Presence of Humans suggest more conducive climate.

5j. Impact Craters

Sengupta et al. (1997) used TL dating of impact glass (~52 ka) in the Lonar crater from Deccan basaltic traps to understand the terrestrial impact structures, events as these are common in the basaltic surfaces of Mars and other planets. The experimental work was carried out at PRL.

5k. Coastal deposits and coastal dunes

Miliolites: Dating of the coastal deposits paved the way to secure well constrained chronology for the miliolitic limestones, miliolites, bioclastic deposits that abound at western coast of India, in the Saurashtra region. Using quartz grains embedded in the calcrete matrix, Sharma *et al.,* 2017 dated coastal deposits of mixed environments (marine, fluvial, aeolian) from coast toward inland, and provided OSL ages on three type of deposits–shell limestones (age >165 to 44 ka), fluvially reworked sheet deposits (75-17 ka) and miliolites (80-11 ka) formed by aeolian processes. This study suggested that previous Uranium series and radiocarbon ages were incorrect due to reworking, diagenesis and contrary to the suggestion of extreme tectonics based on Uranium series ages, luminescence ages provide a more plausible inference that region has been tectonically stable (Sharma *et al.,* 2017).

Tsunamis: Murari *et al*. 2007 demonstrated that the component-specific OSL dating can be effectively used for dating sediments transported by tsunamis. Here bleaching occurs during long residence of sediment in the shelf zone due to finite light penetration up to a water depth of 20 m and repeated reworking of sediment during tides. Given that 2004 Tsunami gave a near zero signal, it was taken to suggest that the tsunami picked up sediment only from the area where zeroing could have occurred prior to the event. Based on this premise, an estimate of potentially transportable sediment was calculated and this agreed with the observed data. Thus, OSL provided both dating and an estimation of potentially transportable flux during a future tsunami.

Teris- the red sands: Kaveri delta on the south-east coast of India exhibited widespread coastal dunes which formed/reactivated during 9-4 ka to up to present time due to climatic variation and land use changes (Alappat *et al.,* 2011). Red sand dunes in the southwest coast of Tamil Nadu gave depositional ages between 16-9 ka and at 4.5 ka (Alappat *et al.,* 2016). Geomorphological and OSL dating investigations of teri sediments of SE coast indicate different type of sands; inland fluvial teri, coastal teri and near coastal teri dunes which were deposited around >15 ka, >11 ka, ~6 ka respectively. Association of microlithic sites with coastal teri dunes indicate the presence of Modern Humans in the region during 11 - 6 ka, (Jayangondaperumal *et al.,* 2012).

Barrier Spits and beach ridges: Murray and Mohanti (2006) investigated the formation of outer barrier spit at the Chilika Lake, Odisha through OSL dating of the sand grains. The ages of top and bottom sediments estimated to be were ~40 years and ~300 years respectively and suggest potential use of OSL dating to estimate rates of sand movement over the past few hundred years.

Morthekai *et al*. (2021) analyzed eight sandy paleo-beach ridge samples from the Krishna-Godavari twin delta using quartz OSL, feldspar IRSL50°C, and feldspar pIR IRSL290°C. Using standard statistical and Bayesian approaches, they deduced synthesized ages with uncertainty and compared these with published radiocarbons ages to infer the reservoir age in this region. This study demonstrates conjunctive use of quartz and feldspar luminescence signals to improve accuracy of the estimated ages and identify reworking of sediments.

5l. Chemical Precipitates

Chemical Precipitates are important climatic markers as they form under specific time windows and are often resistant to post depositional alterations. *Gypsum* is one such mineral that forms under extreme aridity and its formation age was determined using the dating of syn-sedimentary quartz (Kocurek *et al.,* 2007. This approach was used to develop chronology of gypsum in Thar lakes and that of white sands. More recent studies suggest that the loss of water of hydration does not affect the luminescence signal and therefore providing a prospect of direct dating of gypsum (Sharma *et al.,* pers com). Studies on *Barites* have demonstrated its use for direct dating of the formation events of Barites in the age range of few to 20 ka (Sharma *et al.,* 2015).

An important methodological development was the dating of pedogenic carbonates that form post the sediment deposition. Formation of pedogenic carbonate nodules in a sediment leads to a change of radiation environment of quartz entrapped in carbonate matrix. Thus, after carbonation, the rate of growth of luminescence of quartz grain with in it, is different as compared to those outside it and a simple calculation suggest the ratio of difference of paleodose and dose rate provides the age of carbonation. This method was successfully applied to carbonate deposits in sands, but at that time a limiting factor was the propagation of errors on paleodoses and dose rates, leading to a larger error in the age. Present possibility of measuring single grains offers prospects of reducing this error (Singhvi *et al.,* 1994b; Banerjee, 1996, PhD Thesis).

5m. Applications to Archaeology

The beginning of luminescence dating was inspired with the prospect of dating of pottery from archaeological sites that did not yield well preserved organic material like charcoal for radiocarbon dating. Some of the key results based on TL and OSL dating are

1. One of the key luminescence dated sites was the famed Ramayana site at Sringaverapura near Prayagraj (Agrawal *et al.,* 1981). Excavations by Prof. B.B. Lal, at this site suggested that Ochre Colored Pottery (OCP) was the basal pottery and this was dated to 3000 years. The overlying black slipped ware was common to the excavated sites mentioned in Ramayana and was dated to 2700 years and were taken to be the antiquity of the story of Ramayana. Similarly, five pottery samples from Bet Dwarka site were dated 1800 years with one sample to 3200 years and this was taken to be the antiquity of the story of Mahabharat (Vora *et al.,* 2002; Singhvi *et al.,*1991). These inferences however need more data.
2. The demonstration that sediments constituting archaeological layers could be used to date the archaeological culture as represented by pottery and artefacts. Dating of pottery from several sites in India, and sediments showed a good concordance and was explained to be due to onsite bleaching of sediments due to human activity that led to repeated reworking of sediments. This work now forms the basis of a large volume of data on paleolithic archeology and these have informed the debate on human migration (Chawla and Singhvi, 1989). Pottery samples retrieved from the burial sites in Kanchipuram district of Tamilnadu dated ~2.4 – 1.4 ka shed light on contemporary cultural practices (Haricharan *et al.,* 2013).
3. Dating of sediments carrying geometric microliths in-situ at a site Mehtakheri on Narmada suggested their antiquity to be at least 50 ka and possibly 60-65 ka. This led to the need to revisit the narrative of the arrival of modern human into (or out of) India (Mishra et al., 2013). It is noteworthy that in India, presence of geometric microlithic tools to up to 3 ka indicated their association with the Modern Humans. During the late eighties, Luminescence dating of geometric microliths to 28 ka from Sri Lanka (Singhvi *et al.,* 1986) attracted deep skepticism in the archaeological community and questions on the reliability of luminescence dating were raised as the conventional wisdom suggested the geometric microliths to be much younger. *et al.,* 2013).
4. Petraglia *et al*. (2007) investigated the effect of the Youngest Toba Tuff (YTT) eruption (~74 ka) on existing humans at that time in Jwalapuram archaeological site along the Jurreru River valley of South India. They found stone tools, sediments from archaeological layers lying above and below of Toba ash layer. Dating of these sediments (77-74 ka) helped to constrain the age of Toba ash (~74 ka) which implied that hominins were present before and after YTT event and survived during this eruptive episode.
5. More recently, dating of middle paleolithic assemblage from Attaripakkam in Tamilnadu returned stratigraphic OSL ages in the range 385-80 ka with middle paleolithic tools *in-situ*. These results make these coeval to their counterparts in Africa and mandate a revisit of the out of Africa debate (Akhilesh *et al.,* 2018).
6. An interesting use of TL was through the use of a phenomenon of pre-dose sensitization. The luminescence sensitivity of the 110°C TL peak quartz (luminescence/mg/Gy), depends on past radiation dose and past temperature. The temperature dependence is such that once sensitized to a certain temperature, further increase in sensitivity would occur only at temperature higher than these. Sunta and David, 1982, exploited this and were able to deduce the firing temperatures of pottery to a precision of ±25°C. This approach was also used in the estimation of thermal excursion during the injection of a dyke due to an earthquake event (Singh *et al*., 2009; Tyagi, 2007, PhD Thesis).
7. Recently, at Vadanagar, Gujarat a 4-6th century BCE archaeological stratigraphy was dated using OSL (Agnihotri *et al.,* 2021).

For those interested in methodological aspects, we refer to a series of seminal papers by Sunta, David and the BARC group (David *et al.,* 1977,1978) on varied properties of quartz luminescence. These, if explored, could provide the basis of the development of numerous new applications.

5n. Other applications

One of the important applications of thermoluminescence has been in elucidating the thermal and radiation history of meteorites with some path breaking results. The sensitivity of luminescence depends on the crystallinity of minerals producing it. Sears *et al.,* 1980 demonstrated that TL sensitivity of a meteorite could be a precise indicator of its metamorphic grade as compared to characterization using conventional petrography and this has now been used commonly (Sears *et al.,* 1980)

Luminescence in meteorites arises due to its exposure to cosmic rays in space and in the absence of any heating these results a characteristic plateau behavior in the paleodose vs. glow curve temperature plot. Any deviation from an average shape can occur only due to temperature - either in the space due to lower than perihelion being 1AU resulting in higher average temperature or due to oriented entry and have been cleverly used to estimate orbits and oriented entries (Melcher, 1981; Singhvi *et al.,* 1982b).

Banerjee *et al*. (2008), explored TL of single chondrules and concluded that higher sensitivity of chondrules were related to higher degree of metamorphism in the parent body. Biswas and Singhvi (2013) examined TL from individual chondrules to find two interesting observations. These include a large variation in TL parameters of individual chondrules, suggesting that they were formed under differing crystallization conditions. Also, anomalous fading covaried with degree of disorder but the sample with highest disorder did not show any fading. This suggest the need to further explore athermal fading in respect of crystal order. These studies suggest that it is possible to tease out much information on metamorphic conditions seen by a grain and needs to be exploited in the context of terrestrial rocks.

6. Future outlook

Luminescence is an ultrasensitive phenomenon and even ppt level of impurities can play a substantive role in modulating the sensitivity and the dose response of a sample. The signal depends on traces of impurity states and a ppm of impurity leads to 10^{17} defect states, some of which participate in the luminescence process, a few could enhance and a few others could quench possible luminescence. Modeling of these processes are complicated and need exhaustive computing for each grain, which is impractical. Therefore, most of the studies are based on a bootstrap between observation and experiments to establish the self-consistency of a deductive reasoning.

A judicious use and understanding of this sensitivity, offers the potential to unravel the history of a minerals since their formation and the events thereafter including their provenance. Besides the age, luminescence offers many other avenues that have not been explored. These includes e.g., monochromatic analysis to target specific defect centers, akin to ESR, and their long term behavior in terms of diffusion. In principle these defects can be used for geochronology till the origin of earth, as has been tried by Odom and Rink (1989). An equivalent luminescence signal should exist and is waiting to be probed.

Investigation of the source or provenance of grains in a specific environment has long been explored to better understand the processes and sediment dynamics leading to landscapes. As grains on the earth surface can be dispersed by multiple processes (such as fluvial, aeolian, glacial and coastal, etc.), they record crucial information about the pathways and environmental conditions in which they traveled. Therefore, it is essential to unravel the primary sources to reconstruct past events by teasing out grain's long term history and OSL offers great possibility (Sharma *et al.,* 2015). This work by Sharma *et al.* 2015, needs to be taken forward with ultralow temperature measurements to refine the correlations between luminescence sensitivity and the OH concentrations and possible develop new methodology for quantitative provenance studies

Some of the experiments currently underway at PRL are towards the conjunctive use of OSL and Cosmogenic ages to further constrain the long term history of landforms and of transit time of sediments. Future studies on erosion, on surface paleo-thermometry and sediment flux changes through time would also need conjunctive use of OSL and CRN as also conjunctive use of various OSL and IRSL, pIRIRSL and IRPL signals and the use of their bleachability to tease out more information on geomorphic processes.

OSL records near instantaneous, more recent reworking and depositional event and the CRN records the long term history since denudation with some caveats on burial history. Careful sampling and analysis promise possibilities to constrain the erosion rates rocks and sediment fluxes. Similarly, conjunctive use of TL and OSL and the prospects of exploring deeper traps via TL and shallower trap through OSL. Initial studies by Bailiff (1976), need to be explored further. More recent studies by Devi *et al*. (2022) using multiple OSL excitations holds some promise to derive more information on the luminescence process in minerals.

Another possible area is the use of TL glow curve especially for feldspars, where a continuous distribution of traps is seen (Biswas *et al.,* 2018). An increase of activation energy with temperature implies increased residence time of a charge in a defect state – the trap. Meteorites carry signals for cosmic ray exposure, and when probed, signal at each glow peak temperature would provide, cosmic ray dose rate averaged over the mean residence time of particular glow peak. Therefore, a meteorite luminescence with multitude of glow peaks, preserves a record of cosmic ray dose integrated over various period of time, one each for glow peak. Clever physics and laboratory experiments can then provide a combination of elevated dose rates at elevated temperature that give same signal as in a meteorite sample as received. This can then be extended to estimate cosmic ray fluxes through time, over a million-year time scales. Some initial experiments have been reported by Geake and Walker (1975) in the context of lunar soils, and these need to be followed.

Similarly, the suggestion of Biswas *et al.* (2011) on the extent of anomalous fading with cosmic ray exposure ages offers new promise for the estimation of cosmic ray exposure ages, over time scales of several millions of years. TL/OSL offer good means of active and passive dosimetry for space mission and currently there is a need to understand the luminescence production mechanism.

An important experiment that needs to be done is the efficiency of luminescence production by heavy charge particle bombardment in a meteorite matrix using particle accelerator. This will provide new physics of radiation interactions at high level and radiation damage effects in different materials. These are critical questions in the use of luminescence for space sciences. The use of OSL for personnel dosimetry has been suggested and holds good promise for real time dose estimations. This needs to be pursued.

In respect of geology, dating of soils, palaeosol and turbation rates of sediments, have not been exploited for the Indian contexts and limited work has been carried out elsewhere. The entire chronology of the Siwaliks is largely based on paleomagentism, soils and geochemistry and this needs to be established though independent chronometric methods. Recently, Rajapara (2021) used these sequences to develop fading correction factors assuming the assigned chronology are correct. These provide empirical but more realistic field based estimates of fading correction. Also, given the multiplicity of signals, it is possible to use their varied fading rates to advantage, as one would do in the case of two cosmogenic radio-isotopes being produced with the same irradiation and at the same time decaying at different rates. Their ratio then would have a time dependence and this will provide a simple measure of time without the tedium of measurement of environmental dose. Initial work has been reported in a Ph.D. Thesis by Haresh Rajapara (2021) based on work done at PRL.

Use of geology to understand physical processes was attempted by Chawla et al. (1998). Using a long geological column, they compared the response of young and old samples. The old sample accumulated all its dose at environmental dose rate (Gy/ka). This was compared this with the response of a younger sample beta irradiated in the laboratory at a dose rate of a Gy/min to examine the effect of a million-time higher dose rate (Gy/min vs. Gy/ka)). They used it to demonstrate the potential dose rate effect beyond an absorbed dose of 250 Gy. This study has applications for radiation accident dosimetry and needs to be followed up. Another area that has not been examined well is the use if low temperature signals to deduce paleostress histories and for provenance, as was done by Mobbs and Singhvi (1984).

An important program of national importance can be the documentation of surface dose from all areas undisturbed by human activity. This has been suggested by one of us variously, but a concerted effort is yet to take off. This effort will be of use in case of any nuclear event as it will provide a way to measure the fall out dose and its energy spectrum almost instantaneously. There is also a need to prepare a standing operating procedure for nuclear accident dosimetry with proven materials and this be updated on a continuing basis.

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