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Luminescence chronology of seismites at Sumdo (Spiti valley) near Kaurik–Chango Fault, Northwestern Himalaya

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Soft sediment deformation structures (seismites) observed at eight stratigraphic levels in fluvio-lacustrine sediments exposed in the Sumdo area of lower Spiti valley, Himachal Pradesh, India have been interpreted to represent eight paleoearthquakes of magnitude > 6.5 on the Richter scale. We present the first attempt to date seismites using luminescence dating techniques. The infra-red stimulated luminescence ages range from 26 ka to 90 ka in samples from four seismites that were investigated. These ages suggest that the activation of Kaurik–Chango Fault and the seismic activity in the region dates back at least to the Late-Pleistocene.

THE Himalaya is one of the active dynamic seismic regions of the world and is known for moderate to large magnitude earthquakes. The historical record of these earthquakes is too short to deduce their long-term recurrence intervals. An effort is currently under way to document the geological record of past seismic events in the Himalaya and establish their chronology[1] so that the repeat frequency of large earthquakes can be established.

In the Sumdo region of the lower Spiti valley, a detailed soft sediment deformation study provided evidence for eight major earthquakes (magnitude ≥ 6.5)[2]. In 1975, the Kinnaur Earthquake caused widespread damage, landslides and ground rupturing. These earthquakes have been correlated to the activation of the Kaurik–Chango Fault[3] striking continuously from Kaurik (north) to Leo (south) across the Paleo–Proterozoic sequence. A correlation with ^{14}C dated lacustrine records in the adjoining region suggests a Late Pleistocene–Holocene antiquity for these events[4]. The deformation structures produced by seismic events are recorded in overbank/shallow-water sedimentary deposits and have been designated seismites by virtue of their similarity to other known occurrences of earthquake-induced sedimentary structures and by virtue of the lateral extent of their deformation. Earlier workers have also used such sediments to study the paleoseismic events[5–9].

Studies on the chronometry of paleoseismic events have been scanty, and have mostly depended on the radiocarbon dating of charcoal/wood associated with sediments. This method has a limited time range of application, and has difficulties in calibration and in establishing an unambiguous association between sample and strata. The method often provides unrealistic ages on account of the contamination by 'old' or 'modern' carbon[10]. Recent advent of the applicability of trapped charge dating methods such as electron spin resonance dating, thermoluminescence (TL) and optically stimulated luminescence (OSL) have now enabled dating of a large variety of sequences associated with paleotectonic/seismic events. Thus the dating of fault gouge, buried soils that originally developed on colluvial debris[11–13] and dating of unpaired river terraces[14] have now made it possible to directly determine the timing of tectonic events. In this study we describe the first attempt of a direct dating of soft sediment deformation structures and hence, paleoearthquake events by infra-red stimulated luminescence[15] (IRSL) and thermoluminescence[16,17] dating techniques. These methods rely upon the fact that the luminescence signals (TL/IRSL) of minerals constituting the sediment are reset by a short duration of pre-depositional sun exposure. On burial, sun exposure ceases and a reaccumulation of luminescence is initiated through irradiation from ambient natural radioactivity (viz. ^{238}U, ^{232}Th and ^{40}K). The luminescence age is expressed as

$$\text{Age} = \frac{\text{Equivalent dose}}{\text{Annual dose}} . \qquad (1)$$

The present study has the premise that the deformation structures were created during or immediately after deposition at the sediment–water interface by seismic events[5,7–9], and consequently the time interval between the deposition of the sediment and its deformation is considered to be small compared to the deformation age of the sediment. Earlier studies have shown that the IRSL/OSL signal of shallow lacustrine/fluvial sediments is completely reset at the time of deposition[18,19]. In view of the bleaching rate of IRSL of sediments (Figure 1) and an estimated pre-depositional transport of several kilometres to several hundred kilometres, it is reasonable to assume that these shallow water fluvial sediments have experienced sufficient predepositional daylight bleaching. The seismites thus have a zero IRSL age at the time of deformation.

Himalaya encompasses numerous NW–SE trending regional thrusts/faults (Figure 2) of which the Main Central Thrust (MCT), the Indus Suture Zone (ISZ), the Main Boundary Thrust (MBT) and the Himalayan Frontal Fault (HFF) are noteworthy[20,21]. In the Spiti basin a number of N–S trending faults, including the Kaurik–Chango Fault have affected the Precambrian–Paleozoic succession of the Tethys Himalaya[22,23]. The study area (Sumdo) lies within 4 km from the active zone of Kaurik–Chango Fault.

The Late Pleistocene–Holocene sedimentary basin in the cold–arid Sumdo region (3200 m above MSL) is represented by fluvio-lacustrine deposits. At the confluence of the Spiti river and Padra Nala, the fluvial/lacustrine sediments associated have soft sediment deformation structures at various levels in the 120 m thick stratigraphic column, comprising sandstone, conglomerate, siltstone and mudstone (Figure 3).

In Sumdo, the soft sediment deformation structures are observed in 120 m thick shallow water fluvio-lacustrine sediments. The deformation structures S_1–S_8 occur at irregularly spaced stratigraphic intervals and can be traced laterally up to a kilometre. These structures include a ruptured anticlinal feature with intrusive sediment plumes/dune-like feature, a flame structure, sand dykes, folding associated with small scale faulting associated with folding and large scale soft sediment folding[2]. These structures are restricted to single stratigraphic layers separated by undeformed strata. The deformation structures observed at Sumdo are similar to those reported by many workers[8,24]. The deformation structures at Sumdo have been related to past episodic seismicity along Kaurik–Chango Fault and it is inferred that the region suffered at least 9 major earthquakes (of magnitude exceeding 6.5 on Richter scale), including the 1975 Kinnaur earthquake[2]. The deformation of sediments during earthquake may have been caused by liquefaction and fluidization due to cyclic loading and undulatory motions resulting from the passage of surface Rayleigh waves[7,8,25]. The absence of lake fills near the Kaurik–Chango Fault Zone during the 1975 earthquake precluded the availability of a modern 'zero' age seismite.

The lithology and the location of samples are given in Figure 3. The grain size analysis of the samples for luminescence dating shows bimodal to polymodal distribution. The statistical parameters of these samples

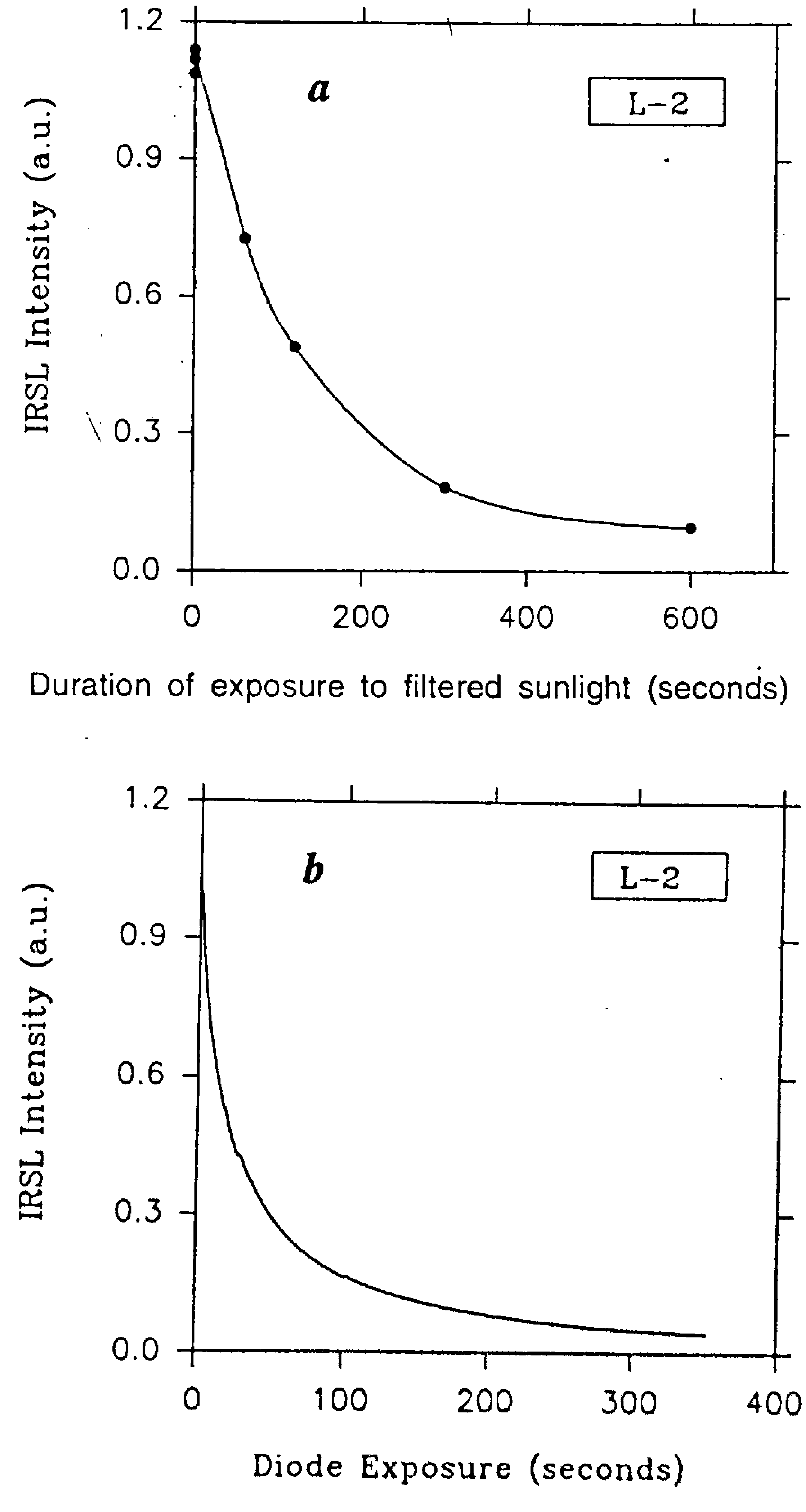

Figure 1 *a*, *b*. *a*, Infrared stimulated luminiscence bleaching curve for a typical seismite. The IRSL intensity is reduced to ~ 8% of its initial value after exposure to natural sunlight filtered through a 4 mm transparent window glass for ~ 10 min; *b*, Decay of IRSL with time for a typical seismite on exposure to light emitting diodes (LED) emitting at 880 ± 80 nm. Comparison with Figure 1 *a* shows that diode exposure for ~ 200 s is equivalent to an exposure of ~ 600 s of natural sunlight filtered through window glass in reducing the IRSL intensity to 8% of its initial value.

show that these sediments are moderately to well sorted and are near symmetrical to negatively skewed. At the transition of fluvial to lacustrine phase, the sediments are well sorted and negatively skewed. The mineralogy of both the fluvial and lacustrine sediments shows dominance of quartz followed by calcite and feldspar. The degree of sorting and the presence of quartz and feldspar offered promise for the use of luminescence dating.

The sediment transport with maximum water discharge occurs during April–August and is minimum during winter. No quantitative data on the river discharge and sediment transport from the basin was available. However, field observations show that the amount of water is about 50 times more in summer in comparison to winter. The transport from the catchment is about 5–300 km and implies a transport duration of 10–200 h and thus it is reasonable to infer that most of the sediments should have experienced finite daylight prior to deposition.

The experimental analyses were carried out using IRSL and TL dating methods. For IRSL measurements the extraction of the K-feldspar was made using a sequential pretreatment of the sample using 1 N HCl, 30% H_2O_2, sieving 70–106 µm and density separation using Na polytungstate (density = 2.58 g/cc). In view of limited sample availability, no HF etching of these grains was done. Monolayers of the grains were deposited on stainless steel discs. The irradiations were made using a 25 mCi ^{90}Sr–^{90}Y beta source. The IRSL intensities of the natural and the irradiated discs were normalized using 1 sec shortshine glows. The optics channel comprised a EMI 9635 QA coupled to Corning 5-58 + 7-59 blue filters and a Daybreak photon counting system interfaced to an IBM/PC with an Ortec Accuspec multiscaling card. Sixteen IRSL diodes (TEMT 484) with peak emission at 880 ± 80 nm (operated with a programmable constant current supply) were used for shinedown curves. In one case (L-4), the 75–106 µm K-feldspar yield was low and hence the fine grain method was used and a R-β (partial-bleach) TL analysis was done. The low photon yield of green light stimulated luminescence (GLSL) from quartz precluded a GLSL analysis. Fine grains (4–11 µm) were extracted after pre-treatment of 1 N HCl, 30% H_2O_2, 0.01 N Na-oxalate and Stokes separation in acetone.

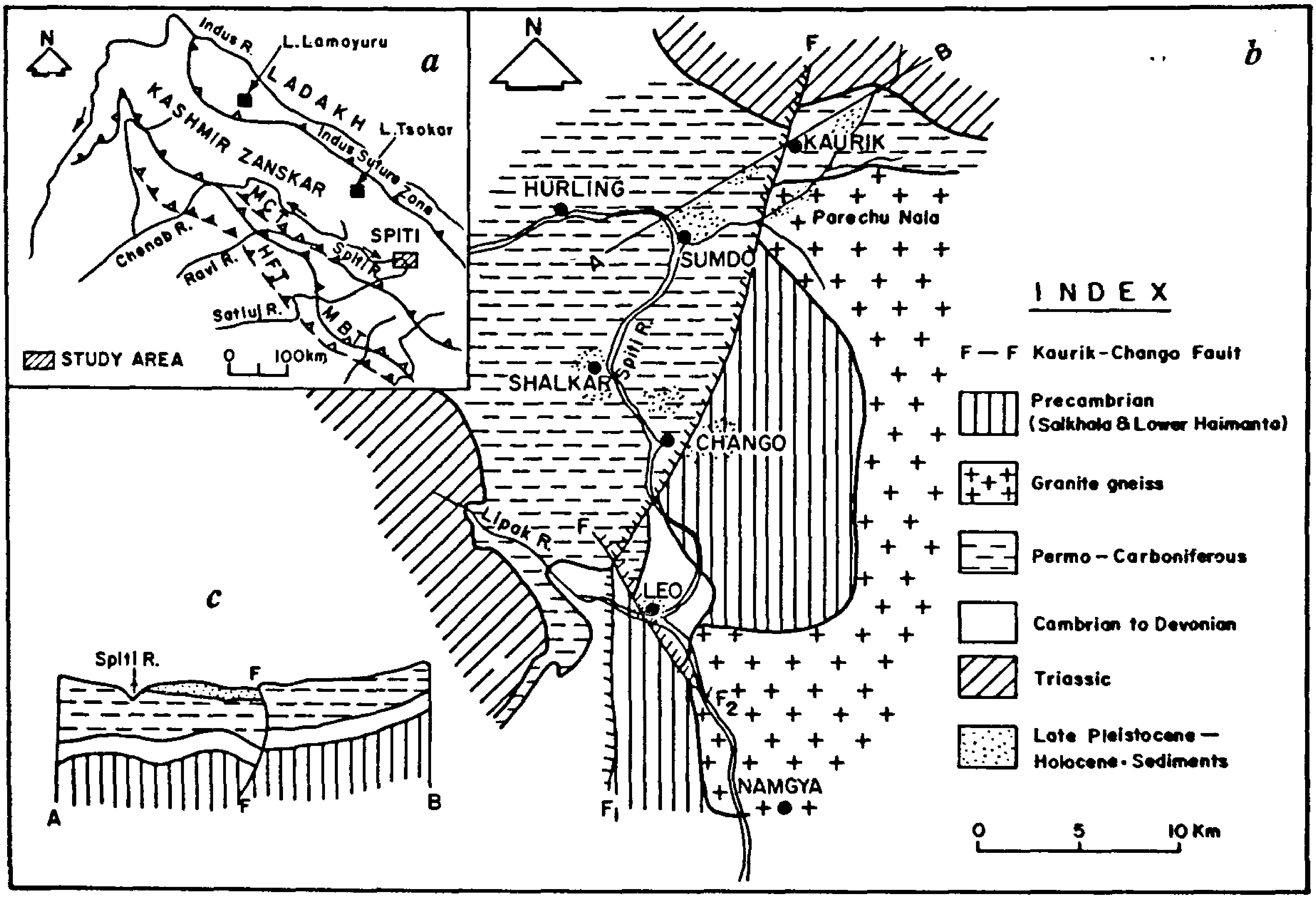

Figure 2 *a–c*. *a*, Index map showing general tectonic trend in the northwestern Himalaya and location of the study area; *b*, Geological map around Sumdo[2]; *c*, Cross-section along A–B[32].

The TL measurements were performed using two Schott UG-11 filters, a quartz ND-1 filter and Chance Pilkington HA-3 filter coupled to an EMI 9635 QA photomultiplier tube and a photon counting system. The heating rate was 2°C/s. Alpha irradiations were made in vacuum using a six seater 0.22 mCi ^{241}Am vacuum alpha irradiation system[26]. The sample aliquots were sunbleached under (i) clear sun for 30 min and (ii) shaded sun for 5 min and the equivalent dose was calculated using the partial bleach method. Second glow normalization was used. Linear and saturating exponentials were fitted for α and β growth curves respectively. The inverse variance method was used for calculation of error in equivalent dose. An α-efficiency factor of 0.15 ± 0.075 was assumed for coarse-grained K-feldspars. U and Th concentrations were estimated using thick source ZnS (Ag) alpha counting method and NaI(Tl) gamma ray spectrometry was used for potassium estimation. A radioactive equilibrium in the decay series of U and Th was assumed in the dose rate calculations.

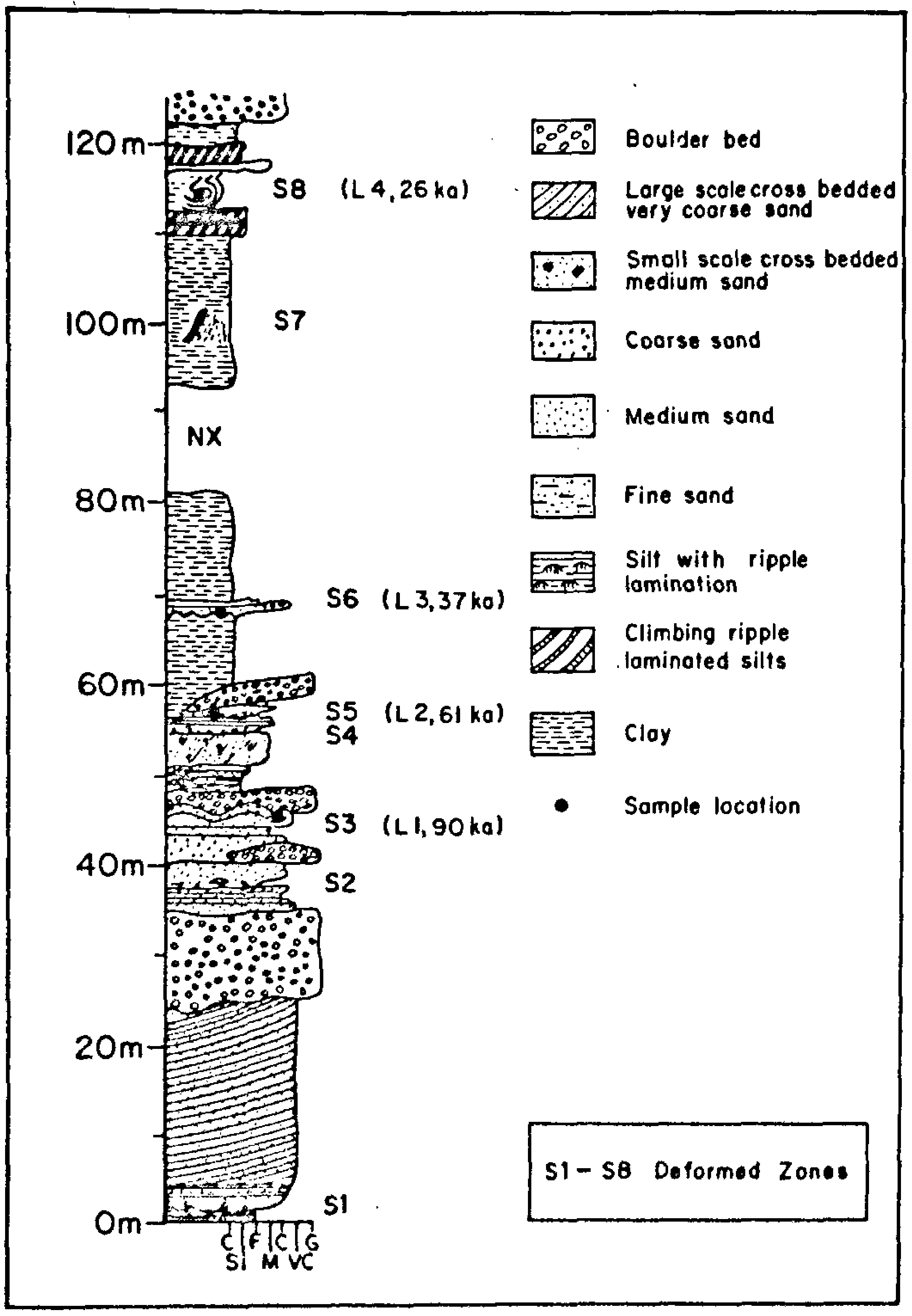

Figure 3. Composite lithostratigraphic column showing deformed zones (S_1–S_8) and facies variation in Sumdo area. Note the location of samples analysed for dating.

The cosmic ray dose rate was assumed to be 150 µGy/a. Error estimation was carried out following the prescription of Aitken[27].

Table 1 provides luminescence data for the four seismites that could be sampled during a limited field work that was permitted in this restricted region. Figure 4 provides a typical IRSL experimental data set. The luminescence (IRSL/TL) dates of the seismic events S_3 (Sample L-1), S_5 (Sample L-2), S_6 (Sample L-3) and S_8 (Sample L-4) are 90 ka, 61 ka, 37 ka and 26 ka respectively. The analysis of the sample L-4 proved enigmatic. The absence of a sufficient amount of coarse grained K-feldspar grains from L-4 meant that fine grains had to be used which yielded far too low total photon counts to carry out a reasonable analysis. Accordingly, a TL analysis was done for L-4 and the partial bleach (clear sun, 30 min) method gave an age of 26 ka. A preliminary analysis with a sun exposure of 5 min under a shaded sun was also carried out for this sample and the reduction in thermoluminescence intensity due to bleaching was used for evaluating an age of ~ 20 ka suggesting that the age estimated of 26 ka is a reasonable estimate for S_8. Quartz extracted from L-4 was also used for the evaluation of a TL age. The slide method[28] equivalent dose was used along with the fractional reduction in TL intensity after a 2-min bleaching (shaded sunlight) to estimate an age for L-4. The quartz (35 ± 9 ka) and fine-grain (26 ± 4 ka) TL ages are concordant within experimental errors despite their varying rates of photo-bleaching with daylight exposure. Further, the TL growth curve of quartz is complex[29] and in the dose region of interest, the growth of luminescence signal with dose is extremely slow. This results in a large error while extrapolating the growth curve to determine the equivalent dose.

It may be apposite to consider the possibility of radioactive disequilibrium in such a fluvial/lacustral deposited system. This could not be attempted in the present case due to limited sample availability. However, in view of the fact that up to ~ 55% of the total dose is contributed by potassium, the material being transported by water over short durations and a general concordance of radioactivity data derived assuming an equilibrium of the decay series in three samples suggest that radioactive disequilibrium may not be a serious problem and that the age estimates are realistic.

The interval between the seismites S_3–S_5, S_5–S_6 and S_6–S_8 is 29, 24 and 11 ka respectively (Figure 3). The interval between the S_8 event and the 1975 earthquake is 26 ka. The presence of a few more seismites in Sumdo area cannot be ruled out as the exposures at places are covered by debris. The erosion in the few fluvial cycles at different stratigraphic levels may have eroded some seismites and it may also be possible that at times seismites do not get preserved due to lack of

Table 1. Luminescence dating results for seismites from Spiti valley, India

Sample	Technique	Mineral	Th (μg/g)	U (μg/g)	K (cg/g)	α value	Water content* (%)	Annual dose (mGy/a)	Equivalent dose (Gy)	Age (ka)
L-4	TL[+]	Quartz	5.4	1.6	0.8	–	0.3	1.9	66 ± 14	35 ± 9
L-4	TL, R-β	Fine grains	5.4	1.6	0.8	0.12[#] ± 0.06	0.3	2.9	74 ± 15	26 ± 4.3
L-3	IRSL, Additive dose	K-feldspar	12.6	3.7	1.6	0.15[§] ± 0.075	0.5	4.5	165 ± 21	37 ± 5
L-2	IRSL, Additive dose	K-feldspar	8.9	2.6	1.75	0.15[§] ± 0.075	0.3	3.8	232 ± 34	61 ± 10
L-1	IRSL, Additive dose	K-feldspar	9.4	2.7	1.96	0.15[§] ± 0.075	0.2	4.1	372 ± 33	90 ± 11

*Water content as percentage of dry weight.

[+] See discussion in the text.

[#] The α-value for L-4 (fine-grains) was experimentally determined.

[§] The α-values for K-feldspars from samples L-3, L-2 and L-1 were assumed to be 0.15 ± 0.075.

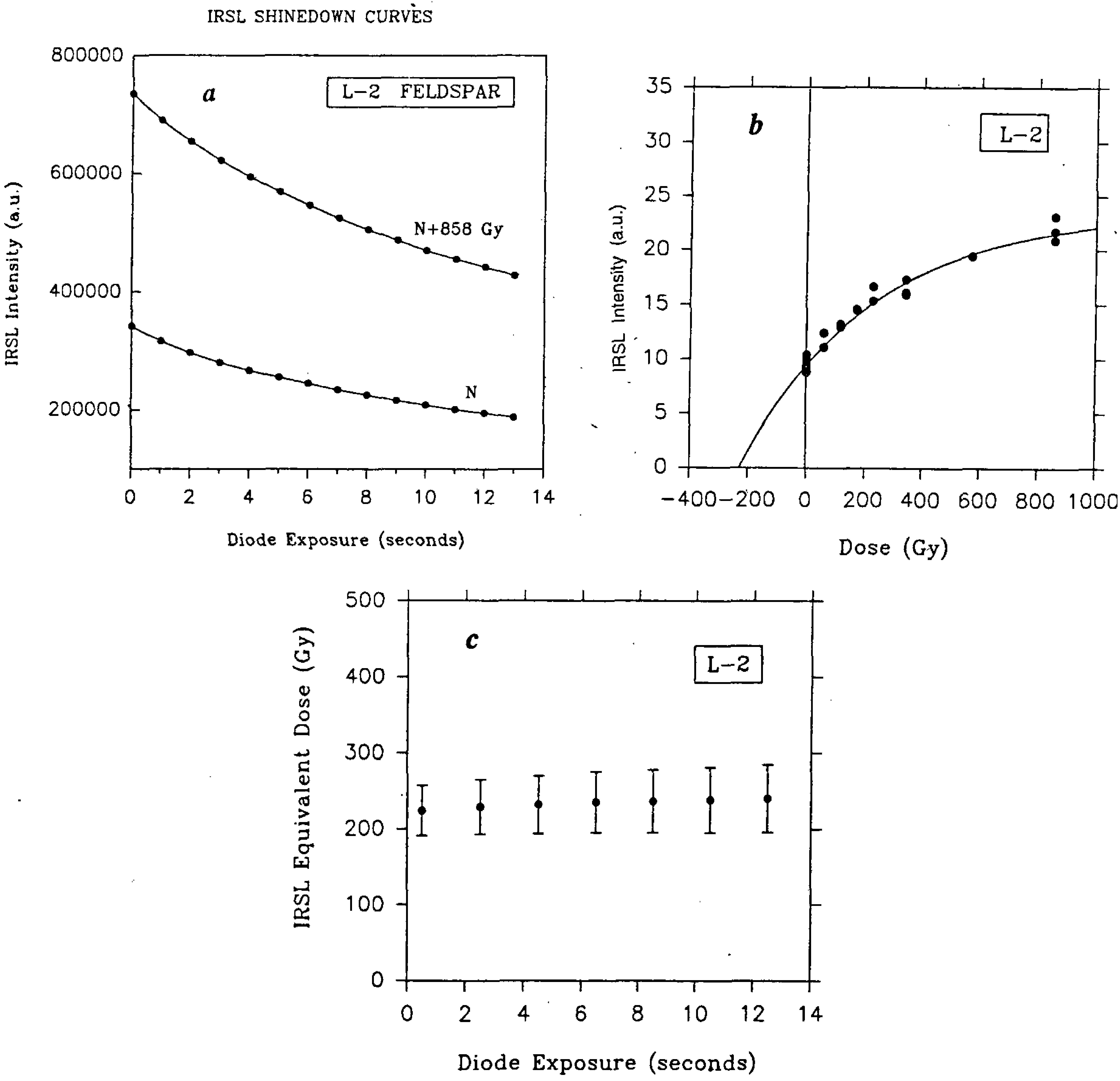

Figure 4 *a–c*. *a*, Infrared stimulated luminiscence shine-down curves for feldspar extracted sample, L-2; *b*, Growth curve for L-2. The equivalent dose (Q) divided by the dose-rate gives the age of the sample; *c*, IRSL shine plateau for L-2.

prerequisite conditions. The higher durations of 29 ka (S_3–S_5), 24 ka (S_5–S_6) and 26 ka in the fluvial part of the section may be due to periodic non-deposition and at places due to erosion. Ideally, it would have been desirable to obtain ages on all eight seismites, but as indicated above, logistical problems restricted collection of only four seismite samples.

The present study provided luminescence chronology to four soft sediment deformation structures designated as seismites based on their lateral extension of deformation and similarity to other known occurrences of earthquake-induced deformation structures in soft sediments. The chronology of seismites S_3, S_5, S_6, S_8 are 90, 61, 37 and 26 ka respectively, indicating that S_1 and S_2 are significantly older than 90 ka, whereas the younger episodes would post-date 26 ka. This indicates that the Kaurik–Chango Fault and related seismicity has been active at least since the late Pleistocene.

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Tectonic settings of Indo-Gangetic basin revealed from magnetotelluric data

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The Indo-Gangetic basin is one of the vast sedimentary basins of India. The knowledge of the subsurface tectonic structure of the basin and shield regions is important in understanding the dynamics of the lithosphere and for the knowledge of its hidden resources. Magnetotelluric (MT) data have been collected at 18 locations along two profiles north-south – Nepal border to Kanpur and east-west – Varanasi to Agra. MT parameters have been analysed at these locations. The pseudo-resistivity and phase plots have revealed resistivity structure and tectonic settings of the basin. The extension of the shield beneath the Indo-Gangetic basin has also been inferred from the MT data.

Indo-Gangetic basin has an extensive coverage of 25,000 km^2 lying between Peninsular shield and Himalayan region (Figure 1). The region lies between the Himalayan mountains on northern side and Indian Peninsular shield on the southern side. The depression of the Indo-Gangetic plains is foredeep. In the north, this region is bounded by the Siwalik hills and in the south by the Bundelkhand granites/gneisses and Vindhyan sandstones. The Indo-Gangetic basin constitutes an asymmetrical prism of sediments with an axis of maximum deposition very close to the present foothills[1]. The basin continues to be a tectonic enigma despite its outward simplicity as a vast alluvial plain. Burrard[2] interpreted it as a rift filled with alluvium to a depth of nearly 16 km and as a trough at the advancing edge of the steeply subducting Indian plate. He further suggested on the basis of the geodetic observations that the Himalayan folds were the result of under thrusting of the Indian sub-crust below the land mass of the central Asia. Burrard believed that this observation explained mass deficiency of the Indo-Gangetic and Himalayan region.