## LUMINESCENCE, GEOMORPHOLOGICAL PROCESSES

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### Definition

Geomorphology is the science that studies the origin and development of landforms and how those landforms combine to form landscapes. Landforms are shaped by *geomorphological processes*, many of which involve the weathering, erosion, transportation, and deposition of surface materials (rock, sediment) by gravity, ice, wind, or water. Both erosional and depositional landforms can be identified, and study objectives may include establishing (1) the initial timing of surface material movement (hence, landform age), (2) the timings of subsequent surface material movement (hence, landform development rate), and (3) the nature of surface material movement (sediment dynamics). Using a similar threefold breakdown, the focus here is on how *luminescence dating* can contribute to these objectives. Luminescence dating is a family of techniques most suitable for investigating fine-grained (typically silt, sand) depositional landforms. The basic principles of luminescence dating and the various techniques are explained in other entries (e.g., see "Luminescence Dating"), and the emphasis here is mainly on optically stimulated luminescence (OSL) dating, which typically can be applied to quartz-rich sediment ranging in age from a few years to several hundred thousand years.

### Principal applications of luminescence dating in geomorphology

Luminescence dating relies on the exposure of transported sediment to light prior to deposition and burial of that sediment. Consequently, OSL and other luminescence techniques are best suited to the investigation of depositional landforms originating and/or developing as a result of one or more of the following processes, all of which involve varying degrees of sediment exposure to light: aeolian (e.g., loess sheets, dunes), colluvial (e.g., aprons, glacis), fluvial (e.g., alluvial fans, river terraces), and wave and tidal action (e.g., beach ridges, spits). Luminescence techniques have been less widely applied to the investigation of glacial, deeper marine, tectonic and volcanic processes because of reduced exposure of sediment to light and/or less suitable (coarser or finer) grain sizes or minerals, although techniques are being developed to cater for these issues (see "Luminescence Dating, Deep-Sea Marine and Lacustrine", "Luminescence, Glacial Sediments", "Luminescence, Earthquake and Tectonic Activity"). Numerous recent reviews have outlined the applications of luminescence dating in specific areas of geomorphological research (e.g., Duller, 2004; Singhvi and Porat, 2008; Fuchs and Lang, 2009; Cunningham and Wallinga, 2012), and the following provides only a brief outline of three main, possibly interrelated, applications.

#### The initial timing of sediment deposition

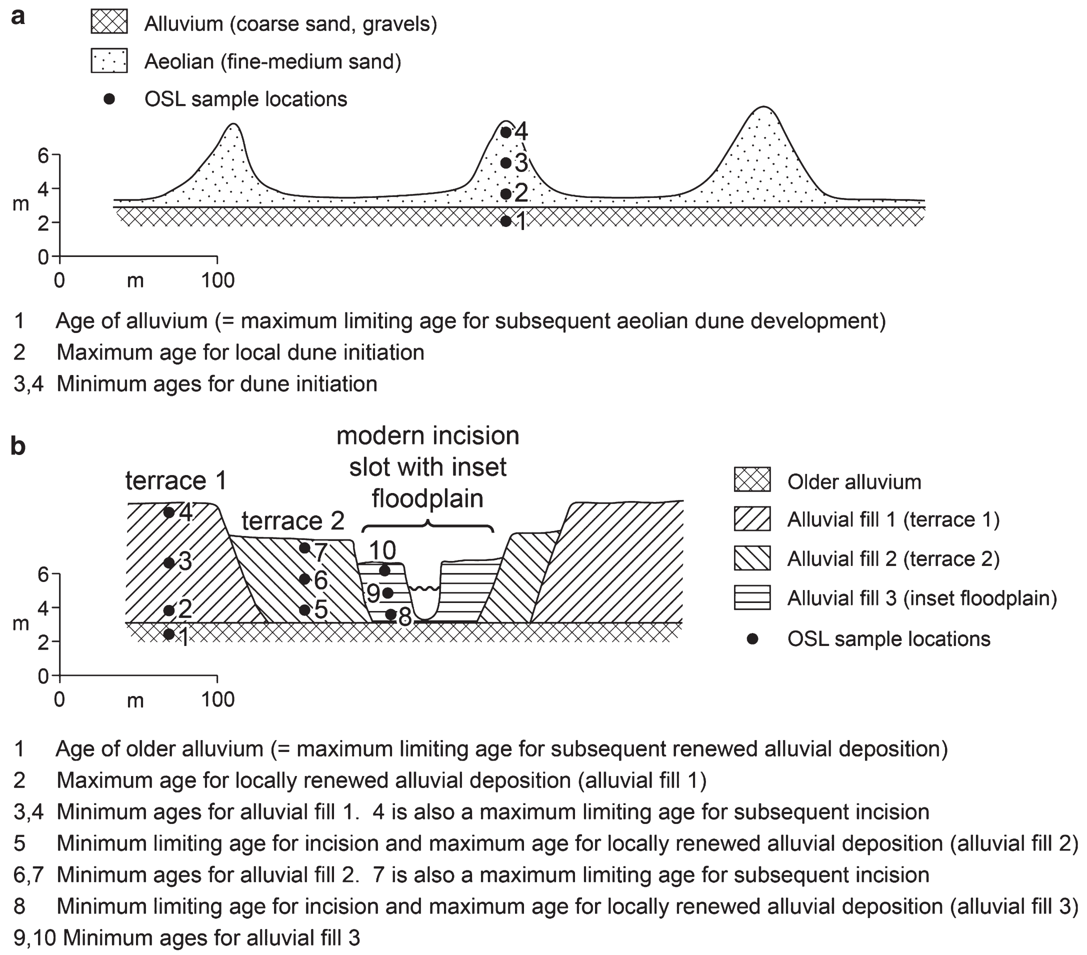
Commonly, luminescence dating is used to establish the initial timing of sediment deposition, thereby providing information on landform age. Examples include OSL dating of the timing of aeolian deposition in deserts (e.g., Hollands et al., 2006); in such instances, the ages for the basal aeolian sediments provide *maximum* ages for the overlying dune landforms (Figure 1a). Similarly, luminescence dating of basal sediment can help establish the maximum ages of a variety of other landforms including colluvial aprons (e.g., Botha et al., 1994), lacustrine beach ridges (e.g., Nanson et al., 1998), and river floodplains and terraces (e.g., Keen-Zebert et al., 2013). In addition, dating of the initial timings of deposition in adjacent landforms may be used to provide bracketing ages for geomorphological processes that partly involve erosion; for example, the timing of river incision can be bracketed by establishing an age for the alluvial sediments into which a river has incised, and an age for the sediments subsequently deposited within the incision slot (Figure 1b). The former provides a maximum limiting age for incision and the latter a minimum limiting age for incision, thereby bracketing the actual timing of incision (e.g., Keen-Zebert et al., 2013).

#### The timings of subsequent sediment deposition

Typically, establishment of the initial timing of deposition is coupled with the investigation of the timings of subsequent deposition, thereby providing information on landform development rate. Examples include using multiple luminescence ages from sediment bodies to establish vertical accretion rates (Figure 1), but sampling strategies also can be designed to establish dune lateral migration and/or forward extension rates (Figure 2a), meander bend growth rates (Figure 2b), or coastal progradation rates (Figure 2c) (e.g., Bristow et al., 2005; Rodnight et al., 2005; Hollands et al., 2006; Roberts and Plater, 2007; Rink and López, 2010; Telfer, 2011). In cases where single or multiple bracketing ages for river incision can be established (e.g., across a flight of alluvial terraces), these can be coupled with the depth of incision to provide a mean long-term incision rate (Figure 1b). Establishing OSL ages for relatively unmodified sediments above and below paleosols can also help to bracket soil formation rates (Figure 2d), as has been demonstrated in studies of loess, aeolian dunes, and sand ramps (e.g., Roberts, 2008; Fujioka et al., 2009; Telfer et al., 2012).

#### The nature of sediment movement

Some recent applications of luminescence techniques have focused less on the timing and rates of landform development and more on sediment dynamics. For instance, OSL dating has been used in combination with




**Luminescence, Geomorphological Processes, Figure 1** Examples of possible strategies for luminescence sample collection and the insights into geomorphological processes and landform dynamics that may result: (**a**) Cross-sectional view of aeolian linear dunes (**b**) Cross-sectional view of an incised river and flanking alluvial deposits.

hydraulic modelling to provide fundamental insights into the nature of storage and flushing of fine-grained matrix sediments in small mountain streams in southeast Australia (Thompson et al., 2007), and investigations of downstream quartz sensitivity (brightness) change in larger, lower gradient Australian rivers potentially may provide information on river style and associated fluvial processes, including bedload transport rate, and water depth and turbidity (Pietsch et al., 2008). In other geomorphological contexts, a variety of analytical approaches have been employed to investigate other aspects of local sediment dynamics, including bioturbation and its implications for depositional stratigraphy and luminescence chronologies (Bateman et al., 2007).

## Key issues in applications of luminescence dating in geomorphology

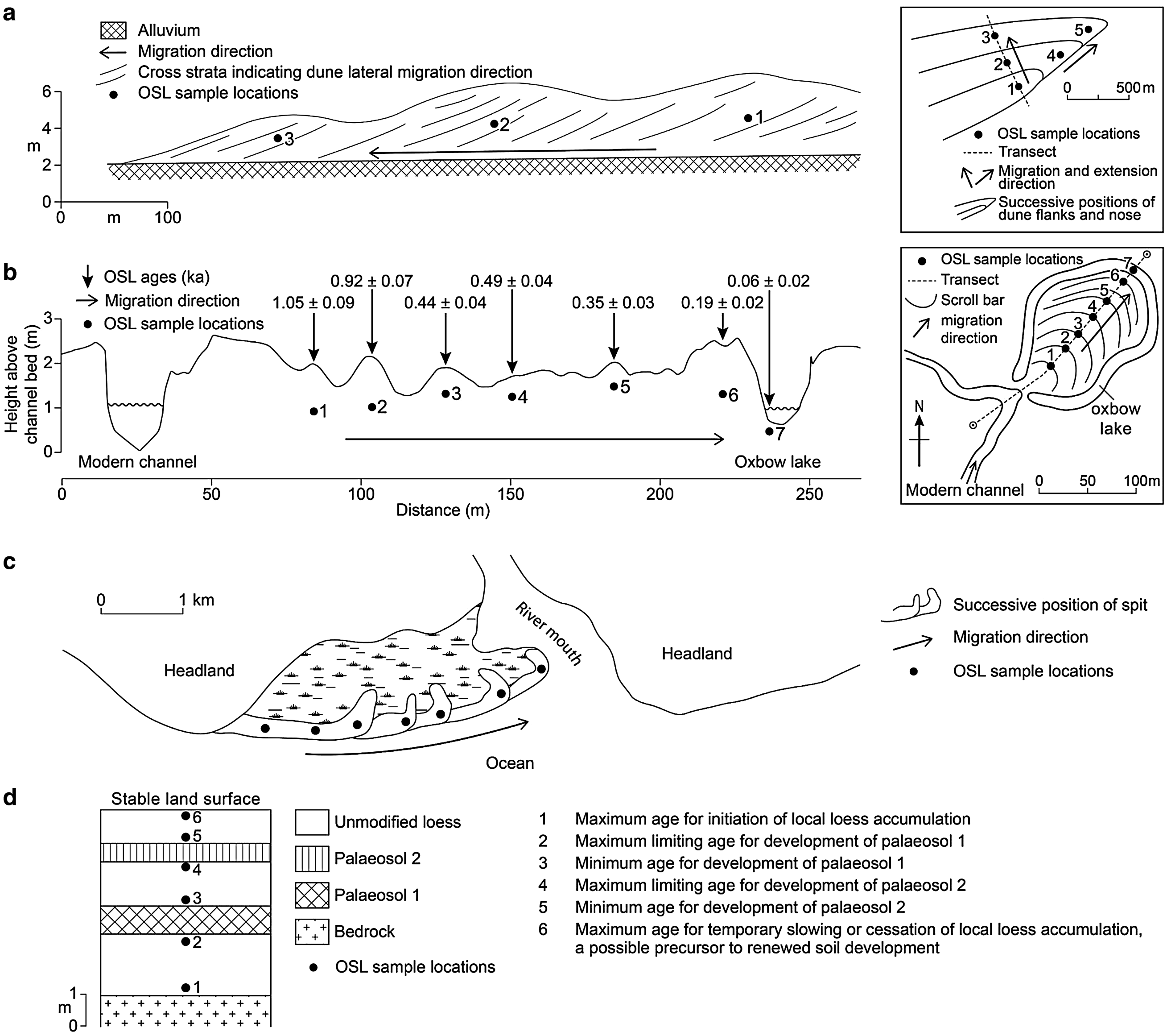
The following outlines some overarching considerations that arise from applications of luminescence dating in geomorphology.

### Sampling design and age consistency

Careful sampling designs can help to provide an internal check on luminescence age consistency. For instance, luminescence ages for the underlying sediments upon which the basal aeolian or fluvial sediments have been deposited provide a *maximum* limiting age for subsequent development of the dune or floodplain and clearly should be older than the maximum ages established by dating of the basal aeolian or fluvial sediments underlying the landform of interest (Figure 1). In addition, where several samples have been collected in vertical, lateral, or longitudinal sequence within or across landforms, normal stratigraphic principles apply; the luminescence ages for sediment that is superimposed upon, laterally adjacent to, or cross-cutting pre-existing sediment should be younger than the ages for the preexisting sediment (Figure 2b).

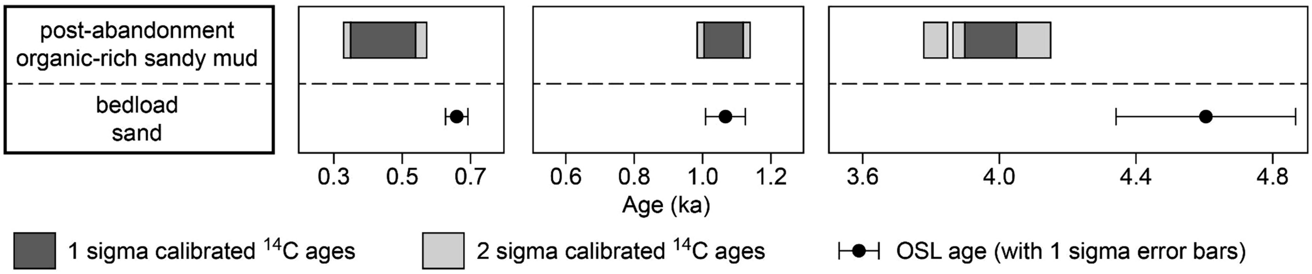
### Comparison with independent geochronometers

Confidence in the veracity of luminescence ages also can be provided by comparisons between different




**Luminescence, Geomorphological Processes, Figure 2** Examples of possible strategies for luminescence sample collection where the focus is on establishing landform development rates: (**a**) Cross-sectional and plan view of a laterally migrating and longitudinally extending aeolian linear dune (**b**) Cross-sectional and plan view of a laterally migrating meander, with scroll bars formed on the inside bend. OSL ages for scroll bars and the oxbow lake infill are derived from Rodnight et al. (2005) and Tooth et al. (2009) (**c**) Plan view of a prograding coastal spit and back barrier complex (**d**) Side view of a vertically accumulated loess-paleosol succession.

luminescence techniques and by comparison with other geochronometers. For Australian fluvial sediments, comparisons have been made between OSL and TL ages (see "Luminescence Dating, History", for TL); in these instances, the ages commonly overlap within error and have been used to argue for the veracity of TL ages in those settings (Nanson et al., 2005; Maroulis et al., 2007). More commonly, luminescence ages have been compared with chronologies obtained using different techniques on the same sediment layers or from underlying or overlying sediment layers (e.g., Madsen et al., 2005; Rodnight et al., 2006). For instance, in the Klip River wetlands, South Africa, OSL dating was used to establish the age of sandy paleochannel sediments, while $^{14}$C dating (see "Radiocarbon Dating") was used to establish the age of post-abandonment, organic-rich infills (Rodnight et al., 2006). As expected, the $^{14}$C ages tended to be younger than the OSL ages (Figure 3), thus providing support for the OSL analyses.




**Luminescence, Geomorphological Processes, Figure 3** Schematic comparison between OSL ages for bedload sand in paleochannels of the Klip River, South Africa, and the generally younger $^{14}$C ages for overlying organic-rich sandy muds (modified from Rodnight et al. 2006).

### Comparison with other paleoenvironmental datasets

Luminescence dating can establish the timing, rates, and nature of sediment movement, but a common aim of geomorphological enquiry is to identify the drivers of change. Drivers of change may be intrinsic to the system dynamics; for example, vertical accretion, lateral migration, and/or forward extension of aeolian dunes, meander bends, or coastal spits (Figure 2a–c) can occur under conditions of constant sediment supply and steady wind regime, discharge, or wave energy. Commonly, however, drivers of change are extrinsic to the system and result from wider paleoenvironmental changes, including those related to climatic, sea level, tectonic, volcanic, or anthropogenic perturbations. Where paleoenvironmental changes lead to marked increases in the magnitude and frequency of river flooding, for instance, this may lead to increased rates of floodplain vertical accumulation or meander bend migration. These changed rates may be established by OSL dating, but inferences regarding the drivers of change require comparison with independently dated paleoenvironmental datasets. Uranium-thorium-dated (see "U-Series Dating") or $^{14}$C-dated lacustrine, cave, or marine deposits, for instance, are commonly used to derive proxy records of paleoclimate change (e.g., past precipitation, temperature, and/or vegetation, or some combination thereof, such as indices of moisture availability). A lack of close correspondence between the timing and rates of landform changes established by luminescence dating and the changes in these proxy records might suggest that the dynamics have been driven independently of paleoclimate, such as by intrinsic system dynamics or by some other paleoenvironmental factor (e.g., past tectonics). Where close correspondence exists, however, this provides a basis for paleoclimatic interpretation of the landform changes, and this line of reasoning has been widely adopted in geomorphological enquiries.

## Limitations of luminescence dating in geomorphology

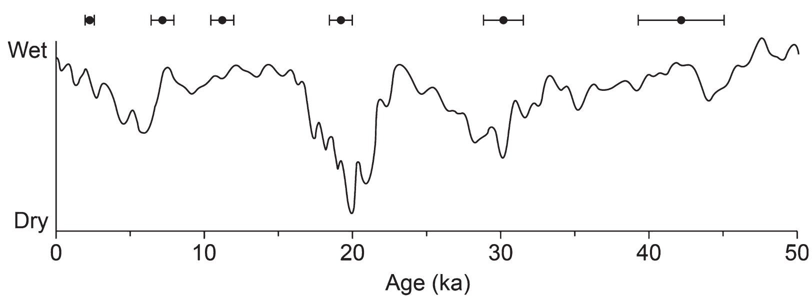
Although the comparison of luminescence chronologies with other paleoenvironmental datasets is common in geomorphological enquiry, potential problems may impinge on this objective. Two common problems are outlined below.

### An inability to establish finite luminescence ages

Where the sediment being dated has a depositional age that approaches or exceeds the age range of the luminescence technique, then saturation of the luminescence signal may occur (see "Luminescence Dating, Uncertainties and Age Range"). In such instances, it may not be possible to determine a finite age, and only a minimum age for deposition can be reported (e.g., >XX years). Although this may provide useful information – for instance, in confirming that basal sediments have minimum ages older than finite ages for overlying sediments – it does not allow calculation of finite vertical accumulation, lateral migration, or forward extension rates and precludes detailed comparison with other paleoenvironmental datasets.

### Limited precision of luminescence ages

Luminescence ages are reported with errors that reflect random and systematic uncertainties; for OSL ages, errors at one sigma (68 % confidence interval) are typically around 5–10 % of the sample age (e.g., see Figures 2b and 3). Hence, although the central age is the most likely, there is actually a 68 % chance that the sample age lies within the reported error range. In some instances, this means that OSL ages for adjacent landforms will overlap within error, causing uncertainty when calculating rates of change. For instance, across a scroll bar sequence in the Klip River floodplain, South Africa, most OSL ages were in the correct order and did not overlap, thereby indicating an approximately steady lateral migration rate of ~0.16 m/year over the last ~1 kyr. Two ages in the middle of the sequence, however, overlapped within error (Figure 2b – samples 3 and 4). In such situations, it may be unclear whether the overlapping ages reflect increased analytical uncertainty associated with particular ages or whether they reflect a short-term increase in the lateral migration rate, although the latter explanation was preferred in the Klip River case (see Rodnight et al., 2005). The limited precision of OSL ages also limits the potential for comparison with high-resolution




**Luminescence, Geomorphological Processes, Figure 4** Hypothetical but realistic illustration of the problems in attempting to correlate luminescence ages (in this instance, from fluvial samples) and associated error bars with the paleoenvironmental changes (paleomoisture index) recorded in higher-resolution datasets for the last 50 kyr. Errors associated with OSL ages generally increase farther back in time and so may encompass one or more peaks and troughs in the paleomoisture index. Consequently, it may not be clear whether periods of fluvial activity identified by the OSL ages have been driven primarily by relatively wet, relatively dry, or transitional (wet-dry, dry-wet) conditions.

paleoenvironmental datasets derived from, say, lacustrine, cave, or marine sediments; errors on OSL ages may overlap with identified fluctuations in past precipitation, temperature, vegetation, or moisture availability (see Figure 4), even those occurring over multimillennial scales, such that paleoenvironmental drivers are hard to establish. In the case of alluvial fans in Death Valley, California, USA, Dorn (1996) has argued that imprecision in many geochronometers means that climatic hypotheses of fan formation are not testable; with some caveats, this argument could be extended to OSL analysis of other landforms. Commonly, however, the lack of precision is acknowledged, and correlation with paleoenvironmental datasets is made using the central ages (e.g., Macklin et al., 2010).

Awareness of these limitations is important when considering the applicability of luminescence dating in geomorphological enquiry, and some may be partially overcome by future developments. For instance, ongoing analytical work using thermally transferred OSL (TT-OSL) is attempting to extend the luminescence dating age range (Rhodes, 2011); in future, this may enable comparisons with longer paleoenvironmental datasets, possibly including those extending back ~500 kyr or farther, although any finite ages are still likely to be associated with large errors. In other instances, the use of luminescence dating in combination with other geochronometers may provide the best approach. In central Australia, for instance, relatively young luminescence saturation ages (typically $<100$ ka) mean that OSL cannot be used to determine the age of aeolian linear dunes that may be many hundreds of thousands or even millions of years old. Hence, Fujioka et al. (2009) combined cosmogenic burial dating (see "Terrestrial Cosmogenic Nuclide Dating") and OSL dating to investigate histories of dune building; cosmogenic ($^{10}Be$–$^{26}Al$) burial dating of the basal sediments helped to determine that the first dunes formed in the western Simpson Desert ~1 Ma, while dating of younger, overlying sediments using OSL indicated that episodic dune reworking and building occurred during late Quaternary glacial intervals. Similarly innovative sampling designs that employ complementary geochronological techniques may be a hallmark of future geomorphological enquiries.

## Conclusions

Over the last few decades, luminescence dating has contributed to a revolution in our understanding of the timing, rates and nature of many geomorphological processes, and their implications for landform and landscape development. Despite some limitations, this increased understanding has occurred in parallel with increasing insight into the paleoenvironmental drivers of change. Further innovations in luminescence sampling approaches (e.g., adoption of "range-finder" OSL dating – Durcan et al., 2010) and ongoing analytical advances (e.g., wider application of single grain OSL dating, the increasing use of feldspars as chronometers, and the development of TT-OSL – Rhodes, 2011) mean that luminescence dating is likely to remain an essential part of the geomorphologist's "toolkit" in the decades to come. This will provide fertile ground for interdisciplinary work in scientific and applied contexts, such as in archaeology, paleoanthropology, paleoseismicity, and environmental management (e.g., Rittenour, 2008; McCarthy et al., 2010; Barré et al., 2012; see also "Luminescence Dating of Archaeological Sediments").

## Bibliography

Barré, M., Lamothe, M., Backwell, L., and McCarthy, T. S., 2012. Optical dating of quartz and feldspars: a comparative study from Wonderkrater, a Middle Stone Age site of South Africa. *Quaternary Geochronology*, **10**, 374–379.

Bateman, M. D., Boulter, C. H., Carr, A. S., Frederick, C. D., Peter, D., and Wilder, M., 2007. Preserving the palaeoenvironmental record in drylands: bioturbation and its significance for luminescence-derived chronologies. *Sedimentary Geology*, **195**, 5–19.

Botha, G. A., Wintle, A. G., and Vogel, J. C., 1994. Episodic late Quaternary gully erosion in northern KwaZulu-Natal, South Africa. *Catena*, **23**, 327–340.

Bristow, C. S., Lancaster, N., and Duller, G. A. T., 2005. Combining ground penetrating radar surveys and optical dating to determine

dune migration in Namibia. *Journal of the Geological Society (London)*, **162**, 315–321.
Cunningham, A. C., and Wallinga, J., 2012. Realizing the potential of fluvial archives using robust OSL chronologies. *Quaternary Geochronology*, **12**, 98–106.
Dorn, R. I., 1996. Climatic hypotheses of alluvial-fan formation in Death Valley are not testable. In Rhoads, B. L., and Thorn, C. E. (eds.), *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology held 27–29 September 1996*. Chichester: Wiley, pp. 191–220.
Duller, G. A. T., 2004. Luminescence dating of Quaternary sediments: recent advances. *Journal of Quaternary Science*, **19**, 183–192.
Durcan, J. A., Roberts, H. M., Duller, G. A. T., and Alizai, A. H., 2010. Testing the use of range-finder OSL dating to inform field sampling and laboratory processing strategies. *Quaternary Geochronology*, **5**, 86–90.
Fuchs, M., and Lang, A., 2009. Luminescence dating of hillslope deposits – a review. *Geomorphology*, **109**, 17–26.
Fujioka, T., Chappell, J., Fifield, L. K., and Rhodes, E. J., 2009. Australian desert dune fields initiated with Pliocene-Pleistocene global climatic shift. *Geology*, **37**, 51–54.
Hollands, C. B., Nanson, G. C., Jones, B. G., Bristow, C. S., Price, D. M., and Pietsch, T. J., 2006. Aeolian-fluvial interaction: evidence for late Quaternary channel change and wind-rift linear dune formation in the northwestern Simpson Desert, Australia. *Quaternary Science Reviews*, **25**, 142–162.
Keen-Zebert, A., Tooth, S., Rodnight, H., Duller, G. A. T., Roberts, H. M., and Grenfell, M., 2013. Late Quaternary floodplain reworking and the preservation of alluvial sedimentary archives in unconfined and confined valleys in the eastern interior of South Africa. *Geomorphology*, **185**, 54–66.
Macklin, M. G., Tooth, S., Brewer, P. A., Noble, P. L., and Duller, G. A. T., 2010. Holocene flooding and river development in a Mediterranean steepland catchment: the Anapodaris Gorge, south-central Crete, Greece. *Global and Planetary Change*, **70**, 35–52.
Madsen, A. T., Murray, A. S., Andersen, T. J., Pejrup, M., and Breuning-Madsen, H., 2005. Optically stimulated luminescence dating of young estuarine sediments: a comparison with $^{210}$Pb and $^{137}$Cs dating. *Marine Geology*, **214**, 251–268.
Maroulis, J. C., Nanson, G. C., Price, D. M., and Pietsch, T., 2007. Aeolian-fluvial interaction and climate change: source-bordering dune development over the past 100 ka on Cooper Creek, central Australia. *Quaternary Science Reviews*, **26**, 386–404.
McCarthy, T. S., Tooth, S., Kotze, D. C., Collins, N., Wandrag, G., and Pike, T., 2010. The role of geomorphology in evaluating remediation options for floodplain wetlands: the case of Ramsar-listed Seekoeivlei, eastern South Africa. *Wetlands Ecology and Management*, **18**, 119–134.
Nanson, G. C., Callen, R. A., and Price, D. M., 1998. Hydroclimatic interpretation of Quaternary shorelines on South Australian playas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **144**, 281–305.
Nanson, G. C., Jones, B. G., Price, D. M., and Pietsch, T. J., 2005. Rivers turned to rock: late Quaternary alluvial induration influencing the behaviour and morphology of an anabranching river in the Australian monsoon tropics. *Geomorphology*, **70**, 398–420.
Pietsch, T. J., Olley, J. M., and Nanson, G. C., 2008. Fluvial transport as a natural luminescence sensitiser of quartz. *Quaternary Geochronology*, **3**, 365–376.
Rhodes, E. J., 2011. Optically stimulated luminescence dating of sediments over the past 200,000 years. *Annual Review of Earth and Planetary Sciences*, **39**, 461–488.
Rink, W. J., and López, G. I., 2010. OSL-based lateral progradation and aeolian sediment accumulation rates for the Apalachicola Barrier Island Complex, North Gulf of Mexico, Florida. *Geomorphology*, **123**, 330–342.
Rittenour, T., 2008. Luminescence dating of fluvial deposits: applications to geomorphic, palaeoseismic and archaeological research. *Boreas*, **37**, 613–635.
Roberts, H. M., 2008. The development and application of luminescence dating to loess deposits: a perspective on the past, present and future. *Boreas*, **37**, 483–507.
Roberts, H. M., and Plater, A. J., 2007. Reconstruction of Holocene foreland progradation using optically stimulated luminescence (OSL) dating: an example from Dungeness, UK. *The Holocene*, **17**, 495–505.
Rodnight, H., Duller, G. A. T., Tooth, S., and Wintle, A. G., 2005. Optical dating of a scroll-bar sequence on the Klip River, South Africa, to derive the lateral migration rate of a meander bend. *The Holocene*, **15**, 802–811.
Rodnight, H., Duller, G. A. T., Wintle, A. G., and Tooth, S., 2006. Assessing the reproducibility and accuracy of optical dating of fluvial deposits. *Quaternary Geochronology*, **1**, 109–120.
Singhvi, A. K., and Porat, N., 2008. Impact of luminescence dating on geomorphological and palaeoclimate research in drylands. *Boreas*, **37**, 536–558.
Telfer, M. W., 2011. Growth by extension, and reworking, of a south-western Kalahari linear dune. *Earth Surface Processes and Landforms*, **36**, 1125–1135.
Telfer, M. W., Thomas, Z. A., and Breman, E., 2012. Sand ramps in the Golden Gate Highlands National Park, South Africa: evidence of periglacial aeolian activity during the last glacial. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **313–314**, 59–69.
Thompson, C., Rhodes, E., and Croke, J., 2007. The storage of bed material in mountain stream channels as assessed using Optically Stimulated Luminescence dating. *Geomorphology*, **83**, 307–321.
Tooth, S., Rodnight, H., McCarthy, T. S., Duller, G. A. T., and Grundling, A., 2009. Late Quaternary dynamics of a South African floodplain wetland and the implications for assessing recent human impacts. *Geomorphology*, **106**, 278–291.

## Cross-references

Luminescence Dating of Archaeological Sediments
Luminescence Dating
Luminescence Dating, History
Luminescence Dating, Deep-Sea Marine and Lacustrine
Luminescence, Earthquake and Tectonic Activity
Luminescence, Glacial Sediments
Luminescence Dating, Uncertainties and Age Range
Radiocarbon Dating
Terrestrial Cosmogenic Nuclide Dating
U-Series Dating

# LUMINESCENCE, GLACIAL SEDIMENTS

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## Definition

*Glacial*. Of, or pertaining to, ice masses of sufficient magnitude that they are able to deform under their own mass.

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