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Optical dating in archaeology: thirty years in retrospect and grand challenges for the future

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ABSTRACT

In 1982, when Richard Klein first became one of the Editors of this journal, the luminescence dating community was embarking on a new phase of exploratory research. Attention was turning from the use of thermoluminescence (TL) dating to estimate the time of last heating of archaeological objects, such as pottery and burnt flint, to the TL dating of unheated sediments that had been transported by wind and then deposited on the landscape. This revolutionary development enabled the extension of TL dating to sedimentary deposits in a variety of environmental settings and to the multitude of archaeological sites that lack suitably heated artefacts. In sediment dating, the age of most interest is usually the time elapsed since grains of quartz or feldspar were last exposed to sunlight, as the energy of the sun's rays is sufficient to evict electrons from their light-sensitive traps. These traps are steadily refilled after sediment deposition and the longer the grains remain buried, the more TL they will emit when measured. In 1985, Huntley and colleagues proposed ‘optical dating’ as a simpler and superior means of stimulating the light-sensitive traps in Quaternary sediments, and this is now the principal luminescence-based method of dating geological and archaeological deposits. Optical dating is an umbrella term for an armada of acronyms, the most common in archaeological contexts being OSL (optically stimulated luminescence), TT-OSL (thermally-transferred OSL), IRSL (infrared stimulated luminescence) and pIRIR (post-infrared IRSL). All of these variants are founded on the same basic tenet – measurement of a light-sensitive signal to determine (typically) the last time that sediment grains were sun-bleached – but each approach has its virtues and vices. In this paper, we review this ‘family’ of luminescence dating techniques and look back on 30 years of optical dating in archaeology. Some of the more interesting and important achievements are highlighted, including the critical insights gained in the last two decades from OSL measurements of individual grains of quartz. We also look to the future of optical dating in archaeological contexts. Efforts to extend the age limits of optical dating to older hominin and archaeological sites will remain a key goal, and understanding how archaeological sites – of all ages – form and evolve over time could be improved greatly by combining micromorphology analysis with optical dating of undisturbed (intact) sediments. The latter poses a series of particularly formidable technical challenges, but if the past is any guide to the future, then we can expect optical dating to illuminate much more of human history before celebrating its Golden Jubilee.

1. Ancestral flashbacks

The potential for luminescence dating in archaeological contexts can be traced back to Daniels et al. (1953), who were the first to suggest that the luminescence response of naturally occurring minerals to ionising radiation could be used as a tool for estimating the time since ancient pottery was last heated. Tests on archaeological ceramics followed within a few years (Grögler et al., 1960).

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For the next two decades, attention was focussed on heated pottery and ceramics from archaeological sites (for dating) and museum collections (for authenticity testing), as well as burnt flints, baked hearth sediments, oven stones from burnt mounds and other heated objects (Fleming, 1979; Aitken, 1985, 1990; Wintle, 2008).

In these pioneering studies, mineral grains were stimulated in the laboratory by heating them to 500 °C, and the thermally-induced glow – or thermoluminescence (TL) – was detected by a photomultiplier tube. Unlike incandescence, the production of TL requires that the grains had received a prior dose of ionising radiation, which is derived mainly from local sources of environmental radioactivity – namely, the sediments surrounding the artefacts and chemical impurities inside the artefacts themselves.

Many minerals emit luminescence, but quartz and feldspar – the two most abundant minerals on Earth – have been used most often for dating. Grains act as tiny radiation dosimeters, absorbing the incoming radiation energy and storing a small fraction of it as trapped electrons at defects in their crystal lattices. These electrons can be released from their traps by heating the grains in the laboratory, with the intensity of the induced TL providing a measure of the time elapsed since the object was last heated. The *Journal of Archaeological Science* was quick to publish a review of TL dating in just its second year (Seeley, 1975).

In the early 1960s, it was noticed that the TL traps in calcite and sediment could be bleached by sunlight (Aitken et al., 1963), but Soviet scientists working on loess deposits in the Ukraine were the first to apply TL dating to unheated sediments (Shelkoplyas and Morozov, 1965). They proposed that the trap-emptying mechanism was weathering, grinding by glaciers and exposure to sunlight. By the late 1970s, the light-sensitive TL traps in silt- and sand-sized grains of quartz and feldspar were being investigated more widely as a means of dating terrestrial and marine deposits (Dreimanis et al., 1978; Wintle and Huntley, 1979). In 1982 – the same year that Richard Klein became an Editor of this journal – a landmark review of these revolutionary developments was published in the first issue of *Quaternary Science Reviews* (Wintle and Huntley, 1982), and three other papers laid the groundwork for TL dating of sediments transported and deposited by wind and water (Prescott, 1982; Readhead, 1982; Singhvi et al., 1982).

Three years later, Huntley et al. (1985) proposed a more direct and effective means of accessing the light-sensitive electron traps: shine a powerful green laser on the mineral grains and measure the resulting optically-induced luminescence. They coined the term ‘optical dating’ for this new method, and reported the first-ever optical ages for archaeological sediments. Hütt et al. (1988) subsequently found that infrared photons were sufficiently energetic to stimulate luminescence from potassium feldspars, thereby enabling optical dating using inexpensive infrared light-emitting diodes (LEDs). By the mid-1990s, optical dating had replaced TL dating as the method of choice for sediments that had been exposed to the sun's rays prior to deposition. Reviews of TL dating and the first decade of optical dating – with examples of archaeological applications – are available elsewhere (Feathers, 1996; Roberts, 1997; Aitken, 1998), including a horizon scan of promising new opportunities for optical dating that was published in this journal (Wintle, 1996).

Here we pick up the story in the late 1990s, when optical dating was undergoing a major transformation – the development of ‘single aliquot’ methods to measure the radiation energy stored in separate portions and individual grains of heated and unheated quartz. We also reflect on some current advances and future directions of optical dating that could further illuminate our human past. However, this paper is not intended as a comprehensive review of either the field of optical dating or the wide range of archaeological questions to which the technique has been applied. The choice of subject matter instead reflects our personal research interests in archaeology and geochronology, drawing extensively on case studies from our own investigations, and we appreciate that others may not share our views of the most important or promising developments. For example, we do not discuss applications of optical dating to heated artefacts, anthropogenic structures or Holocene archaeological deposits, but we cite many other publications that readers can consult for information on such topics, such as the recent overview by Liritzis et al. (2013). Finally, although this paper is focussed on archaeological sediments deposited during the Pleistocene, optical dating also has many uses in much younger contexts and may be preferable to radiocarbon (^{14}C) dating of archaeological events and objects from the recent past.

2. Optical dating: the basics

How do we calculate optical ages? At its simplest, the age equation can be expressed in the following form:

$$\text{age} = \text{equivalent dose}/\text{environmental dose rate}$$

The equivalent dose is reported in gray (Gy), where 1 Gy = 1 J/kg of absorbed radiation energy. Mineral grains will absorb energy while buried and shielded from light, resulting in the gradual filling of vacant electron traps. So the equivalent dose is a measure of the amount of energy stored – and time elapsed – since the traps were last emptied by sunlight. The term ‘equivalent’ is needed because the number of trapped electrons depends on both the dose received and the type of radiation (Huntley et al., 1985). The equivalent dose is sometimes referred to as the palaeodose, but the term used should be ‘palaeodose equivalent’ because the actual past radiation dose is not determined (Huntley, 2001). The denominator in the equation – the environmental dose rate – is reported in Gy per unit time and represents the rate of delivery of all environmental sources of ionising radiation to the grains over the same time span. As the true dose rate is not measured, the term ‘equivalent’ applies to the denominator also, but is frequently omitted (Huntley, 2001; Lian and Huntley, 2001).

Optical ages are calculated directly in calendar years (or sidereal years, strictly speaking), so there is no need for subsequent calibration such as that applied to ^{14}C ages to convert ‘radiocarbon years’ into sidereal years. The denominator and numerator in the age equation are measured using different methods. Here we summarise only the main aspects of their measurement, as currently practiced, to provide background context for the current and future developments described later. Aitken (1998), Lian and Huntley (2001) and Duller (2008a) give additional details, written with end-users in mind, including practical guidelines on how to collect samples in the field. Other overviews of optical (and TL) dating with archaeological examples include Troja and Roberts (2000), Bøtter-Jensen et al. (2003), Feathers (2003), Lamothe (2004), Lian and Roberts (2006), Jacobs and Roberts (2007), Preusser et al. (2008), Rhodes (2011), Burbidge (2012), Lian (2013), Liritzis et al. (2013) and Wintle (2014).

2.1. The denominator

The environmental dose rate is the sum of the individual alpha, beta and gamma dose rates, plus the contribution from cosmic rays, which is usually estimated from published equations (Prescott and Hutton, 1994). Cosmic rays typically account for only a small fraction of the total dose rate, with the majority supplied by the radioactive decay of uranium and thorium (^{238}U, ^{235}U, ^{232}Th and the daughter products in each of these chains) and potassium (^{40}K) in