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Research paper

Testing the applicability of optically stimulated luminescence dating to Ocean Drilling Program cores

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ABSTRACT

Chronologies for marine sediments are usually constructed by tuning marine proxies for global ice volume ($\delta^{18}O$) to the well understood variations in the Earth's orbit, by the identification of event horizons and/or by radiocarbon dating. However, these techniques are not universally applicable. Optically stimulated luminescence dating (OSL) is potentially widely applicable to marine cores and may offer significant advantages over more conventional chronometric techniques but methodological considerations regarding the application of the techniques have yet to be systematically explored. Using material from core Ocean Drilling Program (ODP) core 658B, we assess the applicability of OSL dating to deep ocean sediments. For this core, equivalent dose does not change with depth below the split core face beyond the upper 1 mm, indicating that retrieval and prolonged storage of ODP material does not compromise the OSL signal. However equivalent dose decreases with increasing particle size, reaching a plateau at ~30–40 μm. These data suggest that ocean floor sediment reworking causes the deposition of old material at the sediment-water interface, potentially resulting in OSL age overestimates. This observation strongly suggests that seafloor reworking processes should be considered both when selecting target cores and when interpreting results. Nonetheless, we observe a good general agreement between OSL ages and independent age estimates for a suite of sediments from the Marine Isotope Stage 6-5e transition, suggesting that the application of luminescence dating techniques to deep-sea sediments merits further investigation.

1. Introduction

Marine sediments are widely exploited archives of palaeoenvironmental information. Chronologies for marine sediments are usually constructed by tuning marine proxies for global ice volume ($\delta^{18}O$) to the well understood variations in the Earth's orbit (Lisiecki and Raymo, 2005), by the identification of event horizons such as tephras (e.g. Matthews et al., 2015) and geomagnetic excursions (e.g. Collins et al., 2012) and/or by radiocarbon dating. While tremendously powerful, these techniques are not universally applicable. Dating marine sediments using radiocarbon methods or the $\delta^{18}O$ signal is difficult for sites below the carbonate compensation depth (e.g. much of the Southern Ocean), and radiocarbon dating is not applicable beyond ~50–60 ka even where carbonate is preserved. Correlation of the $\delta^{18}O$ record from a particular core to a “stacked” record (e.g. Lisiecki and Raymo, 2005) is often complicated by site specific factors such as: 1) hiatuses in the depositional record due to bottom current reworking; 2) smoothing of the $\delta^{18}O$ signal by bioturbation, such that only the most pronounced events are discernible and 3) misidentification of events in complex isotopic stages such marine isotope stage (MIS) 5. Event horizons such as tephras are invaluable in integrating marine and terrestrial records, but are only useful where their occurrence is frequent in the period of interest. In addition, accurate identification of both tephra horizons and geomagnetic excursions in marine cores frequently requires an initial lower-precision age model e.g. where a single source emits multiple geochemically similar tephras, such as the Campi Flegrei between c. 17–14 ka BP (Matthews et al., 2015). These limitations have rendered some timeframes and regions difficult to date. For example, in the carbonate free regions of the Arctic Ocean, competing chronostratigraphic interpretations yield sedimentation rates which differ by an order of magnitude (Berger, 2006). Consequently, several authors (e.g. Armitage, 2015; Berger, 2006;

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Jakobsson et al., 2003; Stokes et al., 2003) have advocated the use of optically stimulated luminescence (OSL) as an additional method to provide age information for deep-sea sediments.

OSL is a radiometric dating technique which determines the time elapsed since a mineral grain (usually quartz or feldspar) was last exposed to sunlight (i.e. burial period) and has gained wide acceptance as a tool for developing terrestrial chronologies (Olley et al., 2004). An OSL age is calculated using Equation (1):

$$\text{Age (ka)} = \text{Equivalent dose } (Gy)/\text{Dose rate (Gy/ka)} \tag{1}$$

where the equivalent dose (D_e) is the laboratory estimate of the cumulative exposure of a sample to ionising radiation since deposition, and the dose rate is the rate of exposure to ionising radiation. In principle, luminescence methods can date any marine sediment containing quartz (to ~200 ka) or feldspar (to ~500 ka), provided that these minerals were subaerially exposed immediately prior to deposition. However, a number of potential impediments to the routine application of OSL dating to deep-sea sediments, relating to determination of both the equivalent dose and the dose rate, have been identified. Determination of a chronologically useful equivalent dose may be hampered by: 1) the incorporation of material which was not exposed to sufficient sunlight prior to deposition to completely reset the OSL signal (Berger, 2006); 2) depletion of the OSL signal due to light exposure during core retrieval and storage, and 3) reworking of older material into sediments during deposition, leading to an overestimation of the depositional age (Armitage, 2015; Berger, 2006). Accurate determination of the dose rate for deep-sea sediments is complicated by disequilibrium in the uranium decay series due to incorporation of excess long-lived insoluble isotopes (^{230}Th in the ^{238}U series and ^{231}Pa in the ^{235}U series) into seafloor sediments (Stokes et al., 2003; Wintle and Huntley, 1979) and authigenic uranium uptake at the sediment-water interface under reducing conditions (Armitage, 2015).

In this study we use sediment from Ocean Drilling Program (ODP) core 658B (Ruddiman et al., 1988) to test the applicability of optically stimulated luminescence dating to marine sediments. Specifically we aim to: 1) assess directly the depletion of the OSL signal due to light exposure during core retrieval and storage; 2) test the hypothesis (Armitage, 2015) that coarser quartz grains are less prone to seafloor reworking and hence are the preferred dosimeter for OSL dating of deep-sea sediments, and 3) test the applicability of OSL to sediments beyond the range of ^{14}C by dating known-age material from marine isotope stage MIS 6-5e.

2. Materials and methods

Core 658B was recovered in 1986 from a water depth of 2263 m off Cap Blanc, Mauritania (20°45′N, 18°35′W) during ODP Leg 108 (Ruddiman et al., 1988). Trade winds cause strong upwelling over the site, leading to high surface productivity and high biogenic particle fluxes to the seafloor. Biogenic carbonate comprises 40–60% by mass of the sediment, and until recently the remainder was thought to consist of terrigenous dust (deMenocal et al., 2000) due to the site's location beneath the axis of the summer African dust plume (Fig. 1). However, recent analysis of orbital radar satellite imagery has been used to propose that during the late-glacial to Holocene African Humid Period (~11.5–5 ka, Armitage et al., 2015; deMenocal et al., 2000; McGee et al., 2013) a major river within the Tamanrasset palaeowatershed delivered large amounts of fluvial sediment to this site (Skonieczny et al., 2015). Irrespective of the transport pathway followed by terrigenous sediments in ODP Core 658B, Armitage (2015) was able to measure OSL ages which were consistent with independent chronological information over the timeframe ~10–50 ka, suggesting that the OSL signal in this

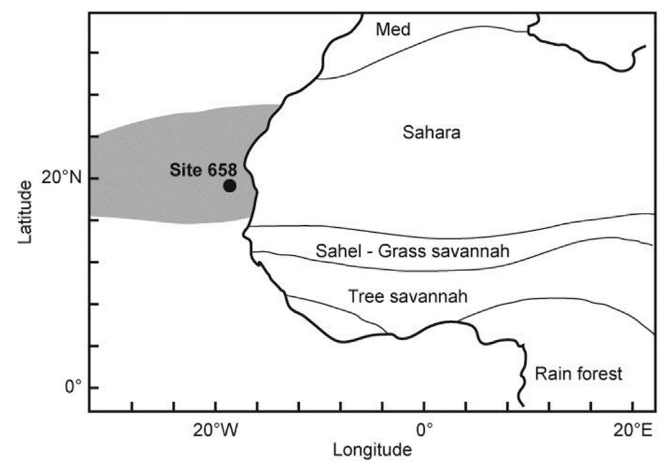

Fig. 1. Location of ODP Site 658 under the summer African dust plume (grey). Redrawn from deMenocal et al. (2000).

material was completely reset by subaerial exposure immediately prior to deposition.

Core 658B is an ideal target for testing OSL dating in the marine realm since: 1) It has a high accumulation rate (c.18 cm/ka,deMenocal et al., 2000); 2) The high terrigenous sediment flux provides a substantial well-bleached quartz component; 3) The terrigenous sediments have a sufficiently wide grain-size range to test the hypothesis that coarse grains are less prone to seafloor reworking; 4) The excess ^{230}Th ($^{230}Th_{xs}$) record for Core 658C (Adkins et al., 2006) may be used to calculate excess activity in Core 658B and 5) Core 658B was 16 years old when sampled so the deleterious effects (if any) of light exposure during storage should be pronounced.

2.1. Equivalent dose determination

Samples were collected in July 2002 from a 66 mm diameter split core at the ODP East Coast Repository, Lamont-Doherty Earth Observatory, USA. Paired samples were taken every ~25 cm through the uppermost 11 m of the core by inserting short sections of 20 mm diameter opaque tubing. This approach yielded two ~7 cm^3 sub-samples per level. Samples were processed under subdued orange light at the Royal Holloway luminescence laboratory. In all cases the outer (closest to the core barrel) ~8 mm was discarded to avoid core barrel smearing (Fig. 2). For the samples presented in Sections 4 and 5 the light exposed upper (split core face) ~8 mm was removed and used for carbonate content and dose rate analysis, while the remaining middle ~8 mm of the sample was dispersed in deionised water and sieved at 150 μm. The >150 μm fraction consisted of foraminiferal tests, and <150 μm fraction was used for equivalent dose measurements. For the samples presented in Section 3, the upper 5 mm of sediment was removed in 1 mm thick slices, and an equivalent dose was measured for material from each slice. Equivalent doses were measured on quartz isolated from samples by treating them with HCl and H_2O_2 to remove carbonate and organic matter respectively. The resulting material was then separated into the required size fraction using Stokes settling for fractions ≤20 μm and wet sieving for larger fractions, and feldspar was subsequently removed using H_2SiF_6 followed by an HCl rinse.

All OSL measurements presented in this study were carried out using a Risø TL/OSL-DA-20 automated dating system. Optical stimulation of single aliquots was carried out using a blue (470 ± 30 nm) light emitting diode (LED) array with a power density of ~90 mW/cm^2. Infra-red (IR) stimulation was carried out