Radiation Measurements 81 (2015) 142–149

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Using grain-size characteristics to model soil water content: Application to dose-rate calculation for luminescence dating

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HIGHLIGHTS

- Using grain size characteristics to generate water retention curves.
- Saturation water content was estimated using laboratory and computer modeling.
- *In situ* water content is compared with the model outputs.
- Dose-rate variability with new water content estimates is evaluated.

ARTICLE INFO

Article history:
Available online 21 February 2015

Keywords:
Water content
Dose-rate determination
Luminescence dating
Mean annual water state
Soil moisture regime

ABSTRACT

Soil moisture is an important factor for dose-rate determination in luminescence and other dating methods as soil water content impacts sediment bulk density, alters rates of chemical reactions and attenuates effective exposure to nuclear radiation from the surrounding sediments and incoming cosmic rays. Given its importance in dose-rate calculation, methods for measuring and modeling soil water content are discussed, with special focus on semi-arid environments and other situations where modern *in situ* values are unlikely to be representative of mean soil moisture conditions. We present an alternative method for calculating sediment water content based on grain-size characteristics using the freely available Rosetta Lite v.1.1 software. Modeled outputs include saturation, residual and other water retention curve (WRC) parameters. WRCs were generated from model outputs using the van Genuchten (1980) equation, and mean annual water state was determined using soil moisture regime maps and classifications. Dose-rate values using modeled outputs and laboratory-measured *in situ* and saturation water content are compared in a test case using Holocene alluvial sediments from Kanab Creek in southern Utah, USA. Best practices for how to estimate mean annual water state for different soil moisture regimes and past soil moisture content in situations where *in situ* values are not representative of the burial history are discussed.

1. Introduction

Pore-space water content in surficial deposits can range from desiccated to saturated, and can vary between these end members on seasonal, decadal, and/or geologic time-scales. Variations in soil water content are especially dramatic in semi-arid environments that experienced past pluvial climates, such as the southwestern U.S. Water content can vary due to intense short-term precipitation events, seasonal moisture variations, inter-annual to decadal-scale drought and centennial to millennial-scale fluctuations in groundwater levels related to changes in base level and shifts in climatic regime. Moreover, natural and man-made sediment exposures are influenced by surface drying effects, reducing soil moisture in the outer decimeter to meter of the sediment–air interface. Similar drying effects from evapotranspiration can be seen below the land surface, although opposite influences of perched water lenses can also occur at any depth due to impermeable sediment layers that retard infiltration. Construction of reservoirs and ground water pumping can also alter mean soil moisture at a site. Additionally, chemical weathering of clay minerals and mineral precipitation in pore spaces (i.e. carbonate) over longer time-scales can also modify the soil water content of a

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http://dx.doi.org/10.1016/j.radmeas.2015.02.016
1350-4487/

deposit (Jeong et al., 2007; Nathan and Mauz, 2008). For these reasons, samples collected for measurement of *in situ* moisture content can under- or over-estimate the average sediment moisture content, depending on circumstances prior to sampling and recent meteorological, climate and ground water conditions at the site.

While difficult to estimate, mean soil moisture conditions are an important variable in rate calculations for a number of Quaternary dating techniques. For example, soil temperature and moisture conditions affect the rate of chemical alteration used in the obsidian-hydration dating technique (Friedman and Smith, 1960; Friedman et al., 1997). Soil water content (and snow cover) is also important for calculation of terrestrial cosmogenic nuclide (TCN) production rates (Gosse and Phillips, 2001), especially for TCNs that are produced via low-energy epithermal and thermal neutron capture (^{36}Cl, or ^{41}Ca for example), as hydrogen in water is a strong moderator of neutrons (Phillips et al., 2001). While less of a problem for surface exposure dating using TCNs generated by high-energy particles (^{10}Be and ^{26}Al for example), variable water content will also influence time-averaged TCN production rates due to changes in mass-depth (bulk density) history (Hidy et al., 2010). This is especially important for age calculation from depth profiles (Hancock et al., 1999) and cosmogenic burial dating (Granger and Muzikar, 2001), causing significant uncertainty in older samples. Moreover, pore-space water content affects radioisotope concentration per unit mass and attenuates sub-atomic particles produced by nuclear decay (alpha, beta and gamma), which reduces effective dose-rates used in age calculation for election-spin resonance (ESR; Zeller et al., 1967; Grün, 1997) and luminescence dating (Aitken, 1985, 1998) techniques.

Although the methods and discussion described here are applicable to all techniques that are dependent on soil moisture for age calculation, this paper focuses on the influence of water content on dose-rate calculation for luminescence dating. Methods for water content measurement are presented, with particular focus on the use of grain-size characteristics to model water retention curve (WRC) parameters used for determining the water content at the mean annual water state (MAWS) for sites where *in situ* measurements are either not possible or inaccurate due to recent drying or anomalously wet conditions during sampling.

2. Influence of water content on dose rate

Water within sediment pore spaces affects environmental dose rate by dilution, causing a decrease in radioelement concentration per unit mass, and absorption, as water can absorb more radiation per unit mass than sediment with air filling pore spaces (Aitken, 1985). Therefore, dry environmental dose-rate calculations derived from radioisotopes of potassium, uranium and thorium in the sediments and incoming cosmic radiation need to be adjusted for water content. As the equivalent dose (D_E) of radiation received during burial is divided by the dose rate (D_R) to calculate a luminescence age, failure to incorporate water content in the dose-rate calculation could cause a significant age underestimation.

Dry dose-rate values are adjusted for water content by dividing the contribution from each radiogenic particle type (alpha, beta, gamma) by $1 + xWF$, where W is the saturated gravimetric water content, F is the fraction of pore-space occupied by water, and x is the attenuation factor (see Zimmerman, 1971; Aitken and Xie, 1990; and updates to gamma attenuation by Guérin and Mercier, 2012). While the saturation water content (W) can be measured in the laboratory (see section 3 below for methods), the fraction of saturation (F) is a more subjective term and is driven by presumptions of the average water content at the sample site. Therefore, it is common that *in situ* water content measurements are used instead of WF. However, as described above, *in situ* water content is commonly not representative of mean soil moisture conditions over burial history. This paper aims to address these problems and provides an alternative method for estimating mean soil moisture state.

3. Methods for determining water content

Water content within sediments can be determined using *in situ*, laboratory or model-based methods. The method used will depend on the specific conditions related to sample collection, the representative nature of the field state of the sediments and the available laboratory and field instrumentation.

3.1. Measurement of in situ water content

In most cases, samples for *in situ* moisture content determination can be collected from the same material as collected for D_R and the light-safe sample for D_E determination. These samples should be collected in air-tight containers such as a plastic canister or triple bagged and measured for gravimetric water content as soon after field sampling as possible to reduce moisture loss by evaporation. Samples for water content should be collected far back from the free face of the sediment exposure to minimize surface drying effects. Notes should also be made on how representative the sample is relative to assumptions regarding average moisture conditions during burial history. For the laboratory gravimetric water content calculation, the difference between the weight of the wet sample and that of the dry sample (obtained after drying in a 100 °C oven at least overnight) is divided by the weight of the dried sample.

In situ field water content measurements can also be determined by using various soil moisture probes (e.g. Walker et al., 2004). While some of these probes require complete burial of the sensor, some can be inserted into an outcrop exposure horizontally, allowing measurement from the same location as sampled for luminescence dating. Techniques used for determining soil water content vary by sensor and include the use of electrical conductivity, neutron scattering, gamma ray attenuation and the soil dielectric constant.

Irrespective of the method used, all *in situ* moisture content measurements can suffer from non-representative conditions at the time of sampling or effects of surface drying at the exposure front. For this reason, it is commonly beneficial to measure the saturation water content to calculate end-member conditions and WF for dose-rate calculation. In some circumstances, such as with museum specimens of pottery or long-exposed trenches and natural outcrops, samples for *in situ* moisture content are not available or are non-representative of environmental or burial conditions.

3.2. Measurement of saturation water content

Saturation water content can be measured in the laboratory either by collecting samples in the field that preserve the original grain packing of the sediment or by compressing sediments into a container to replicate original grain packing and then carefully filling the void space with water. Grain packing can also be achieved by use of a centrifuge or by packing in a large syringe cylinder with plunger. After pore space is filled and excess water has been allowed to drain off, the saturation gravimetric water content can be calculated by the difference between the wet and dry weight of the sample.

The greatest problem with the saturation water content measurement has to do with the need to replicate the level of compaction of the sediment in the field as this will greatly affect pore space volume. This is especially important for lacustrine and marine sediments that have undergone compaction and water loss