Quaternary International 362 (2015) 42–49

Contents lists available at ScienceDirect

Quaternary International

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

Variables and potential models for the bleaching of luminescence signals in fluvial environments

Harrison J. Gray [a, b, *], Shannon A. Mahan [a]

[a] U.S. Geological Survey, Box 25046, MS 974, Denver Federal Center, Denver, CO 80225, USA
[b] Cooperative Institute for Environmental Research, University of Colorado – Boulder, CO 80302, USA

ARTICLE INFO

Article history:
Available online 3 January 2015

Keywords:
Bleaching
OSL
Luminescence
Fluvial
Model
IRSL

ABSTRACT

Luminescence dating of fluvial sediments rests on the assumption that sufficient sunlight is available to remove a previously obtained signal in a process deemed bleaching. However, luminescence signals obtained from sediment in the active channels of rivers often contain residual signals. This paper explores and attempts to build theoretical models for the bleaching of luminescence signals in fluvial settings. We present two models, one for sediment transported in an episodic manner, such as flood-driven washes in arid environments, and one for sediment transported in a continuous manner, such as in large continental scale rivers. The episodic flow model assumes that the majority of sediment is bleached while exposed to sunlight at the near surface between flood events and predicts a power-law decay in luminescence signal with downstream transport distance. The continuous flow model is developed by combining the Beer–Lambert law for the attenuation of light through a water column with a general-order kinetics equation to produce an equation with the form of a double negative exponential. The inflection point of this equation is compared with the sediment concentration from a Rouse profile to derive a non-dimensional number capable of assessing the likely extent of bleaching for a given set of luminescence and fluvial parameters. Although these models are theoretically based and not yet necessarily applicable to real-world fluvial systems, we introduce these ideas to stimulate discussion and encourage the development of comprehensive bleaching models with predictive power.

1. Introduction

The successful dating of fluvial deposits by luminescence geochronology often involves identifying populations of grains that have had their prior luminescence signal removed by exposure to sunlight via fluvial processes. This process of signal removal, known as bleaching, zeroing, or resetting, is a function of geomorphic variables such as sediment flux, turbidity, and depth of water, turbulence of flow, light spectrum, grain size, and transportation distance among others (Jain et al., 2004). Incomplete removal of a prior signal is referred to as partial-bleaching. While awareness of the connections has existed, the use of luminescence signals as proxies for geomorphic processes remains a significant research frontier (Heimsath and Ehlers, 2005). The goal of this paper is to present hypotheses that initiate discussion on building comprehensive, quantitative, and falsifiable models, which in turn will clarify the connections between fluvial geomorphic process and the luminescence signal. While aspects of the proposed models presented here are untested, they potentially set a theoretical framework and starting point for future models. Further refinement of the models will allow stronger connections between luminescence data and geomorphic change.

A review of residual luminescence signals in modern or active channel sediment has been offered by other researchers (e.g. Berger, 1990; Jain et al., 2004; Rittenour, 2008; Porat et al., 2010; Murray et al., 2012). Numerous studies have tested the degree of luminescence resetting in modern sediments (Singarayer et al., 2005; Alexanderson, 2007; Fiebig and Preusser, 2007; Vandenberghe et al., 2007; Hu et al., 2010; Alexanderson and Murray, 2012). Generally, far-traveled modern sediments contain equivalent doses indistinguishable from zero (Singarayer et al., 2005; Arnold, 2006), however significant residual doses are possible if sediment is transported at night or as high sediment loads (Jain et al., 2004; Hu et al., 2010). A general pattern of equivalent dose (D_e) decrease with transport distance has been observed (Stokes et al., 2001; Hu et al., 2010; Summa-Nelson and

* Corresponding author. U.S. Geological Survey, Box 25046, MS 974, Denver Federal Center, Denver, CO 80225, USA.

http://dx.doi.org/10.1016/j.quaint.2014.11.007

Rittenour, 2012) and is possibly dependent on grain mineralogy and size (Hu et al., 2010). Interestingly, some researchers have observed an exponential decrease in equivalent dose with transport distance such as the minimum D_e values seem in the sediment of Loire River in France (Stokes et al., 2001), or it can appear with the form of an individual infrared stimulated luminescence (IRSL) decay as seen in the post-infrared (pIR) IRSL values for Mojave River sediment in California, USA (McGuire and Rhodes, 2015). However, Pietsch et al. (2008) note that this may be due to the generation of luminescence grains due to repeated bleach and irradiation cycles. The relationship between partial bleaching and transport mechanics, i.e. transport rate and system storage time, represents a potentially new frontier in applying luminescence towards fluvial geomorphic processes.

1.1. Light penetration through matter

The ability of a geomorphic system to promote bleaching in a luminescence signal is dependent on the availability of sufficient light to detrap electrons stored in lattice defects (Aitken, 1998; Rhodes, 2011). In aeolian systems, the exposure of light is often enough such that residual signals are minimal (Singarayer et al., 2005; Porat et al., 2010). However, in typical geomorphic environments involving the fluvial transport of grains, zeroing assumptions are not always valid (e.g., Stokes et al., 2001; Wallinga, 2002) and the rate of bleaching is dependent on a number of variables (Jain et al., 2004). We note that in the most general case, the bleaching of a luminescence signal whether it be a grain under a water column or a grain within a mass of stationary sediment, is some function of time of light exposure (t) and attenuation of light controlled by depth (z), which scales based on the physical properties of the material through which the light is traveling.

The bleaching of luminescence signals can be described by the general order kinetics equation:

$$\frac{dn}{dt} = -\frac{f}{n_0^{b-1}} n^b \quad (1.0)$$

where n is the number of trapped electrons, b is a dimensionless number of the system order, and t is time. The bleaching rate, f is given by:

$$f = \int \sigma(\lambda)\Phi(\lambda)d\lambda \quad (1.1)$$

where the integral is taken over the bleaching spectra of the mineral of interest (Arnold, 2006). Here, σ is the photoionization cross section which is dependent on the photon energy and Φ is the photon flux dependent on wavelength, λ (Chen and Pagonis, 2011). The depth of light penetration into a given material is set by the extinction coefficient in the Beer–Lambert law (k_i). The Beer–Lambert law is given as

$$I(z, \lambda) = I_0(\lambda)e^{-k_i z} \quad (1.2)$$

where I_0 is the initial intensity of light at the surface, I is the intensity at some depth, z, under conditions described by the extinction coefficient, k_i. The extinction coefficient varies depending on the translucency of the material such as turbid or clear water.

The bleaching rate f can be obtained by taking the Beer–Lambert equation in photon flux form:

$$\Phi(z, \lambda) = \Phi_0(\lambda)e^{-k_z z} \quad (1.3)$$

and substituting it into the equation for bleaching rate (Singarayer, 2003)

$$f = \int \sigma(\lambda)\Phi_0(\lambda)e^{-k_z z}d\lambda \quad (1.4)$$

and in turn substituting it into the general order kinetics equation,

$$\frac{dn}{dt} = -\frac{\int \sigma(\lambda)\Phi_0(\lambda)e^{-k_z z}d\lambda}{n_0^{b-1}} n^b \quad (1.7)$$

assuming first order kinetics ($b = 1$), single wavelength interactions (λ), and that the incoming spectrum does not change significantly for simplification, equation (1.7) solves to:

$$n = n_0 e^{-k_t t e^{-k_z z}} \quad (1.8)$$

where

$$k_t = \sigma\Phi_0. \quad (1.9)$$

Finally, we make the assumption that the number of electrons is proportional to the observed luminescence, L:

$$L = L_0 e^{-k_t t e^{-k_z z}}. \quad (1.10)$$

This equation then predicts a double-exponential form for the bleaching of luminescence signals as a function of depth and time (Fig. 1). Fig. 1 demonstrates the equation (1.10) expression as a sinuous curve where the bleaching of a signal for a given time is greater near the surface exposed to a source of light than at depth. Sohbati et al. (2011) arrived at a similar equation during investigations of the change in luminescence signal as a function of light penetration through solid rock.

1.2. Sediment transport bleaching models

In terms of luminescence bleaching, rivers can be thought of as falling between episodic and continuous flow endmembers. These two endmembers host different bleaching conditions for traveling sediment. Both models are simplistic and for both cases, we assume

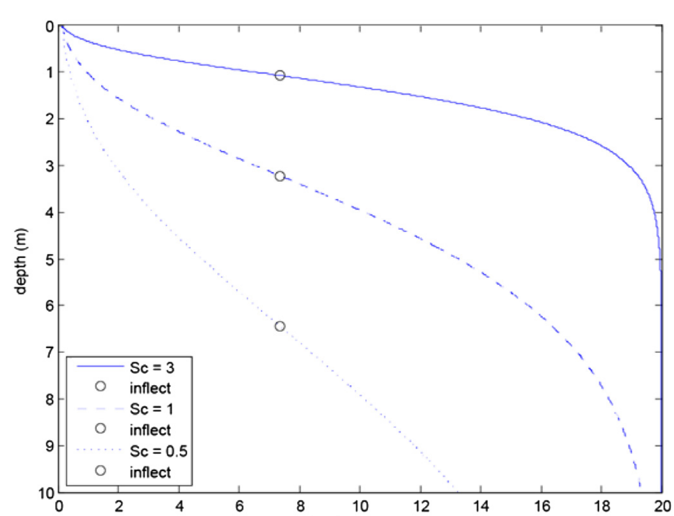

Fig. 1. Equation (1.10) plotted as a function of remaining luminescence signal versus depth. Arbitrary units are used to demonstrate the form of the equation rather than express actual values. Relative values of sediment concentration (S_c), in arbitrary units of 0.5, 1, and 3 are shown to demonstrate how the curve responds to changes in sediment concentration (S_c). Note the location of the inflection point, given by a black circle.