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Travelling at the Speed of Light: Using Luminescence to Quantify Fluvial Sediment Transport

Gregory E. Tucker, University of Colorado

1. Introduction and Motivation

Each year, rivers carry gigatons of sediment to the world's oceans. On geological time scales, this transport helps to form the sedimentary record, and the resulting deposits host petroleum and other valuable resources. On engineering time scales, the movement of sediment brings both costs and benefits: sediment can fill and thereby preserve sinking coastal plains and deltas, but it can also clog harbors and waterways and damage infrastructure. Whatever the application may be, there remains a pressing need for methods that can estimate rates and patterns of sediment transport in rivers, at a variety of space and time scales.

The main goal of this project has been to test the potential for using mineral in luminescence sediment grains as a means for estimating the rate at which sediment moves downstream in a river, and the rate at which it is exchanged between a channel and its adjacent floodplains. Luminescence is a property of certain types of mineral grain, including quartz and feldspar (two of the most common sedimentary minerals). When mineral grains are subjected to ionizing radiation, as they are during burial in soil or sedimentary deposits, the radiation causes bonding electrons to become trapped in defects in a mineral's crystal lattice. These trapped electrons occupy energy levels between the valence and conduction bands, and remain stable until a source of energy such as heat or sunlight gives the electrons the energy needed to escape the trap, releasing photons in the process. The emission of these photons manifests as a brief pulse of electromagnetic radiation, which is the origin of the term "luminescence." When the energy release falls in the visible spectrum, the phenomenon is termed optically stimulated luminescence (OSL); emission can also occur in the infrared (IRSL).

2. Mathematical Model for Luminescence in Fluvial Sediment Grains

We began by formulating a mathematical model that describes the gain and loss of the luminescence signal in a population of sand grains moving as suspended sediment in a river channel. The mathematical model is based on the following conceptual view. When sand grains enter the head of a river channel, they begin their journey with some degree of luminescence signal, which they acquired during a period of prolonged burial in soil or in a sedimentary deposit. As they move downstream, exposure to light in the water column causes them to lose their signal, or "bleach." Depending on the nature of the grains and the luminescence spectrum of interest, the bleaching process in full sunlight may take only minutes to seconds to occur. But grains suspended in a river's turbulent flow don't normally experience full daylight; instead, the light intensity is attenuated by both the water and the surrounding sediment. The intensity of light exposure depends on the time of day and year, the sky conditions, the depth beneath the water surface, and the water turbidity (concentration of fine particles and other opaque constituents).

As they pass downstream, some suspended sediment grains will be deposited on floodplains or river bars, where they may rest briefly, or may be stored for thousands of years. During this period of storage, exposure to ionizing radiation can partly or wholly restore the luminescence signal. Sediments that have been stored for a period of time may be re-entrained by the river channel—for example, during the lateral migration of a river bend—and thereby re-enter into a state of transport. Thus, there is a constant exchange of sediment between the active channel and the floodplains, bars, and other deposits that surround it. As a result, some grains that have been partly or wholly bleached while moving in the river end up being exchanged for grains that have been buried for some period of time, and which therefore possess a stronger luminescence signal.

The mathematical model that we developed for this project describes these various inputs and outputs, including the bleaching of sediment during active transport, and the process of exchange between channel and floodplains. In order to capture the main effects on sediment over periods of years to centuries, the model is necessarily somewhat simplified. We assume, for example, that the full range of different sky and water conditions can be represented by an average intensity of incoming sunlight, and an average rate of decline in light intensity with depth in the water column.

3. Testing the Mathematical Model

A key prediction of the model is that the luminescence signal in river sand should decline with distance downstream, until reaching a uniform value (Figure 1). The decline reflects progressive bleaching as the grains move downstream and their cumulative sunlight exposure grows. The "plateau"—the uniform value that occurs after some distance downstream—reflects a balance between signal loss to bleaching, and signal replenishment bleached grains are replaced by previously buried grains in which the signal has had time to replenish. Our first test was to determine how well it described existing data sets. Of those, we were aware of only two: on the Mojave and Loire rivers, respectively. Both show downstream decline in luminescence up to a certain distance, and then a relatively uniform signal beyond, as predicted by the model. Furthermore, using reasonable values for its parameters, the model yielded a good match for the signal intensity and rate of downstream decline. Importantly, by fitting the model's predicted luminescence-versus-distance curve to the data, it was possible to estimate three useful aspects of the river's sand transport: the net rate of channel-floodplain exchange, the characteristic transport distance (distance a grain travels before being temporarily trapped and stored in floodplains or other deposits), and the virtual velocity (average downstream speed, taking account of storage periods). The model itself, and the results of these initial tests, were presented in a paper by Gray et al. [2017].

To perform a second test, fluvial sediment was collected from three drainage basins in Virginia and Maryland. These basins were chosen because prior work had provided independent estimates of the three transport properties noted above: channel-floodplain exchange, characteristic transport distance, and virtual velocity. The luminescence content of these sediments was measured, and the results plotted against downstream distance; the results are presented in Gray et al. [2018]. The technique worked well in the first (and simplest) of the three catchments, which indicates that luminescence can indeed tell us about sediment transport over relatively long time periods. However, we also found that complications can arise in a river system that has been subject to intensive human disturbance. This is not a wholly surprising result, as one expects that extensive disturbance of surface soil (as for agriculture or suburban development) should erase the signal stored over time in natural soil. Despite this caveat, and the requisite need for caution in identifying field sites and interpreting data, the project results indicate that the prospects for using luminescence as a sediment tracer are good. Potential future steps would include identifying and exploiting additional test sites, and developing more sophisticated models of luminescence dynamics during transport (for example, spatially distributed models that extend the original one-dimensional framework).

4. Training and Professional Development

The project provided the basis for a PhD dissertation by Harrison Gray, who graduated in August 2018 and is now employed at the US Geological Survey. The PI acquired experience in luminescence methods—a new direction—and developed closer collaborative ties with the US Geological Survey's Luminescence Dating Laboratory.

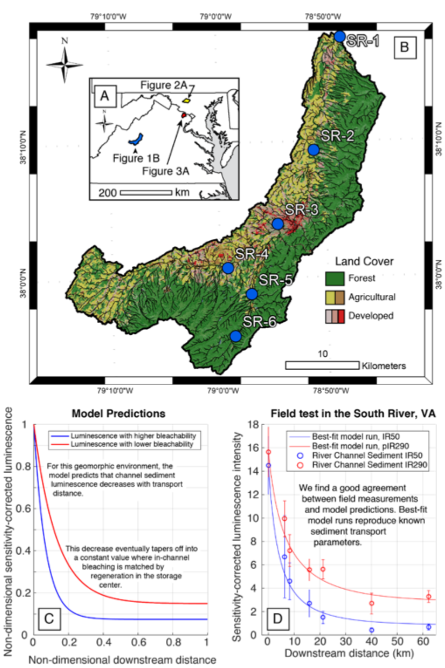

Figure 1. A) Map of the South River catchment showing land cover and drainage network. Land cover and elevation data in all figures are from Homer et al. [2011] and U.S. Geological Survey [2016]. B) Predictions made by the Gray et al. [2017] model for the geomorphic environment of the South River, VA. C) Comparison of sensitivity-corrected luminescence measurements taken from channel sediment with best-fit model results shown as lines. Circles show the average sensitivity-corrected luminescence intensity taken from large aliquots; bars indicate the standard error. From Gray et al. [2018].

References

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