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Invited review

Measured rates of sedimentation: What exactly are we estimating, and why?

John C. Tipper

Institut für Geowissenschaften - Geologie, Albert-Ludwigs-Universität, Freiburg im Breisgau, Germany

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ABSTRACT

Data on rates of sedimentation are essential in studies of sedimentation systems. These data are obtained in three main study contexts: (1) the study of sedimentation systems that are active today, (2) the source-to-sink study of sedimentation systems that no longer are active, and (3) the study of the relationship between accumulation rate and measurement timespan. The aim of this paper is to question the meaning of measured rates of sedimentation, and their interpretability, particularly in these three contexts.

Individual measurements of rate of sedimentation must always be interpreted with care. Firstly, there are different definitions, for instance with different statistical support or measurement dimension; values that are defined differently cannot be compared directly. Secondly, appropriate sampling schemes must have been used for the measurement; this minimises sampling bias. Thirdly, the inherent limitations of the data sources must be taken into account. Rates of sedimentation can usually be measured successfully in active sedimentation systems. The same is not true for systems that are no longer active; these can only be studied using the stratigraphic successions left behind. Rates of erosion can never be measured successfully in stratigraphic successions.

Rate of sedimentation is essentially a ratio – an amount of sedimentation per length of time – therefore the obvious strategy to use in determining it is first to measure the amount and the time independently, then to combine the values. The amount can be measured in terms of thickness or volume or mass per unit area. The duration of the time interval can be preset using quasi-continuous measurement techniques or site reoccupation, or it can be identified from interval-specific sedimentary structures, or it can be measured using dated horizons. An alternative strategy is to use a surrogate measurement variable. Rates of erosion in ancient systems are usually measured in this way, using cosmogenic radionuclide concentrations. These two strategies are reviewed in this paper.

Sets of measurements made in systems that are active today can certainly be used to estimate the rate of sedimentation for the system as a whole. This estimation is best carried out using geostatistical estimation techniques. The alternative is simply to average the measured rate values. This latter approach should not be used, however, because the mean sedimentation rate in a system gives information only about the net sediment movement at the system boundaries. It says nothing at all about how the system is operating or about its spatial and temporal variability.

Measurements of rates of sedimentation made for source-to-sink studies are necessarily made in stratigraphic successions. The measurements are used to estimate quantities in the sediment mass budget equation. The amount of decumulation is inherently incapable of being measured in stratigraphic successions, therefore there are always unknowns in the mass budget equation whenever the lithic surface at the start of the time interval considered cannot be recognised everywhere. This means that the mass budget equation is applicable in practice only when all the systems involved in the study are entirely non-erosional for that entire time interval — a highly unrealistic situation.

The consistently inverse relationship documented between accumulation rates and measurement timespan is taken usually to indicate that this relationship is substantially scale-invariant. This in turn is often taken as indicating that the stratigraphic record is fractal in nature. There are nevertheless grounds for doubt, all of which relate to the ways that the data are collected and used for estimation. The relationship is in fact the natural mathematical result of last-in-first-out (LIFO) operation and is produced in any type of system in which addition and removal processes both operate. It says nothing particular about sedimentation processes. The future analysis of accumulation rate data collected from stratigraphic successions will sensibly be framed in the context of estimating the parameters of a LIFO model.

E-mail address: john.tipper@geologie.uni-freiburg.de.

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1. Introduction

Sedimentation processes of one kind or another operate over much of the Earth's surface. The consequences are readily seen: landslides, eroded river banks, migrating dune fields, silted-up lakes and reservoirs — these are just a few obvious examples. Often there are associated economic and societal effects, sometimes catastrophic ones. It is not surprising that earth scientists should want to know the rates at which sedimentation processes operate; equally, that they should want to measure the quantity that usually is termed 'rate of sedimentation'.

Data on rates of sedimentation are essential in every study of modern and ancient sedimentation systems. As a result there have been innumerable measurements made and reported. There is considerable variation in these rates, as is surely to be expected given the different measurement techniques used and the different systems studied. In some cases the rates have satisfactory interpretations; they are compatible with what else is known about the systems in question, for instance about their paleoclimatic and paleoenvironmental context. In other cases the interpretations are less clear. Sometimes it is difficult to see what particular measured rates mean; sometimes it is even difficult to see what they ever could mean. Hence the question posed in the paper's title: "Measured rates of sedimentation: what exactly are we estimating, and why?"

The paper is organised in five sections. The first considers the meaning of the term 'rate of sedimentation' and offers advice on its use; the second comments on some general matters of scientific procedure, as they apply particularly in the study of sedimentation systems; the third outlines strategies used in measuring rates of sedimentation; the fourth looks critically at the three main contexts in which rates of sedimentation are measured, asking in each case what is being estimated and why. The answers are summarised in the paper's final section.

2. 'Rate of sedimentation': the term and its use

By itself, the term 'rate of sedimentation' means nothing more than the rate at which sedimentation takes place. It is accordingly a very general term, which must be used with care. Firstly, sedimentation must be given its full modern meaning; it is not simply synonymous with deposition. Secondly, the dimension of the units in which sedimentation is measured must be specified; one alternative is length, the other is mass per unit area. Thirdly, a clear distinction must be drawn between the rate at which sedimentation takes place and the rate at which sediment accumulates (McKee et al., 1983). Fourthly, rate of sedimentation must be treated as a stochastic variable, not as a deterministic variable. Finally, the matter of what statisticians term 'support' must be fully appreciated; see Journel and Huijbregts (1978) and Davis (1986). These issues are discussed in detail below.

2.1. Sedimentation systems, sedimentation processes and sedimentation

Sedimentation systems are defined as complexes of interrelated processes involving deposition, erosion, stasis and transport (Tipper, 2015; cf., Fairbridge and Bourgeois, 1978, p. 682). These processes, which of course are of many different types, are referred to generically as sedimentation processes. Sedimentation itself can be defined simply as the net result of the operation of sedimentation processes (McKee et al., 1983, p. 632). Every sedimentation system has boundaries defining the area over which it operates and the range of time through which it operates. These boundaries are in practice a formality. They are set by the investigator studying the system, on whatever grounds are thought appropriate. Sedimentation systems can be treated mathematically as comprising two distinct but coupled layers – the active layer and the inactive layer – within which mass is conserved. The active layer is sediment that is in transport; the inactive layer is sediment that has been deposited and is available for erosion. The layers are coupled together by the depositional and the erosional processes operating within the system; the active layer is coupled internally by the lateral transport processes. A full mathematical formulation is given by the generalised Exner equation for sediment mass balance (Paola and Voller, 2005). A simple series–parallel box model for sedimentation is shown in Fig. 1. This model is used as the basis for much of the analysis presented later in the paper.

2.2. The dimensions of sedimentation

Sedimentation processes change the elevation of the lithic surface; they also change the distribution of mass. Studies focusing on changes in elevation measure sedimentation in units of length, i.e., units with dimension L; rate of sedimentation then has the dimension LT^{-1}. Studies focusing on changes in mass distribution use units of mass per unit area, i.e., units with dimension ML^{-2}; rate of sedimentation then has the dimension $ML^{-2}T^{-1}$. The choice of which dimension to use is a matter for the investigator.

2.3. Sedimentation and sediment accumulation

A conceptual framework that is helpful in analysing the operation of sedimentation systems is the so-called three-dimensional stratigraphic space–time diagram (Tipper, 1998). This is a rectangular Cartesian coordinate system x–y–t, where x and y are spatial base plane coordinates and t is time. $z(x,y,t)$ is the elevation of the lithic surface at time t; $m(x,y,t)$ is the mass of sediment per unit area at the lithic surface at time t; $R(x,y,t)$, the sedimentation rate, is dz/dt; $R'(x,y,t)$, the mass sedimentation rate, is dm/dt; $S(x,y,t)$, the accumulation rate, is given by $S(x,y,t) = \max(0,R(x,y,t))$; $S'(x,y,t)$, the mass accumulation rate, is given by $S'(x,y,t) = \max(0,R'(x,y,t))$. S and S' are equivalent to R and R' only in entirely non-erosional systems; otherwise they are totally distinct variables. It goes without saying that the terms 'sedimentation rate' and 'accumulation rate' should always be used with care.

There is an alternative definition for accumulation rate, one that is used mostly in studies of the relationship of accumulation rate to measurement timespan (e.g., Sadler, 1981; Sadler and Strauss, 1990; Sadler and Jerolmack, 2015). By this definition, $S(x,y,t) = (R(x,y,t)|R>0)$. The reasons for using this definition in this particular context are pragmatic ones. Firstly, accumulation is widely taken to be synonymous with increase, i.e., with strictly positive addition. Secondly, stasis ($R = 0$) is logically incapable of recording itself in sediment; therefore accumulation rates equal to zero can never be found in stratigraphic successions. The definition has a significant drawback, however, namely that the parameters of the distribution of S are impossible to estimate properly if S cannot have the value zero. This is because it is in practice impossible to distinguish between intervals of barely positive deposition (which would have to be included in the parameter estimation) and intervals of stasis (which would have to be excluded). Extremely small positive values of R are common in most sedimentation systems (Tipper, 1983, his Fig. 2; Strauss and Sadler, 1989, their Fig. 1). So too is stasis (Tipper, 2015). The definition of S used in this present paper is accordingly the one given earlier: $S(x,y,t) = \max(0,R(x,y,t))$.

2.4. Stochastic variables and deterministic variables

Rate of sedimentation is not a deterministic variable. It is a stochastic variable, i.e., a variable whose value is subject to chance variation. Many of the other variables used in calculating rates of sedimentation are also stochastic variables, for instance measured thickness and measured age. Chance variation can arise for a number of reasons: (1) because the variable concerned is associated with some random process, (2) because the definition of the variable is uncertain, (3) because of measurement imprecision, or (4) because of sampling effects. A stochastic variable is described completely by its probability distribution.