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On the use of sedimentation rates in deciphering global change

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[1] The amount of sediment deposited through time at a given place is controlled by both tectonic and climatic factors that change over several length and time scales. For these reasons the sedimentary record is commonly exploited to study global change. To understand this record, most studies have relied on assembling data from a few localities within a given reservoir and have extrapolated those data to whole of the reservoir. Here it is shown not only that this approach has very large inherent uncertainties, but also that the use of extrapolating sedimentary records has little physical significance. A much better approach, although much more difficult, is via a full, three-dimensional mass balance calculation. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 8105 Tectonophysics: Continental margins and sedimentary basins

[2] In order to decipher past global change one must differentiate between tectonic and climate processes that together shape the Earth's surface. As sedimentary basins record the erosion history resulting from these processes, it has been a usual practice to relate the regional and global sedimentary signals to either global change or tectonics over geologic time. This major challenge has been the focus of many studies over the last few decades [e.g., *Molnar and England*, 1990; *Rea*, 1992; *Burbank and Anderson*, 2001; *Zhang et al.*, 2001, and references therein]. For example, *Zhang et al.* [2001] recently used the sedimentary record to address global change. The authors claimed that most of the world's sedimentary basins experienced a profound increase in accumulation rate during the last 2–4 Myr, which they attributed to change in the cyclicity of climatic fluctuations at the Earth's surface. The data they used are diverse, with some of the sedimentary profiles represented in units of mass per unit time, some in volume per unit time, and others in height per unit time. An important aspect of their analysis was that the vast majority of the sedimentary record were derived from local sedimentation rates. Using such local sedimentary records to infer past global change therefore relies on a very strong assumption: that local accumulation rates can be extrapolated to the basin scale without significant bias. This article is written to show that (1) this assumption is generally wrong, and (2) only a basin-wide mass balance reconstitution of the sedimentation rates may yield information on the flux of material eroded and eventually deposited in the oceans. *Hay et al.* [1989], *Syvitski* [1993], *Métivier et al.* [1999], and *Dromart et al.* [2002] have addressed the problem of local and regional sedimentation rates and suggested how the integration from one scale to another is important. Correctly integrating local sedimentation rates to the basin scale must take into account many factors such as shifts in depocenters and basin geometry. These factors may be responsible for changes in the accumulation rates on a local basis whereas, the sediment flux to the basin remains constant. For example, sedimentation rates may increase at one point and decrease at another. In the case of the Bengal fan, sedimentary columns show an increase of sediment accumulation in the proximal part of the fan during the late Tertiary [*Métivier et al.*, 1999, and references therein] whereas a decrease is recorded in the distal part of the fan [*Burbank et al.*, 1993]. Basin-wide analysis is thus the only way to account for such variability.

[3] The simplest way to demonstrate the necessity of making conservative mass balances at the basin scale is to examine a bathtub-like filling model of a sedimentary basin. Let us consider a two-dimensional submarine basin. Its triangular cross-section is defined by its length L at the top of the trough and its central depth $H = L/2 \tan\theta$ where θ is the angle of the side slope of the basin (Figure 1a). This basin fills with sediment at an increasing rate through time

$$Q = Q_0\sqrt{\frac{t}{\tau_f}} \tag{1}$$

starting at time $t = 0$ (Q is in m^2/s and τ_f is the characteristic evolution time of mass flux). For simplicity it is assumed that deposition propagates uniformly from the bottom to the top of the basin due to, say, successive turbidity currents that transport material on the slope and deposit it in the trough. Here, compaction that results in second order nonlinearity is neglected [see *Baldwin and Butler*, 1985; *Métivier et al.*, 1999]). Thus, the depth of the basin bottom varies with time according to the equation of conservation of mass and can be expressed as

$$h^2 \tan\theta = \int_0^t Q(u)du \tag{2}$$

which can be recast as

$$h = \sqrt{\left(\frac{2Q_0\tau_f}{3\tan\theta}\right)}\left(\frac{t}{\tau_f}\right)^{3/4} \tag{3}$$

Derivation of equation 3 gives the accumulation rate. At the center of the basin it is

$$\frac{dh}{dt} = \sqrt{\frac{3Q_0}{8\tau_f\tan\theta}}\left(\frac{t}{\tau_f}\right)^{-1/4} \tag{4}$$

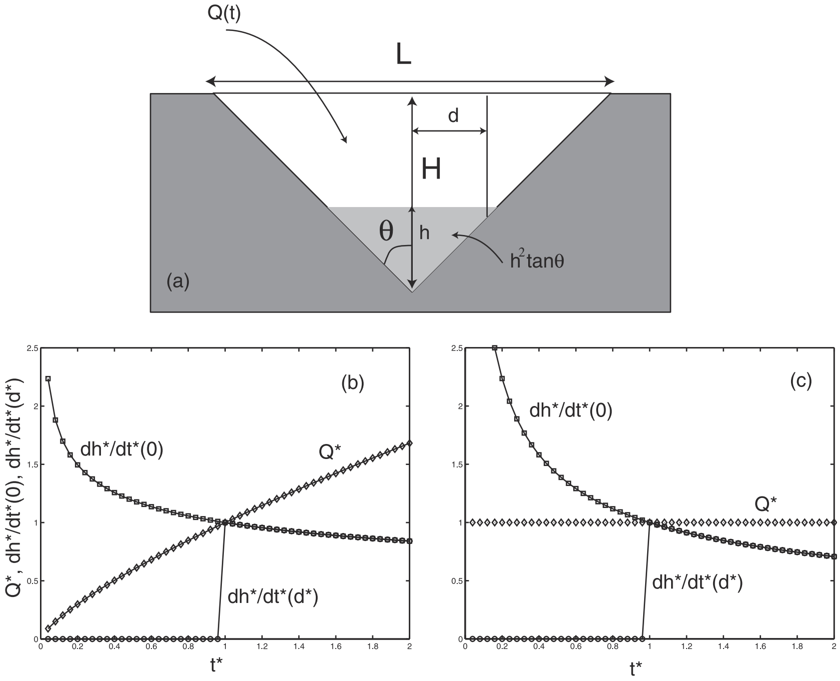

Figure 1. (a) Schematic representation of a model basin. (b) Evolution of the nondimentional input flux of sediment Q^* (diamonds) and local sedimentation rates ($dh^*(d^*)/dt^*$) at the center of the basin ($d^* = 0$, squares) and at a distance $d^* \neq 0$ from the center (circles) in the case of an increasing sediment flux to the basin. (c) Same representation for a constant sediment flux. For simplification purposes all parameters are set to 1.

[4] At a horizontal distance d measured from the center of the basin, accumulation will start at a time t_d as

$$t_d = \left(\frac{3d^2}{2Q_0\tau_f \tan\theta}\right)^{2/3} \tag{5}$$

The local accumulation rate at that place can be reduced to (still valid for $d = 0$),

$$\frac{dh}{dt}(d) = 0, \qquad t < t_d \tag{6}$$

$$\frac{dh}{dt}(d) = \sqrt{\frac{3Q_0}{8\tau_f \tan\theta}}\left(\frac{t}{\tau_f}\right)^{-1/4}, \qquad t \geq t_d \tag{7}$$

[5] Equations (1), (5) to (7) can be nondimensionalised for comparison purposes. Defining $d^* = d/L$, $t^* = t/\tau_f$, $Q^* = Q/Q_0$ and $h^* = h/L$. The problem reduces to

$$Q^* = \sqrt{t^*} \tag{8}$$

$$t^*_{d^*} = \left(\frac{3L^2 d^{*2}}{2Q_0\tau_f \tan\theta}\right)^{2/3} \tag{9}$$

$$\frac{dh^*}{dt^*}(d^*) = 0, \qquad t^* < t^*_{d^*} \tag{10}$$

and

$$\frac{dh^*}{dt^*}(d^*) = \sqrt{\frac{3\tau_f Q_0}{8L^2 \tan\theta}}\,t^{*-1/4}, \qquad t^* \geq t^*_{d^*} \tag{11}$$

[6] Figure 1b illustrates this result. It shows that although the sediment flux into the basin increases with time, the local sedimentation rate decreases at the center of the basin simply because its shape is not rectangular. Furthermore at a distance d^* from the basin's center the sedimentation rate is null until time t^*_d, where after it rises abruptly and then decays with time.

[7] Let us now assume that in another sedimentary basin of the same shape that the sediment input flux is constant through time $Q(t) = Q_0$. Equations (8) to (11) become

$$Q^* = 1 \tag{12}$$

$$t^*_{d^*} = \frac{d^2}{Q_0 \tan\theta} \tag{13}$$

$$\frac{dh^*}{dt^*}(d^*) = 0, \qquad t^* < t^*_{d^*} \tag{14}$$

$$\frac{dh^*}{dt^*}(d^*) = \sqrt{\frac{1}{4\tan\theta}}\,t^{*-1/2}, \qquad t^* \geq t^*_{d^*} \tag{15}$$

where $d^* = d/L$, $t^* = L^2/Q_0$, $Q^* = Q/Q_0$ and $h^* = h/L$. Figure 1c illustrate this result. Comparison between Figures 1b and 1c shows that the local sedimentation pattern at any distance d^* from the center is weakly dependent on the input flux. Given the resolution of the sedimentary record, the difference between the two patterns would hardly be seen in the natural environment. Thus, conclusions based solely on a few isolated observations of sedimentation rate can not reliably estimate the total sediment flux that feeds a particular basin. This is why, for example, the conclusions of *Zhang et al.*

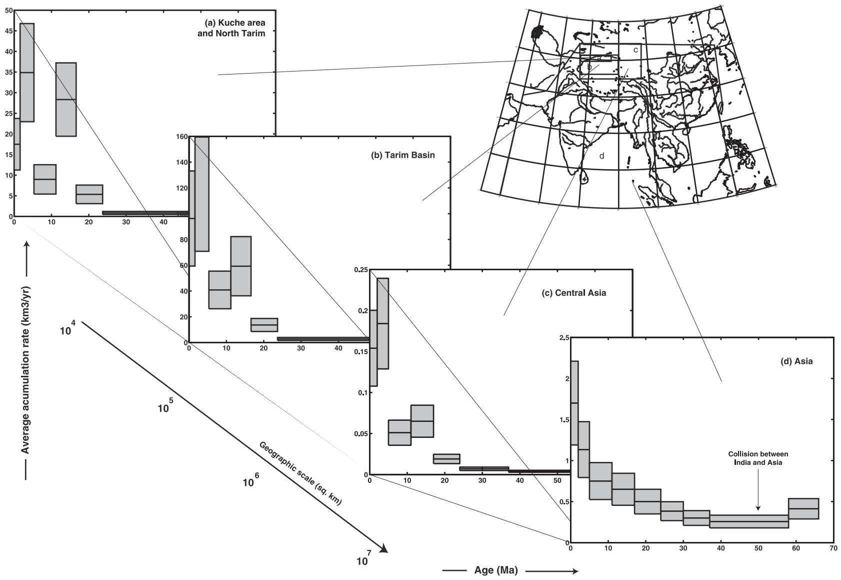

Figure 2. Evolution of solid phase accumulation rates (conservative estimate in km^3/yr), during spatial integration from the sub-basin to the continental scale. Reconstruction from *Métivier and Gaudemer* [1997]; *Métivier et al.* [1999]. Gray boxes represent reconstruction uncertainties.

[2001], which are based on only sparse local sections, naturally and logically find that sedimentation rises abruptly at a given time (4 Ma in their case) and correlate it with global change.

[8] This crude and schematic example shows the likely pitfalls of interpreting nonconservative, local accumulation rates and extrapolating those to the basin-wide scale. In natural settings the geometry of the basin is three dimensional and much more complex than a simple triangle. James Syvitski [*Syvitski*, 1993] has addressed the problem of a three dimensional sedimentary basin and its influence on accumulation rates for Canadian glaciomarine sediments. His analysis shows that high local accumulation rates in the fjords of Glacier bay (Alaska), should be treated with great caution. Moreover, in a recent study *Dromart et al.* [2002] using statistical analysis have shown that the relative error of a one-dimensional to a three-dimensional estimate of Jurassic carbonate accumulation rates may be as high as 65 %. Certainly the bathtub sedimentation model is an over simplification. Sedimentation depends on many factors including input sources, marine currents, and granulometry. All these factors control, to some degree, both the geometry and timing of sediment deposition [e.g., *Paola et al.*, 1992; *Syvitski*, 1993]. Increase in grain size of the sediments induces, for instance, an increase in proximal sedimentation rate independent of the total sediment flux.

[9] Building on Curray's [*Curray*, 1994], and Hay et al's work [*Hay et al.*, 1989], *Métivier et al.* [1999] made a conservative estimate for the largest sedimentary basins in Asia. An example of the evolution of the sedimentary accumulation rates is shown in Figure 2. In this case compaction is taken into account and volumes represent the solid phase [*Baldwin and Butler*, 1985; *Métivier et al.*, 1999]. In Figure 2a the accumulation rates are given for only the northern Tarim basin in central Asia. Two peaks can be seen in the sedimentary record – one between 11 and 16 Ma and one around 2 to 5 Ma. When the sedimentary signal is observed over the entire Tarim basin (Figure 2b), then at the scale of Central Asia (Figure 2c), and finally integrated over whole of Asia (Figure 2d) these abrupt changes in sedimentation rates are diluted. At the scale of Asia, the remaining sedimentary signal shows that, within uncertainties, the sediment flux follow an exponential curve increase through time. The reconstitution shown in Figure 2 therefore demonstrates the necessity of doing a conservative estimate of mass accumulation rates in order to decipher between local and more global trends.

[10] Most large oceanic basins are fed by large river systems. These river systems represent transfer zones that distribute mass between the elevated regions, where erosion takes place, to the deposition sites. It has been shown that these river systems can be modelled as diffusive-like transfer systems [*Paola et al.*, 1992; *Humphrey and Heller*, 1995; *Dade and Friend*, 1998; *Métivier*, 1999]. Mass flux input to these large rivers can thus change radically in both amplitude and frequency during transport until final deposition. Therefore care must be taken when reconstructing the fluxes of mass transported to the oceans because the fluxes reconstructed using the sedimentary record may not be representative of the intensity of erosion processes that take place hundreds to thousands of kilometers away from the deposition sites. Thus, studies of the sedimentary record that do not make a conservative balance of mass accumulation are unlikely to have any physical sense.

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