QUANTIFYING DENUDATION ON PLANETARY SURFACES.

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Introduction: The amount of net erosion on planetary surfaces is typically measured by the vertical lowering of a representative surface and the erosion rate through dividing by the elapsed time [*1, 2*]. The problems with using this are several fold. Firstly, the initial elevation must be known as well as the temporal interval. In addition, most erosional processes vary appreciably from place to place depending upon local materials, gradients, and exposure of the surface to erosional mechanisms. More fundamentally, on most planetary surfaces denudation is a zero-sum game, with volumes of erosion being balanced by deposition of the eroded materials in some other place. A more basic measure of the amount of surface modification of planetary surfaces is suggested here based on "work"-like concepts of transport of mass (or volume) over vertical or horizontal distances and changes of relief through time. These measures treat the evolution landscape as a whole. Although not without issues of measurement, they offer the possibility of a more general characterization of geomorphic modification.

Measuring Denudation I: Vertical Transport: In any time step Δt a unit mass of material $\rho g \Delta A \Delta z$ may be moved a vertical distance Δz, where ΔA is the surface area being eroded, ρ is the density of the eroded material, and Δh is the amount of vertical erosion (where $\vec{g}$ determines the measurement axes). The measure of work done per unit time per unit area, or power per unit area, P_v, is:

$$P_v = \frac{\rho g \Delta h \Delta z}{\Delta t},$$

and for a landscape as a whole an average value of P_a would be measured.

Measuring Denudation II: Horizontal Transport: A parallel measure of denudation quantifies the rate of lateral transport of material in the landscape, P_h, where the distance eroded material is transported per unit time is Δx:

$$P_h = \frac{\rho g \Delta h \Delta x}{\Delta t}.$$

These measures of work done can be assessed for geomorphic processes are directly controlled by gravity, as in mass wasting and bed material transport by wind, currents and waves. In a broad sense they can be used as well for glacial erosion and transport. They are less easily measured for transport of materials in suspension in fluids.

Measuring Denudation III: Reduction in Relief: Erosion by gravitationally-controlled processes transfer mass from high areas to low, reducing relief (unless counterbalanced by constructive processes such as tectonics or impact cratering). Although relief (and its changes) can be measured locally, areal measures of relief, such as average slope gradient, $\bar{S}$, or the standard deviation of relief, E_{SD}, can be measured for a landscape as a whole and tracked through time.

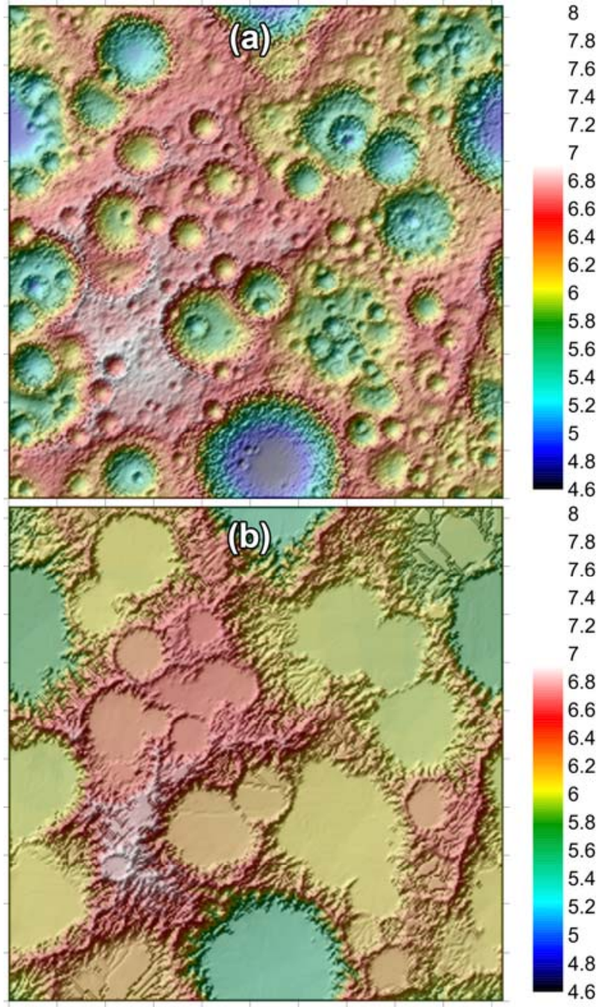

Fig. 1. Simulation of cratered surface erosion by fluvial and mass wasting processes. (a) Initial surface. (b) final surface. Lateral boundaries are periodic so that there is no average elevation change during denudation. Simulated domain is 100x100 km.

Application: The direct use of any of these measures to quantify denudation requires a temporal record of process fluxes and net landform changes, which in general are not readily obtained. They can be assessed, however, in quantitative simulation models of landform evolution (LEMs) to measure temporal changes in denudation rates and the relative importance of different processes. In LEMs both P_v and P_h can be tracked through time for both mass wasting and fluvial processes, and $\overline{S}$ and E_{SD} can be tracked for the landscape as a whole.

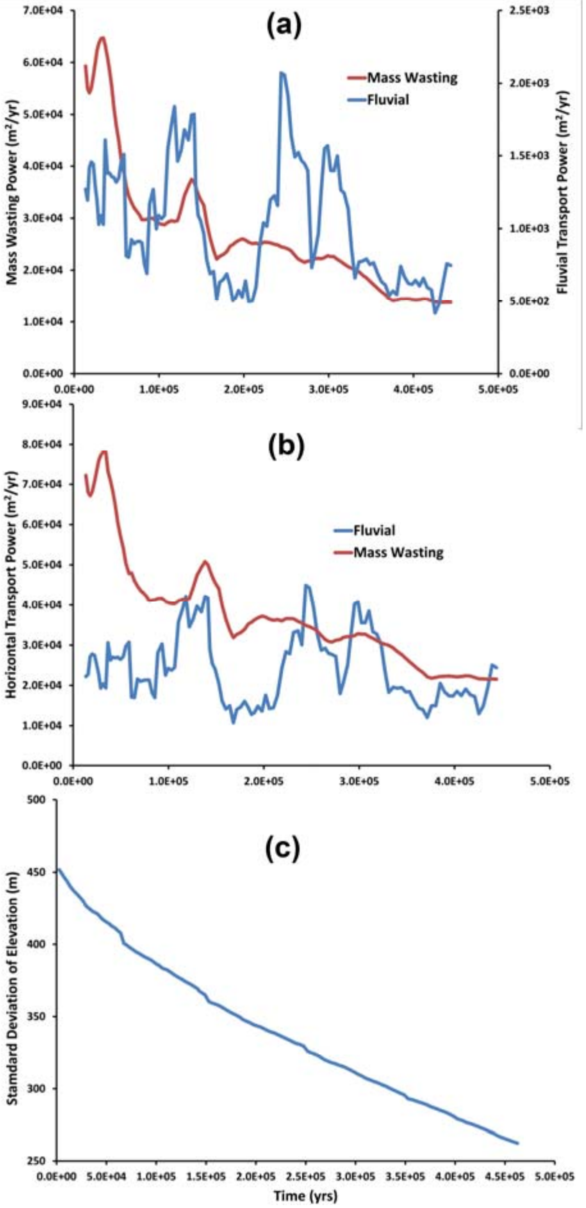

Fig. 2. Measures of denudation for the simulation shown in Fig. 1. (a) Vertical transport, P_v. (b) Horizontal transport, P_h. (c) Standard deviation of elevation, E_{SD}.

Fig. 1 shows a simulation of erosion of a cratered surface by fluvial and mass wasting processes[*3*]. The evolution of vertical, P_v, and horizontal, P_h, power per unit area is shown in Fig. 2. The spikes in fluvial and mass wasting power occur when divides between crater basins are breached and a wave of dissection works headward through the crater floor (e.g., upper right in Fig 1b). The standard deviation of relief, E_{SD}, decreases steadily as a result of denudation, although mean elevation is unchanged because the lateral boundaries are periodic. Note that mass wasting and fluvial transport are of comparable importance for horizontal transport, but that mass wasting clearly dominates over fluvial transport in the usual definition of work, P_v, because it acts on the steepest parts of the landscape.

Other processes can be quantified similarly. Impact cratering involves both horizontal transport and vertical work (negative, or relief-increasing in this case). Lava emplacement results in negative P_v. Transport by eolian saltation will give a positive P_h but either positive or negative P_v because of less direct gravitational control. Some processes, such as erosion or deposition of sediment by eolian suspension, as well as volatile sublimation and precipitation can be well quantified by P_v but generally impossible to measure by P_h.

Denudation in Natural Landscapes: In attempting to measure denudation in natural landscapes we are usually presented with the present topography (equivalent to Fig. 1b), but limited information about the initial conditions (e.g. Fig. 1a) and no evolutionary sequence. Landscape evolution modeling, as in Figs. 1 and 2, can in some circumstances provide a general means of process evaluation. Statistical measurement of landform properties can be useful in certain cases. For example, the standard deviation of elevation, E_{SD}, is readily quantified for DEMs of natural landscapes. If the type of initial landform can be identified, such as a saturation cratered landscape (either simulated as in Fig. 1a or natural, as on the Moon), then statistical characterization of the topography (e.g. E_{SD}) can provide an index of relative degree of denudation. Other statistical measures can be employed, such as other moments of elevation (skewness and kurtosis), frequency of summits, cols and sinks, variograms, and spatial autocorrelation. For fluvially eroded landscapes drainage density, valley profiles and concavity, characteristics of slope profiles can be measured, *inter alia*. Several statistical landform properties comparing natural and simulated DEMs in a terrestrial setting are discussed in [*4*]. Such statistical comparisons (or even comparing natural DEMs) do not rely on direct concordance of landforms. In some cases evolution of specific regions is modeled, and more direct comparisons, such as erosion depth histograms can be used [*5*].

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