Humans as geologic agents: A deep-time perspective

Bruce H. Wilkinson
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA

ABSTRACT

Humans move increasingly large amounts of rock and sediment during various construction activities, and mean rates of cropland soil loss may exceed rates of formation by up to an order of magnitude, but appreciating the actual importance of humans as agents of global erosion necessitates knowledge of prehistoric denudation rates imposed on land surfaces solely by natural processes. Amounts of weathering debris that compose continental and oceanic sedimentary rocks provide one such source of information and indicate that mean denudation over the past half-billion years of Earth history has lowered continental surfaces by a few tens of meters per million years. In comparison, construction and agricultural activities currently result in the transport of enough sediment and rock to lower all ice-free continental surfaces by a few hundred meters per million years. Humans are now an order of magnitude more important at moving sediment than the sum of all other natural processes operating on the surface of the planet. Relationships between temporal trends in land use and global population indicate that humans became the prime agents of erosion sometime during the latter part of the first millennium A.D.

Keywords: denudation, erosion, humans, deep time.

INTRODUCTION

Rates of soil erosion associated with agricultural practices are generally thought to exceed soil-loss tolerances over most of Earth's cropland regions (Troeh et al., 1999). However, the magnitude and significance of this difference remain matters of debate. Some studies (e.g., Pimentel et al., 1995; Pimentel and Skidmore, 2004; U.S. Department of Agriculture [USDA], 1994) indicate that rates of soil loss from United States croplands exceed those of soil formation by over an order of magnitude, implying that current agricultural practices are far removed from sustainable levels. Others (e.g., Brady and Weil, 1999) conclude that rates of agricultural denudation and soil generation are sufficiently similar that U.S. soil erosion does not yet constitute a land-use calamity. The issue here is one of determining magnitudes of natural rates of rock and sediment erosion; these are the significant processes of land-surface denudation across most of Earth's surface. One of the major difficulties in evaluating the degree to which human activities have augmented continental erosion is that, in a given area, the onset of such anthropogenic influences frequently predated historical records.

Assessing the magnitude of human-induced erosion is of obvious pragmatic as well as intellectual importance. However, in order to appreciate changes induced by a growing world population, it is also necessary, as a basis for comparison, to determine the importance of natural denudation processes. An estimate of a deep-time baseline rate of natural erosion (such as that associated with glaciers and rivers) has been attempted (1) through radionuclide dating of land surfaces and (2) by examination of data on river-borne sediment fluxes. Some ambiguity is inherent in either approach. The determination of erosion rates using cosmogenic isotopes is still in its infancy, available data are sparse, and current rates are primarily from orogenic regions (e.g., Kirchner et al., 2001; Small et al., 1997). Denudation rates calculated from river-borne sediment loads (e.g., Meybeck, 1988; Harrison, 2000; Summerfield and Hulton, 1994) are also somewhat biased because current sediment loads reflect both natural and anthropogenic processes, the latter of which have influenced drainage sediment yields for thousands of years (Ruddiman, 2003) and are also changing rapidly in response to societal evolution and population growth.

Much of the geologic cycle entails transfer of rock materials into the sedimentary reservoir through the weathering of preexisting rocks, the movement of particulate and dissolved components resulting from weathering to sites of sediment accumulation, and the deposition of this material as terrigenous clastic, carbonate, and evaporite units. Moreover, subsequent uplift and erosion result in a progressive decrease in epoch-long interval rock volume with increasing age. Data on surviving amounts of sedimentary rock (Ronov, 1983) therefore allow for estimation of epoch-long rates of sediment accumulation, which in turn relate to rates of physical and chemical denudation over Earth's subaerially exposed surface for at least the past half-billion years. Sedimentary rock volumes are here employed in this way to derive deep-time global denudation rates (e.g., Harrison, 1994). These values are then compared to approximations of near-recent rates of denudation derived from major river-borne particulate and dissolved loads, as well as estimates of human-induced erosion from construction and agricultural practices.

GLOBAL PHANEROZOIC SEDIMENT FLUXES

Continental (85% of total) and oceanic (15%) sediments make up the current ~630 $\times 10^6$ km^3 of terrigenous clastic (69%), carbonate (28%), and chert and evaporite (3%) units that have accumulated on Phanerozoic oceanic (basaltic) and continental (granitic) crust (Ronov, 1983), an amount sufficient to blanket all continental surfaces to a depth of ~3 km and all ocean basins to a depth of ~300 m. This amount of sedimentary material embodies the surviving volume of products from Earth-surface erosion spanning the past ~542 m.y. Moreover, rock volumes of any given age in both oceanic and continental settings decrease with increasing age, a relationship that reflects the progressive destruction of sedimentary (and other) rocks with the passage of geologic time. Amounts of surviving oceanic and continental sediment decrease exponentially with increasing age, relationships reflecting the fact that first-order cycling rates are primarily dependent on the amounts of material that make up different parts of the

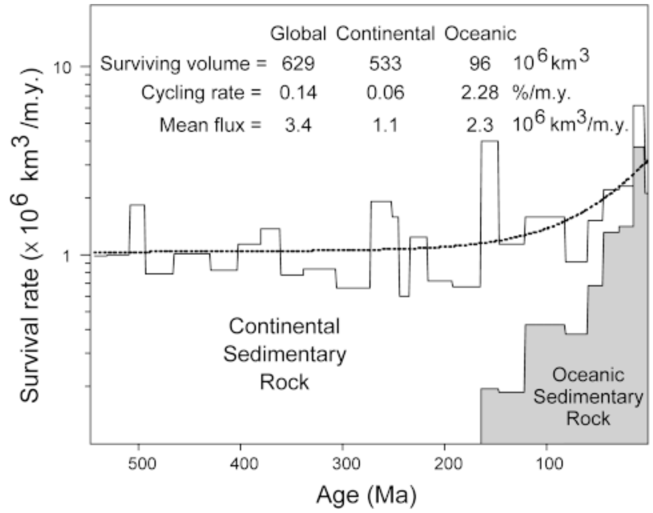

Figure 1. Data from Ronov (1983) on volumes of sediment of given age deposited on oceanic (shaded) and continental (unshaded) crust. Dashed line is best-fit model of decrease in global volume of sedimentary rock under assumptions that mean oceanic and continental sediment fluxes are 1.1 and 2.3 × 10^6 km^3/m.y., respectively (*y*-intercepts), and sediment destruction by subduction and erosion of 2.28%/m.y. and 0.06%/m.y., respectively (see text).

sedimentary rock reservoir. Surviving volumes of continental sedimentary material define a trend of progressive and proportional destruction (primarily by subaerial erosion) at 0.06% ± 0.05%/m.y. (Fig. 1). Surviving volumes of oceanic sediment decrease exponentially at a rate of 2.28% ± 0.24%/m.y. (Fig. 1). Although the Phanerozoic history of deep-sea oceanic crust generation and destruction is currently a subject of some debate, oceanic sediment destruction, primarily by subduction, is therefore ~38 times faster than that by erosion of continental rocks. Collectively, surviving amounts of sediment deposited on granitic continental and basaltic oceanic crust decrease at a rate of 0.14% ± 0.06%/m.y. Phanerozoic sedimentary rock represents ~52% of the present global sedimentary rock reservoir; the balance (~606 × 10^6 km^3) exists as Precambrian deposits on various continents.

Discrepancy between measured sedimentary rock volumes for each epoch-long interval and those expected from a mean global destruction rate of 0.14% ± 0.06%/m.y. reflects the collective influences of (1) greater or lesser fluxes of weathered rock material that were transported to continental and oceanic sites of sediment accumulation, (2) faster or slower rates of postdepositional destruction by erosion or subduction, and/or (3) imprecision in volume estimates. Because this approach is primarily concerned with determining epoch-long rates of continental denudation, the most conservative assumption (that maximizes potential epoch-to-epoch variation in sediment flux) is to presume that differences between the amount of surviving sediment and that expected from proportional volume-dependent cycling are entirely the result of greater and lesser rates of erosion, transport, and deposition over Phanerozoic time.

In addition to epoch-long sediment volumes and compositions, Ronov (1983) also calculated the proportion of continental surfaces undergoing erosion and that undergoing deposition for each geologic time interval. During the 25 epoch intervals that collectively span the Phanerozoic, ~64% ± 9% of Phanerozoic continental crust was exposed to subaerial erosion. At present, ~79% of ice-free continental crust is subaerially exposed. This value is somewhat higher than the Phanerozoic average because continental blocks are now generally more emergent than has been the case over much of the past half-billion years. Under the assumption of a global mean cycling rate of 0.14%/m.y. (Fig. 1), extant volumes of Phanerozoic sedimentary rock therefore record epoch-long interval denudation rates on the order of 24 ± 11 m/m.y. (Fig. 2). Of this, ~18 ± 9 m/m.y. was transported by global rivers as particulate clastic material and accumulated as terrigenous conglomerate, sandstone, siltstone, and shale sequences, whereas ~6 ± 4 m/m.y. was transported as dissolved load and was deposited as carbonates, phosphorites, evaporites, and chert (Fig. 2).

These data also suggest that global denudation rates irregularly decreased from early Paleozoic values of ~30 m/m.y. through the Mesozoic to values of ~15 m/m.y.; the rates then increased abruptly through the Cenozoic to values slightly >65 m/m.y. This overall pattern is similar to that of seawater $^{87}Sr/^{86}Sr$ ratios (Veizer et al., 1999), which are thought to serve as a geochemical proxy for rates of continental erosion. Others have interpreted the abrupt increase in Neogene flux as a global manifestation of glaciation associated with cooler late Cenozoic climates and/or Neogene uplift (Peizhen et al., 2001). Regardless of the reasons for epoch-to-epoch differences, sediment fluxes inferred from sedimentary rock volumes suggest long-term continental denudation rates on the order of a few tens of meters per million years.

RIVER BASIN SEDIMENT LOADS

Deep-time denudation rates based on sediment volumes are somewhat lower than those derived from modern, large river-borne sediment loads. Area-normalized suspended and dissolved fluxes for the several dozen large river basins draining ice-free continental surfaces (e.g., Pinet and Souriau, 1998) suggest a mean denudation rate of ~67 m/m.y.; terrigenous particulate and dissolved fractions

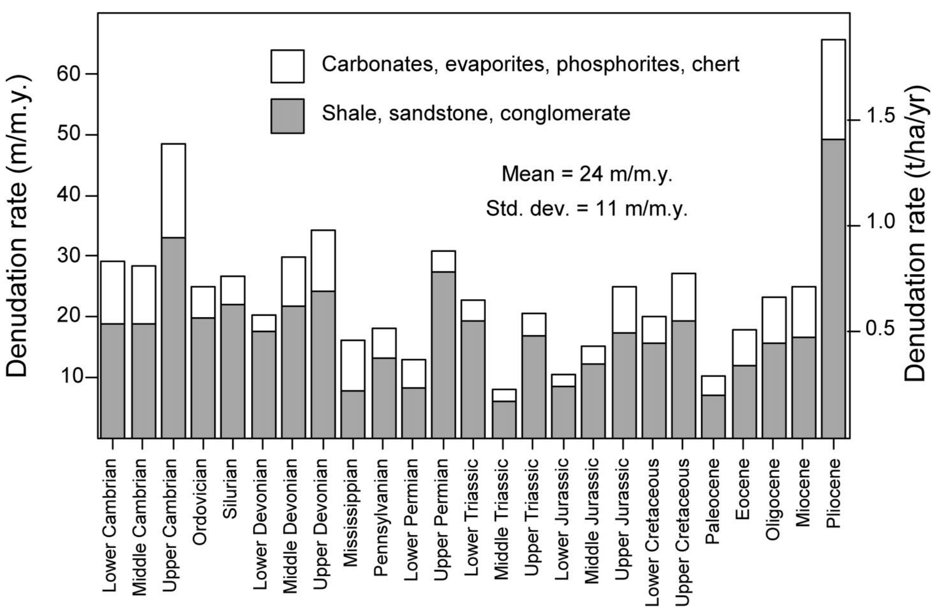

Figure 2. Continental denudation rates for epoch-long intervals determined from compositions of sedimentary rocks in Ronov (1983) and fluxes and cycling rates in Figure 1. Terrigenous debris makes up 69% and chemically precipitated phases are 31% of current 630 × 10^6 km^3 of rock in global Phanerozoic sedimentary reservoir.

represent 81% and 19%, respectively. These values are close to 47 m/m.y. (75% particulate; 25% dissolved) reported by Harrison (1994); to 64 m/m.y. (86% particulate; 14% dissolved) reported by Walling (1987); and to 41 m/m.y. (89% particulate; 11% dissolved) reported by Summerfield and Hulton (1994). Although these river-derived rates are within the range inferred from global sedimentary rock volumes (Fig. 2), mean values are approximately three times higher. This difference may reflect increased sediment delivery by major rivers in response to Quaternary glaciations (e.g., Hallet et al., 1996) augmented by construction and agricultural practices.

HUMANS AS GEOLOGIC AGENTS

Although river-borne sediment fluxes and deep-time denudation rates indicated by Phanerozoic rock volumes are of the same order of magnitude, erosion resulting from construction and agricultural practices is significantly higher. The movement of rock and soil during construction accounts for ~30% of all humanly transported material; the balance results from agriculture (Hooke, 2000a). When converted to geologic time scales, rates of soil loss from the development of pastureland (USDA, 1988) translate to ~400 m/m.y. (~1 $kg \cdot m^{-2} \cdot yr^{-1}$ or 10 $t \cdot ha^{-1} \cdot yr^{-1}$). These rates are somewhat lower than those resulting from cropland tillage, which range from 680 to 1400 m/m.y. in developed and undeveloped countries, respectively (Pimentel et al., 1995; Pimentel and Skidmore, 2004). Human-induced erosion rates therefore far exceed those represented by the deep-time baseline.

Given these rates of pasture and cropland denudation, one might then consider their net effect on the surface of Earth in the context of (1) the total area of land under agricultural control and (2) the net amount of soil that is removed through agrarian activities. At present, some 38% of Earth's ice-free land surface is being utilized as farmland (Tilman et al., 2001), of which ~15 $\times$ 10^6 km^2 (31%) is cropland and 35 $\times$ 10^6 km^2 is pasture (Food and Agriculture Organization of the United Nations, 2004). If it is assumed that (1) net loss from pastures is ~400 m/m.y. (USDA, 1988), (2) loss from cropland in underdeveloped countries is ~1400 m/m.y. (Pimentel et al., 1995), and (3) cropland loss in developed countries is ~580 m/m.y. (Nearing et al., 2000), Earth's agricultural land is currently being denuded at a mean rate of ~643 m/m.y. This is ~28 times faster than deep-time erosion rates inferred from natural processes (24 m/m.y.). If this quantity of soil and rock loss were evenly distributed over all ice-free continental surfaces, current agricultural practices alone would serve to reduce the average global land surface by 242 m/m.y. Human activity through construction raises this amount by ~30%, yielding a hypothetical (across all land surfaces) net anthropogenic denudation rate of ~360 m/m.y., an amount ~10 times that imposed by glaciers, rivers, and other natural processes combined.

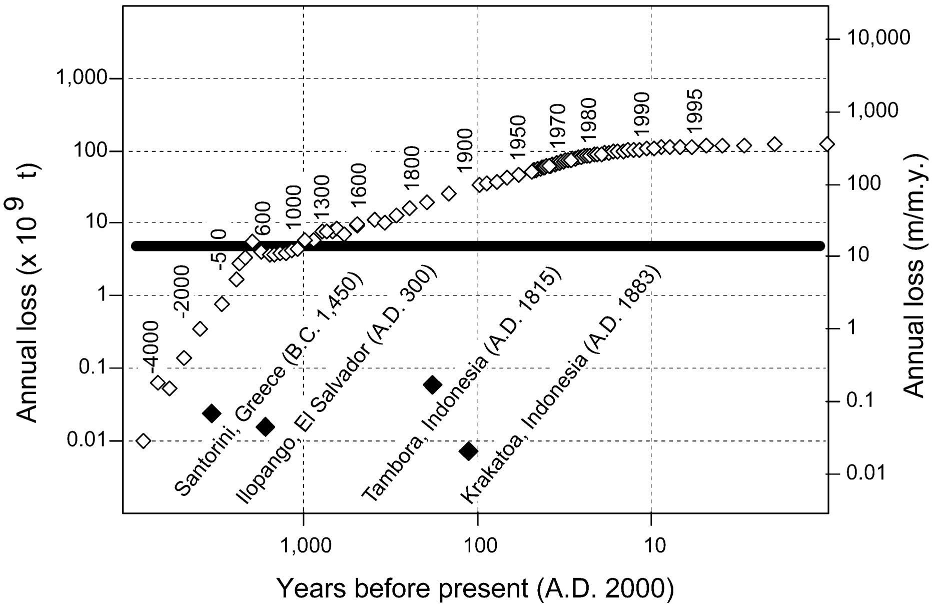

Figure 3. Historical rates of anthropogenic erosion (open diamonds) from data in Hooke (2000a). For comparison, solid black diamonds are volumes of several large volcanic eruptions (dates in parentheses); heavy black line is mean deep-time denudation rate of 24 m/m.y. determined from Figure 2.

If current amounts of human-induced erosion are more than an order of magnitude greater than that resulting from all natural processes, it is instructive to also consider when this state of human geomorphic dominance came to be. Hooke (2000a) estimated that per capita annual amounts of soil and rock movement from construction and agriculture exhibit different trajectories of increase over the past 5000 yr, but that both have increased over the history of human expansion to a current amount of ~21 t per person per year (6 from construction; 15 related to farming). This estimate yields a current net rate of ~120 $\times$ 10^9 t/yr, an amount similar to the 75 $\times$ 10^9 t/yr (which largely excludes contributions arising from construction) given by Pimentel et al. (1995). These two estimates indicate that human-induced rates of denudation surpassed that resulting from all natural processes (~5 $\times$ 10^9 t/yr) toward the end of the first millennium (Fig. 3). As context for these numbers, current annual amounts of rock and soil moved over Earth's surface in response to construction and agricultural practices are ~18,000 times that of the 1883 Krakatoa eruption in Indonesia, ~500 times the volume of the Bishop Tuff in California, and about 2 times the volume of Mount Fuji in Japan. At these rates, this amount of material would fill the Grand Canyon of Arizona in ~50 yr.

CONCLUSIONS

From the preceding considerations, it seems obvious that human activity is many times the most important geomorphic agent acting on the surface of the modern Earth, a conclusion that evokes several nontrivial consequences. It should be made clear, however, that anthropogenic and natural rates of erosion embody somewhat dissimilar measures of continental denudation. Rock volume and river fluxes are inherently estimates of material transfer based on data that are collected after weathering and significant downslope transport has occurred; these data are generally determined at points of coastal entry, localities where rivers meet oceans—where sediment exits the erosional realm and enters the depositional one. In contrast, cropland and building fluxes are generally measured as transported material exits some prescribed area of tillage or site of construction; these rates are generally derived at those points where material has as yet to enter the realm of sediment transport by rivers. As a result, cropland-construction rates and deep-time rates should not be directly compared as equivalent entities (Trimble and Crosson, 2000).

In fact, the two situations largely represent opposite ends of the sediment-cycling spectrum. At those epoch-long durations when geomorphic surfaces might approach steady state, rates of tectonic uplift are largely balanced by rates of continental denudation.

However, over the considerably shorter interval of anthropogenic erosion, delivery of sediment to rivers quickly exceeds rates of transport that are possible in fluvial systems that have more or less attained geomorphic equilibrium over a significantly longer prehistory with an appreciably lower sediment flux. Human earth moving and soil loss do not equal sediment yield, and this axiom is clearly reflected in differences between rates of erosion inferred from construction and agricultural practices ($\sim 120 \times 10^9$ t/yr) and those suggested from various estimates ($16–24 \times 10^9$ t/yr) of large river fluxes (Milliman and Syvitski, 1992; Vörösmarty et al., 2003). Even though human activity has significantly increased the downslope delivery of rock and soil, an important amount of this material is evidently now stored in proximity to these sites of accelerated erosion (Tilman et al., 2001). Vörösmarty et al. (2003) reported that $4–5 \times 10^9$ t of eroded material (~30% of particulate flux) is currently being stored behind reservoirs; Pimentel et al. (1995) estimated that ~60% of soil lost from croplands is deposited on adjacent hill slopes, in floodplains, and behind dams on streams and rivers.

It should also be recognized that accelerated denudation, particularly that ensuing from agriculture, occurs across different regions from those undergoing the most rapid erosion by natural processes. Maximum large-river sediment yields occur from those orogenic basins with the steepest slope angle (Hooke, 2000b), with the greatest relief (Summerfield and Hulton, 1994), and at the highest elevation (Harrison, 2000); erosion of bedrock takes place almost entirely in catchment headwaters. In contrast, agricultural lands are concentrated across those low-relief regions that constitute continental stable cratons and passive margins. Accelerated erosion and short-term sediment storage in response to cropland practices therefore represent the imposition of a temporal and a spatial pulse of geomorphic disequilibrium on lower-elevation parts of Earth's surface.

In this context, deep-time denudation rates derived from sedimentary rock volumes are perhaps most important from the standpoint that they provide a long-term geologic framework for evaluating shorter-term human impacts. Pimentel and Skidmore (2004), for example, cited studies indicating that rates of United States cropland soil loss exceed those of soil formation (40 m/m.y.) by a factor of 12, a difference that suggests a significant gap between current and sustainable agricultural practices. Trimble (2004), on the other hand, cited studies suggesting that soil-loss tolerances in areas of U.S. agriculture are ~440 m/m.y. (or more) and concluded that U.S. soil erosion, while serious, does not seem to constitute an actual crisis. In light of deep-time rates on the order of a few tens of meters per million years, this latter statement is difficult to substantiate.

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