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On the Efficacy of Humans as Geomorphic Agents

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Figure 1. A slope in Nepal, terraced for agriculture. The rock tower in the center is inferred to be a volcanic neck. Its height above the rest of the slope (see house for scale) represents differential erosion over a time period that must be long compared with that represented by the terracing.

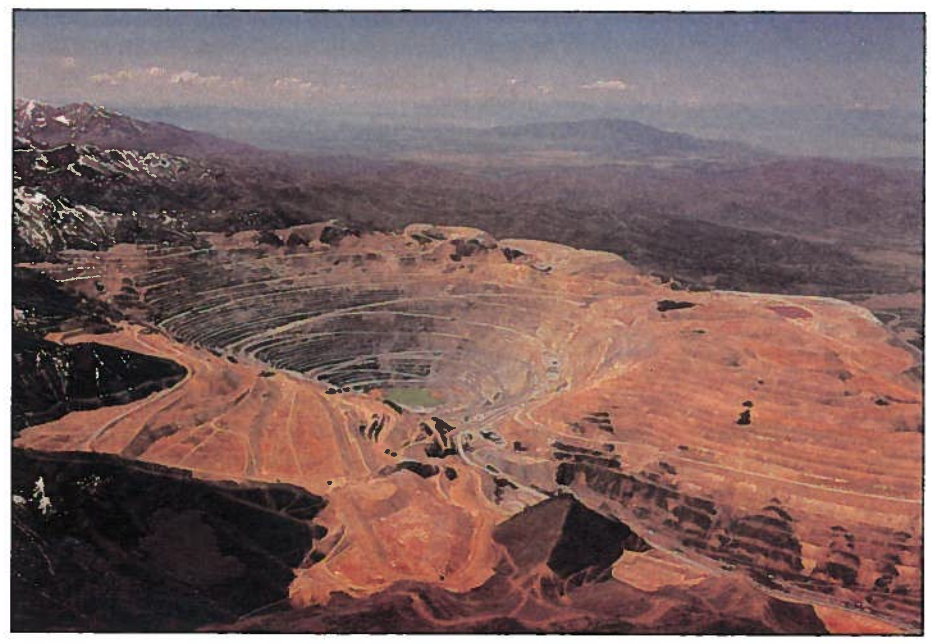

Figure 2. Oblique aerial photograph of Kennecott's Bingham Canyon open pit copper mine, Utah. In the middle distance, where the deepest hole now is, there was a mountain 130 years ago. (Photograph courtesy of Don Green Photography. Reproduced with permission.)

ABSTRACT

Humans are geomorphic agents. They move vast quantities of soil and rock, and have a major visible impact on the landscape. To place this impact in perspective, I have compared humans with more traditional geomorphic agents on the basis of the mass of material moved per year. In most instances we can identify a line, such as the coast, across which this material is moved. For example, the annual sediment load delivered to the oceans and interior basins by rivers is about 24 Gt, and during the Pleistocene, glaciers probably deposited about 10 Gt of till in moraines and outwash fans every year. In the case of humans, movement of material is more random, so it is not possible to identify such a line. However, the total moved by humans, estimated herein to be 40–45 Gt/yr if the effect of agriculture on river sediment loads (10 Gt/yr) is included, is comparable to or significantly greater than that of any other single geomorphic agent. Considering, in addition, the visual impact of their activity, humans are arguably the most important geomorphic agent currently shaping the surface of Earth.

INTRODUCTION

Early geomorphologists focused on descriptions of the landscape and on evolution of landforms on geological time scales. Attempts to understand the *physical* and *chemical* processes that produced different landforms evolved nearly simultaneously, however, and the modern science emphasizes this approach.

Biological processes generally have not been assigned major importance in landscape evolution. However, weathering, soil formation, and the development of karst landscapes are accentuated enormously because microbially produced CO_2 combines with percolating rain water to form carbonic acid. Likewise, soil creep is greatly enhanced by burrowing fauna. But compared with landforms created by more traditional agents such as rivers and glaciers, the effects of these biological agents are limited in both magnitude and extent. Furthermore, as the size of the organism increases, its population usually decreases. Thus although larger organisms are capable of doing more geomorphic work in a short time, they act less frequently, both in space and time, and thus generally have less impact. This rule breaks down, though, when we consider Homo sapiens, both because the population of this species is so out of proportion to that of any other organism of similar size and because this organism has developed an impressive array of tools, from hoes to tractors, for modifying the landscape (Figs. 1, 2).

This role of humans has been long recognized. Over a century ago, Marsh (1869, 1882) called attention to our ever-increasing impact on the landscape, and the modern environmental literature documents many specific examples (e.g., Turner, 1990). However, a quick survey of several textbooks on geomorphology revealed only one that mentioned humans (or man) in the index, and none that devoted a chapter to this agent.

In short, geomorphologists seem reluctant to give humans equal press with more traditional geomorphic agents. Perhaps this is because there is little mystery about either the processes or the products, or perhaps it is because authors prefer to address only "natural" processes. Humans, however, are not unnatural. They are just as much a part of the natural environment as any other organism, and so the products of human activities also must be considered to be natural, be they books, buildings, or sanitary landfills. For the sake of our environment, and thus our future as a species, it is crucial that we recognize and accept that we are not above nature, somehow supernatural.

My objective herein is to compare the efficacy of various geomorphic agents, humans included, on a global scale. How such a comparison should be made is unclear, however. To calculate the work done per unit time—that is, the force exerted to move a mass of soil or rock times the distance it was moved divided by the time required—would be an approach soundly based in physics. This, however, quickly becomes unwieldy; a rock is entrained by a glacier in Hudson Bay, but what force was exerted on that rock to move it to Ohio and how long did it take? Trying to estimate energy expenditure results in similar problems; most geomorphic agents move material to positions of lower gravitational potential, and thus release (potential) energy rather than consume it.

MASS OF MATERIAL MOVED: A MEASURE OF THE EFFICACY OF A GEOMORPHIC PROCESS

An obvious alternative to a comparison of geomorphic agents based on work or energy expenditure is one focusing on the mass of material moved. Here, however, it is necessary to distinguish between processes that simply move sediment back and forth, those that move material away from a location only to replace it with other material, and finally those that move material away without replacing it.

Examples of the first type are waves approaching normal to a beach, wind moving sand back and forth in dunes, and farmers with plows turning up soil on the ~1.7×10^7 km^2 of Earth that is under cultivation (Ehrlich, 1988). Such processes move incredible volumes of sediment. Plowing land area under cultivation annually with furrows 0.2 m wide and 0.1 m deep, for example, involves moving 1500 Gt of soil, most of which soon slumps or is washed back into the furrows. Because the lasting effect of such processes on the topography is small, I have ignored them.

Among processes that move sediment away from a location in a single direction, usually downslope in response to gravity, are rivers, glaciers, and slope processes. These "unidirectional" processes are readily quantified because data are available upon which to base estimates of their prowess. For example, the delivery of sediment to the oceans by rivers is well studied.

A common characteristic of such unidirectional processes is that their efficacy can be equated with the rate of movement of sediment across a well-defined line or plane. In the case of rivers, this could be the boundary

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between oceans and continents or, in interior basins, the boundary between erosional and depositional regions.

In all such unidirectional processes, however, there are intermediate steps in which a particle that is moved is soon thereafter replaced by another, as, for example, the transfer of a sand grain from one point bar to the next downstream and its replacement by a grain from upstream. To the extent that such internal sediment transfers have no long-term geomorphic effect, I have disregarded them. Some internal transfers are not completely balanced, however, and thus do have a lasting effect. The migration of river meanders is an example.

Sediment transfers resulting from human activities are also internal in the sense that there is no well-defined line or plane across which material is moved. Furthermore, they are decidedly unbalanced, because much of the material removed is not replaced.

HUMAN ACTIVITIES

To quantify the geomorphic impact of *Homo sapiens*, I have chosen to consider three types of earth-moving activity: excavations for houses, mineral production, and road building. One can make a reasonable estimate of the quantities of earth moved in each of these three activities in the United States, as follows:

1. Housing starts average ~1.3 x 10^6/yr (*New York Times*, 1/23/92). If the average house measures 10 x 20 m and half of them require foundation holes 3 m deep, or an equivalent amount of regrading of the landscape, 300 m^3 of earth is moved per house. At a mean density of 2 t/m^3, house building involves moving ~0.8 Gt/yr (1 Gt = 10^9 t or 10^{12} kg).

2. Mineral production in 1988 totaled 3.2 Gt (U.S. Bureau of the Census, 1991, p. 694). Of this, the three largest products were stone (1.1 Gt), sand and gravel (0.86 Gt), and coal (0.86 Gt). Making an adjustment for the mass of ore moved to yield a unit mass of mineral product increases this to ~3.8 Gt. In making this adjustment, I conservatively estimated that mining of stone and of sand and gravel did not involve movement of material other than that produced, and that in producing coal, the mass of overburden removed was about one-third that of coal produced. For metals, figures on the concentrations required to yield an economically viable deposit were obtained from texts such as Dennen (1989).

3. There are ~6.23 x 10^6 km of highways in the United States (U.S. Bureau of the Census, 1991, p. 605). Assume that the principal period of construction of these was during the past 80 years, and that the construction (and reconstruction) rate in the past decade or so has been double the mean. Assume further that ~10 m^3 of earth with a density of 2 t/m^3 is moved per meter of road. This does not include gravel that is mined and hauled to the construction site, as that is included in the mineral production above. Then road construction may involve movement of ~3 Gt/yr.

To extrapolate these figures to worldwide activity, let us assume that the geomorphic activity of humans scales with the gross national product. The GNP of the world as a whole is about four times that of the United States (U.S. Bureau of the Census, 1991, p. 840–841), and so my estimate of the worldwide geomorphic activity of *Homo sapiens* becomes ~30 Gt/yr. Alternatively, one might scale human geomorphic activity with energy consumption. As energy consumption in the United States is 21.7% of the world total (Holdren, 1991), the estimate then rises to 35 Gt/yr.

TABLE 1. SUMMARY OF RATES OF GEOMORPHIC ACTIVITY

Agent	Mass moved (Gt/yr)
Humans	
GNP scaling	30
Energy use scaling	35
Energy use scaling and including effect on river sediment load	45
Rivers	
Long-distance sediment transfer	
At present	24
In the absence of human disturbance	14
River meandering	
Starting on 4th order streams	39
Starting on 5th order streams	23
Glaciers	
At present	4.3
Pleistocene	10
Slope processes	0.6
Wave action	
Sediment flux	1
Erosion	0.24
Wind	1
Mountain building	
Continental	14
Oceanic	30
Deep ocean sedimentation rates	7

RIVERS

Long-distance Sediment Transfer

Milliman and Meade (1983) estimated that the worldwide flux of clastic sediment to the oceans in rivers is ~16 Gt/yr, a figure that is generally consistent with other estimates (see Judson, 1968, Table 3). Dissolved load contributes an additional 2 to 4 Gt/yr (Judson, 1968; Lisitzin, 1972, p. 36), making a total of ~19 Gt/yr.

Judson (1968) estimated that in the absence of human disturbance, the combined clastic and dissolved load of rivers would be only ~9 Gt/yr. Thus human activities, particularly agriculture, may be responsible for as much as ~10 Gt/yr. In Table 1, the last estimate of the human impact on the landscape includes this contribution.

To the estimates of Milliman and Meade (1983) and Judson (1968) should be added the flux of river sediment to interior basins. On the basis of Judson's calculations, this is ~4.6 Gt/yr. Thus, in round numbers, we take the total sediment flux in rivers prior to human intervention to be ~14 Gt/yr, and thereafter ~24 Gt/yr.

Meandering

To estimate the amount of sediment moved in the process of river meandering, we must first estimate the total length of meandering streams in the world. Assume that the average drainage density is 1.5 km of stream channel per square kilometer of land. Assume further that streams of low order do not meander. Then, using relations developed by Horton (1945), calculate the total length of streams of order greater than this limit. In this calculation, I used a bifurcation ratio of 3.6 and a length ratio of 2.1, both of which are reasonable mean values. Finally, assume that the density of the eroded sediment is 2 t/m^3, the mean migration rate is 0.2 m/yr (Rohrer, 1982), and the mean stream depth is 1.5 m. Then, if streams of order 4 and higher are assumed to migrate by meandering, ~39 Gt/yr of sediment are moved by this process (Table 1).

GLACIERS

Rates of erosion by valley glaciers can be as high as 5 to 10 mm/yr, but more typically they are closer to 1 mm/yr, and for continental ice sheets they are an order of magnitude less (Embleton and King, 1975, p. 309–313, 320–321; Andrews, 1972). Glaciers, principally continental ice sheets, now cover about 15.86 x 10^6 km^2 of Earth's surface (Haeberli et al., 1989). Assuming a density of 2.7 t/m^3 for the rock eroded, the total annual erosion rate is ~4.3 Gt/yr. During the late Pleistocene glacial maximum, ice covered ~38.6 x 10^6 km^2 (Embleton and King, 1975, p. 14); this figure suggests a potential erosion rate of ~10 Gt/yr.

SLOPE PROCESSES

The land area of Earth is ~1.5 x 10^{14} m^2. Of this, probably one-third is so flat that slope processes are negligible. Then, if the length of a typical slope, top to bottom, is ~100 m, the total width, parallel to the contour, would be ~1 x 10^{12} m. Creep and slope wash can deliver ~3 x 10^{-4} m^3 of soil per year to the base of a typical slope of unit width (Kirkby, 1967; and unpublished data). Assuming a soil density of 2 t/m^3, the total mass of soil moved to the bottoms of slopes worldwide may be on the order of 0.6 Gt/yr.

WAVE ACTION

Typical rates of littoral drift range from 80 000 to 380 000 m^3/yr (Herbich and Haney, 1982). Let us assume that the primary sinks for this sediment are submarine canyons that have eroded headward across the continental shelf. The average spacing of submarine canyons along the Atlantic and Pacific coasts of the United States is ~200 km (Kennish, 1989). Thus, along the 0.5

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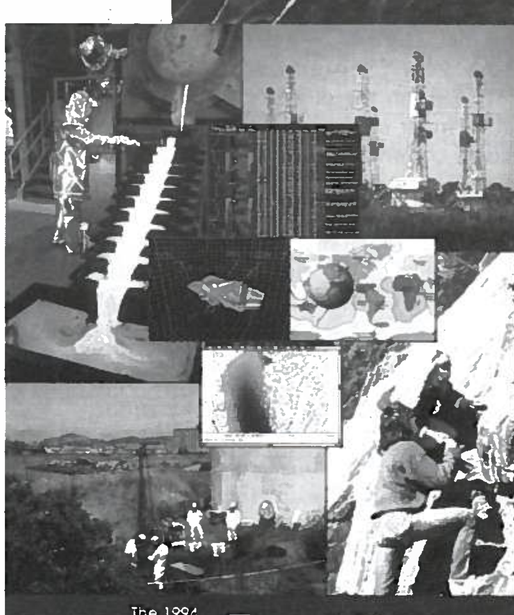

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x 10^6 km of coastline in the world (Bird and Schwartz, 1985, p. vii) there may be ~2500 canyons. If each receives ~200 000 m^3/yr of sediment with a density of 2 t/m^3, the total thus discharged is 1 Gt/yr.

Of course, much of that sediment is delivered to the coast by rivers. Herbich and Haney (1982) suggested that actual erosion of beaches and beach cliffs along the coastlines of the world may be only ~1.2 x 10^8 m^3/yr, or ~0.24 Gt/yr.

WIND

G. Arnason (cited by Peterson and Junge, 1971, p. 312) estimated that wind may export ~0.5 Gt/yr of dust from the continents. This dust is believed to originate "primarily from arid regions, particularly the Sahara." This estimate is thus broadly consistent with a numerical model developed by Schütz et al. (1981) that predicted a dust transport from the Sahara of 0.26 Gt/yr.

Wind also moves sand, but sand dunes occupy only a small fraction of Earth's surface, so the geomorphic work done must be small compared with many other geomorphic processes. Furthermore, in many cases sand is simply moved back and forth as storm and prevailing winds alternate (Sharp, 1966). The total unidirectional transport of clastic sediment by the wind is thus estimated, very roughly, to be ~1 Gt/yr.

MOUNTAIN BUILDING

Because rather different processes are involved, it is convenient to consider orogenic movements on land separately from "mountain building" at midocean ridges. Rates of orogenic uplift of land areas vary widely, so rather than attempt to estimate a global average rate, I assume that this uplift is roughly balanced by river erosion. Thus, the estimate above for the rate of sediment delivery to the oceans and interior basins in the absence of human activities suggests an addition to the continental land mass above sea level of ~14 Gt/yr.

At midocean ridges, it is the geomorphic relief of the ridges themselves, and not the total production of lithosphere, that is relevant to the present comparisons. The ridges rise an average of ~2 km above the surrounding ocean floor (Sawkins et al., 1974, p. 119), and their total length is ~84 000 km (Hamblin, 1985, p. 404). The mean spreading rate is ~0.06 m/yr (Sawkins et al., 1974, p. 125). Assuming a density of 3 t/m^3 for the rock formed, the rate of midocean ridge formation is 30 Gt/yr.

DEEP-OCEAN SEDIMENTATION RATES

The ocean basins occupy about 3.55 x 10^{14} m^2, and typical sedimentation rates are of the order of 1 x 10^{-5} m/yr. Assuming a density of 2 t/m^3 yields a rate of ~7 Gt/yr. Of this, 2 to 3 Gt/yr may be biogenous sedimentation (Lisitzin, 1972, p. 135), and most of the rest is presumably fine clastic river sediment, together with a small eolian contribution, mentioned above, that is carried far from the continents before being deposited. The geomorphic effect of this sediment is to bury the irregular volcanic landforms originating at midocean ridges and elsewhere, and thus to smooth the abyssal plains of the ocean.

THE PREMIER GEOMORPHIC AGENT

Perhaps I have underestimated the role of some traditional geomorphic agents. More weight could be given to the impact of moving tens of millions of separate 1 g parcels of sediment each 1 km in a river, or of moving tens of billions of sand grains back and forth on beaches.

However, an equally strong case can be made to the contrary. Most geomorphic processes move sediment in a predictable direction, and the ultimate driving force is gravity. Humans, however, move soil or rock hither and yon, often in defiance of gravity, and governed by no apparent physical rules. Consequently, the visual impact of human geomorphic activity is vastly greater than that of most traditional geomorphic agents such as, for example, a river redistributing a similar amount of sediment in a floodplain or depositing it below sea level in a delta.

In conclusion, by the measures developed herein, however imperfect, *Homo sapiens* has become an impressive geomorphic agent. Coupling our earth-moving prowess with our inadvertent augmentation of the sediment load of rivers and the visual impact of our activities on the landscape, one is compelled to acknowledge that, for better or for worse, this biogeomorphic agent may be the premier geomorphic agent of our time.

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GSA Committee Awards Research Grants

June Forstrom, Research Grants Administrator

The GSA Committee on Research Grants met in Boulder, Colorado, on April 7–8, 1994, and awarded $303,073 to 238 student applicants. Two postdoctoral applicants for the Gladys W. Cole and W. Storrs Cole Awards received$14,000. Committee members for 1994 are Raymond V. Ingersoll (chairman), Mary L. Droser, Peter C. Patton, Darryll T. Pederson, Sheila J. Seaman, Ben A. van der Pluijm, and Thomas O. Wright (National Science Foundation conferee).

Of the 238 grant recipients, 98 were master's candidates and 140 were doctoral candidates. The size of the average award was $1273. Proposal requests totaled $1,070,304 from 583 students.

The committee's budget included $156,600 from the Penrose Endowment; $100,000 from the National Science Foundation; $6000 from the Harold T. Stearns Award Fund, the Sedimentary Geology Division, and the Structural Geology and Tectonics Division; $2854 of funds returned too late in 1993 to be reawarded; and $11,000 from the Second Century Fund. It also included $26,400 from the GSA Foundation, which included $12,000 from the Research Fund, $6800 from Unrestricted GEOSTAR funds and $7600 from various restricted special funds and Geophysics Division and Hydrogeology Division funds. The Gladys W. Cole and W. Storrs Cole Awards were funded by $14,000 income from the two Cole Award Funds of the GSA Foundation.

Cole Awards for Postdoctoral Research

The Gladys W. Cole Memorial Research Award for 1994 went to Ellen Eva Wohl of Colorado State University, Fort Collins, to support her project titled "Energy Expenditure in Deep, Narrow Bedrock Canyons of the Colorado Plateau." This award, established in 1980, is restricted to support research for the investigation of the geomorphology of semiarid and arid terrains in the United States and Mexico.

The W. Storrs Cole Memorial Research Award for research in invertebrate micropaleontology was established in 1989. It was presented this year to Pamela Hallock Muller of the University of South Florida, St. Petersburg, for her project titled "Evolutionary Implications of Environmental Stress on Adult *Amphistegina.*"

Eligibility for both Cole awards is restricted to GSA Members and Fellows between 30 and 65 years of age.

Student Awards

Gretchen L. Blechschmidt Research Award. The family and friends of Gretchen Louise Blechschmidt established a fund in her memory in 1990 to support research for women in the geological sciences. The award was presented this year to Katharina Billups of the University of California, Santa Cruz, for her project titled "Early to Late Pliocene Paleoceanography: Reconstructing Seasonal Sea Surface Temperatures from the Stable Isotopic Composition of Individual Planktonic Foraminifera."

John T. Dillon Alaska Research Award. John Dillon was particularly noted for his radiometric dating work in the Brooks Range, the results of which have had a major impact on the geologic understanding of this mountain range. The 1994 recipient is Tracy Marie Siebert of Miami University (Ohio), for "Petrologic Significance of Mafic to Intermediate Volcanism at the Skookum Creek Volcanic Complex, Wrangell Volcanic Field, Alaska."

Robert K. Fahnestock Award. This award is given to honor the memory of Ken Fahnestock, who was a member of the Committee on Research Grants. It is awarded to the applicant with the best proposal in sediment transport or related aspects of fluvial geomorphology. The 1994 recipient is Laurence C. Smith, Cornell University, for "A New Method of Discharge Estimation for Braided Outwash Streams."

Lipman Research Award. The Lipman Research Fund was established in 1993 and is supported by gifts from the Howard and Jean Lipman Foundation to promote and support student research grants in volcanology and petrology in the western United States and Alaska. This year the fund supported the research of two students: Julia G. Bryce,

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