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Geomorphology: Boundaries between Media

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Abstract. An earth boundary surface is the interface between two media, such as the atmosphere-lithosphere, atmosphere-ocean, and lithosphere-ocean. These boundary surfaces separate different density media with their own energy dynamics, composition, and strength. The advantages of an earth-system, boundary strategy in geomorphology is that it is less limiting and brings forth the importance of several concepts, which are intuitively obvious, but are often overlooked or assumed. Thus, a more complete understanding of the nature and origin of landscapes is possible. First, all surface morphology is created from the transfer of mass in 3-d space; second, gravity is the dominant driving force of both exogenous and endogenous processes at meso- and megascales; third, a medium's resistance to change (viscosity or rigidity) is dependent on the strength of the molecular forces holding the medium together, its thermal state and the presence of structural discontinuities; fourth, sympathetic boundaries are commonly found adjacent to the studied surface in one or both media; and fifth, the application of earth-system boundaries is not scale limiting and includes a range from continental scale morphology to mineral surface microtopography.

Keywords: Gravity, Boundary Surfaces, Scale, Geomorphology, Landscape Development

INTRODUCTION

The early development of geomorphology in the late 1800's focuses on two paradigms, one process oriented, developed by G. K. Gilbert, and one historically based, championed by W. M. Davis and others. As circumstances would have it, the focus on physiography, classification and history of landscapes dominates during the first half of the 20th Century. In the latter half of this century, the emphasis shifts toward a study grounded on basic principles of mechanics and fluid dynamics of specific processes (e.g. fluvial, eolian, mass wasting) that form landscapes (Strahler, 1952; Ritter, 1988). Now with the easy availability of satellite imagery to study megascale landforms and scanning electron microscopes to study the very small, it is proposed that geomorphology expand its field of study to surfaces and processes not typically addressed in order to provide a more integrated view and understanding of earth systems. Recent publications by Summerfield (2000) and Allen (1997) reflect this trend.

Traditionally, geomorphologists focus their study of the earth's landforms on exogenic processes at mesoscopic scales (centimeter to hundreds of kilometers range) operating upon 30 percent (sub aerial portion) of the planets surface

(Thorn, 1988, p. 25). Earth surface morphology, governed by endogenic processes, microscopic activity and 70 percent of the earth's surface that lies below the ocean, tends to be ignored by geomorphologists. These subjects are generally left to geologists, geophysicists, chemists and oceanographers, but, unfortunately, these practitioners often ignore the interpretation and ramifications of surface morphologic signatures. By redefining a geomorphic surface, a more integrated and expanded view of earth phenomena is possible.

BOUNDARY SURFACES

1. Definition

A physical boundary surface is an interface between two defined media. Generally these media display different physical and chemical properties and exhibit different energy states. Megageomorphic surfaces, with areas greater than 10^8 square meters (>100 sq km), include air-ocean, air-land, and ocean-seafloor surfaces (Fig. 1). Mesogeomorphic surface morphology, with areas between 10^7 to 1 square meters, embody not only exposed pediments and inselbergs, but hidden surfaces such as sediment-ice boundaries found at the sole of a glacier, soil-rock interfaces below regolith and water table surfaces associated with cave formation.

The most common microgeomorphic surface boundaries studied, with areas less than 10^{-2} square meters, are weathering horizons, but any geomorphic

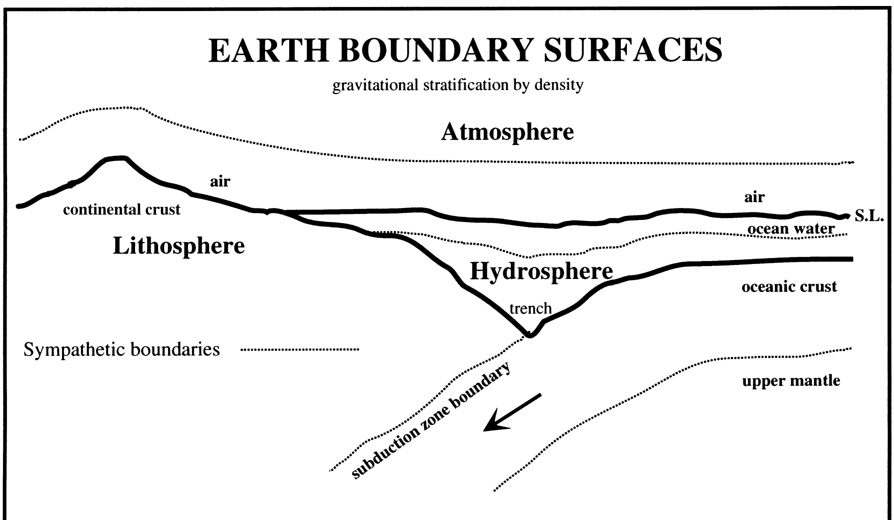

Fig. 1. Earth Boundary Surfaces. Shows megascale primary and sympathetic boundaries found on the earth's surface generated through gravitational segregation by density.

surface can also be studied at molecular scales. The major differences between studying these different scales of landforms are the tools we use. For megascopic landscapes we use aerial photography and satellite imagery, for mesoscopic landforms field observations with the naked eye and for microscopic surfaces optical and scanning electron microscopes (SEM).

2. Geometry

Geomorphologists typically address processes operating upon single surfaces shared between two media, such as wind on sand, or water on sediment. Although, these simple systems have only two general physical components, the inter-media dynamics and resultant morphological signatures are complex because of surface roughness and complicated feedback loops (e.g. Wiggs, 2001; Lawless and Robert, 2001).

When two planar surfaces intersect they share a line. Such is the case when the ocean surface intersects the land surface to produce a shoreline. The shoreline represents the intersection of four media: air, water, water-saturated rock and “dry” rock. This linear zone is subject to energy dispersion by processes from all of the respective media. Multiple lithologies only complicate the system. As such, the shoreline is one of the most dynamic and complex geomorphic regions studied and is influenced by wave action, wind shear, springs, and life from two entirely different ecological habitats. Organic entities, from bacteria, to humans and up to elephants, represent media and processes that need to be addressed as system components (Westbroek, 1991). Without defining the geometry and all the media involved, an investigator could easily overlook the interaction and input each medium might have on the resultant landscape.

3. Exogenous versus endogenous

The boundary surface is where energy is dispersed, reflected and absorbed. The energy can come from either side of the boundary to drive geomorphic processes that modify the morphology. Geomorphologists traditionally use the term, exogenic processes, as those processes operating at or near the earth’s surface while endogenic processes are derived from within the earth (Bates and Jackson, 1987).

These definitions are adequate when addressing mega- and most mesoscale landscapes but they break down when describing processes operating on surfaces in general. Thus, it is useful to use the more general English word, exogenous, that means operating externally while endogenous means operating internally (American Heritage Dictionary). In this paper the surface is the reference plane and the medium with the greatest viscosity or rigidity is considered endogenous. Therefore, at a water-ice contact the water medium is the exogenous medium and the ice is considered the endogenous medium. Solar energy (exogenous) that passes through the atmosphere to the earth’s surface is absorbed and emitted from within the rock as thermal energy (endogenous). Seismic energy dissipating at the earth’s surface is considered endogenous energy.

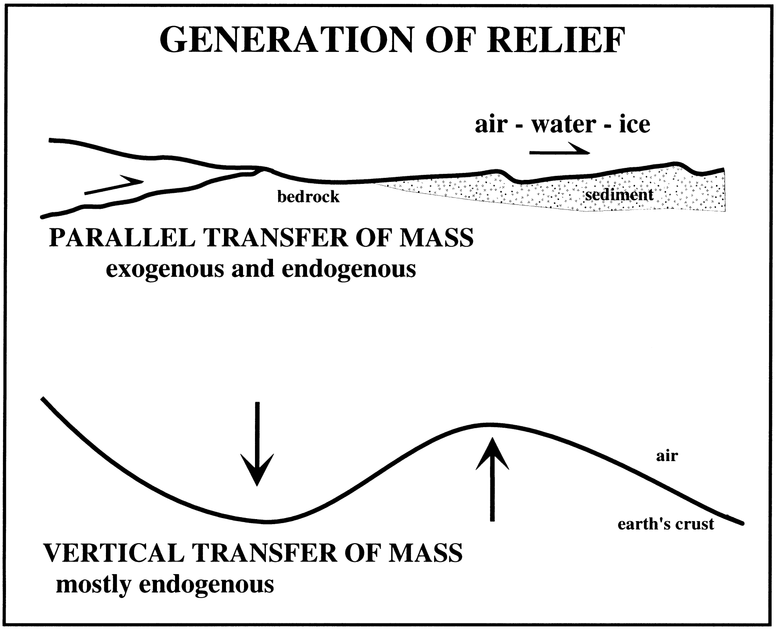

Fig. 2. Generation of Relief. Depicts the lateral and horizontal transfer of mass in 3-d space.

MASS AND ENERGY EXCHANGE AT BOUNDARY SURFACES

1. Gravity forces

Earth surface morphology evolves from the transfer of mass in 3-d space (Fig. 2). At mega and mesoscopic scales, processes under the constant pull of gravity drive this transfer. Gravity can work directly on a surface by pulling denser matter toward the earth's center and allowing less dense material to rise or by indirectly pulling fluid or solid masses across a surface to do work. Examples of mass transfer include horizontal and vertical plate movements to create mountains ranges, erosion of highlands that generates isostatic uplift, wind friction by air across a dune surface to produce wind ripples, and glacial ice dragging stones across bedrock to form scour marks. In these instances, the deposition and erosion tend to create surfaces that, statistically, are near perpendicular to the gravitational pull. In stratigraphy this translates to the law of horizontality.

2. Molecular forces

At microscopic scales, molecular forces control the migration and activity of molecules across microtopographic surfaces. Physicists have further defined these molecular forces. They have identified four fundamental forces in nature:

strong, weak, electromagnetic and gravity (Capra, 1982; Davies, 1983). The strong force is responsible for holding the nucleus of an atom together. The weak force is associated with beta decay in unstable isotopes and the electromagnetic force, which generates the positive and negative force fields, creates molecular bonding and radiation. Recently physicists have shown these three forces, excluding gravity, are permutations of a single-integrated force, described by the Standard Model (Gell-Mann, 1994, p. 125).

The strong and electromagnetic forces hold matter together and create the resistance to morphologic change. Gravity at molecular scales is insignificant compared to the strong and electromagnetic force fields; thus, the microtopographic signature is governed by processes that fall in the realm of surface physics and chemistry (Hochella, 1995; MacDonald *et al.*, 1996). Differential solution of mineral surfaces, microscopic plucking and deposition all leave signatures that can provide clues to surface environmental history (see Potential Applications below).

3. *Thermal energy*

The viscosity and/or rigidity of a medium such as air, water, ice or rock is related to its internal kinetic energy or heat. As kinetic energy increases, molecular vibrations drive molecules apart, which weaken bonding and decrease viscosity and rigidity. The thermal state of the exogenous medium is a factor in the aggressiveness of erosion and the endogenous medium's resistance. How a material behaves under stress is a function of its temperature and the time over which the stress is applied. For example, water at 4°C has a density of 1 g/cm^3 and a slightly higher viscosity than water at 20°C water with a density of 0.998 g/cm^3. This generates a greater shear on a sandy bed and under plain bed energy conditions that can create sand ripples not possible with the warmer less viscous water. More relevant, however, are variations in the temperatures of glacial ice. Ice at 0°C has a Moh's hardness of 1.5 while ice at –80°C has a hardness of 6 (Martini *et al.*, 2001, p. 14). The power flow law is one model that describes ice creep in glaciers and includes a temperature factor:

$$\varepsilon = A\tau^n$$

Where ε = strain rate, A = temperature dependent constant, τ = effective shear stress related to thickness of ice, and n = exponent with a mean value of 3.

The temperature-dependent, constant, A, can change over two orders of magnitude between 0°C and –13°C (Summerfield, 1991, p. 265). It is well known that warm-based glaciers found in temperate latitudes are more effective erosional agents than polar cold-based glaciers (Martini *et al.*, 2001, p. 70).

4. *Structural discontinuities*

It is rare that crystalline materials are homogeneous to any extent without faults, joints, micofractures and mineral dislocations. Thus, as emphasized by

Davis (1899), structure has a profound impact on earth surface morphology both directly and indirectly. It is obvious that structural discontinuities will directly influence the texture and competence of the endogenous media surface. For example, convergent plate boundaries create mountain morphology. Joints control drainage patterns and microfractures allow accelerated erosion rates. Mineral dislocations are targets for chemical weathering.

DISCUSSION

1. Boundary surface interplay

Ritter *et al.* (1995, p. 8) define landforms as representing the interaction between driving forces (climate, gravity and internal heat) and resistance (lithology and structure). This relationship is recognized and described by G. K. Gilbert in 1877 (Ritter, 1988). He describes the interplay between geologic driving forces, primarily running water and the resistance of materials on geomorphic surfaces in the Henry Mountains. Because the dominant exogenous processes at mesoscopic scales are fluids, Strahler (1952) calls fluid dynamics the cornerstone of geomorphology. This is especially true at mesoscales. However, at megascopic and microscopic scales tectonics and molecular forces respectively, become more important.

2. Safety ratio and boundary surface

Engineering geologists and geomorphologists have long recognized the importance of defining the failure threshold or safety ratio that defines slope stability (Rahn, 1996). The safety ratio (SR) is defined empirically as the sum of resisting forces divided by the sum of driving forces (Fig. 3). The prime driving force in the formula is gravity and the resisting forces are defined in terms of friction and cohesion (Derringh, 1998, p. 82). Friction of a free body object is also governed by gravity, hence, the gravity term in the numerator. In essence, the SR at mega and mesoscales is the ratio of the strong/electromagnetic forces that hold matter together, against gravity, which is trying to move matter closer to the center of the earth.

When the resisting forces are greater than the driving forces, the system retains its integrity with little or no observed change. Changes are indeed taking place because matter is in constant motion at the molecular scale. When the ratio becomes less than 1, then gravity overwhelms the molecular forces. The system becomes unstable and a transfer of mass occurs (e.g. slope failure) toward a more stable geometry.

SYMPATHETIC BOUNDARIES

Landform surfaces are part of a system and are influenced by or create other boundaries. Invariably, there are adjacent surface boundaries that are hidden in one or both of the bounding media (Fig. 1). For example, the Andean Mountain chain is a distinct landscape whose morphology reflects the convergent plate

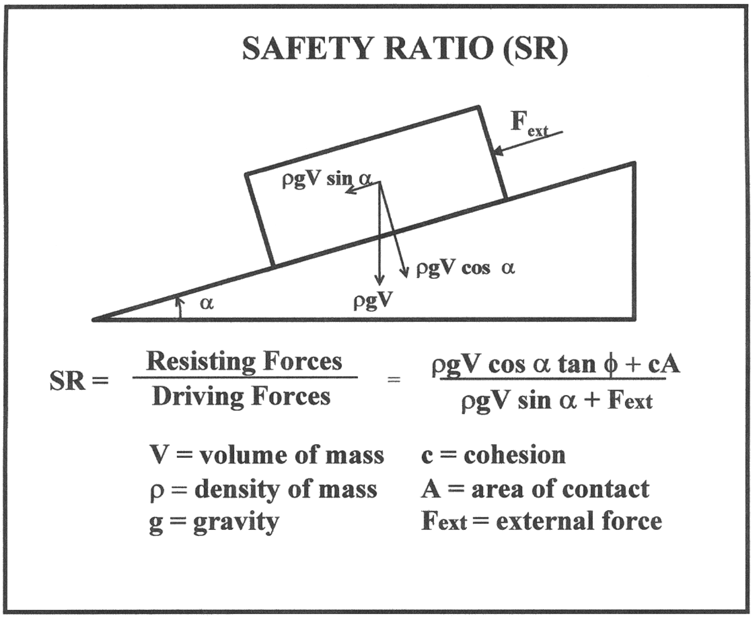

Fig. 3. Safety Ratio. Shows the geometry and forces of a free-body object resting on a solid surface.

boundary between the Nasca and South American plates. The Andean mountain system exists in direct response to the subsurface west-plunging subduction zone. The mountain range, in turn, diverts atmospheric flow and is reflected in cloud layers. Crevasses on the convex surface of a glacier are mirrored at depth by bedrock steps. Pressure release joints in granite on Half Dome in Yosemite National Park parallel the exposed cliff face surface.

These sympathetic boundaries, therefore, can reveal or even control the nature and origin of the primary study surface.

POTENTIAL APPLICATIONS

1. *Endogenous landforms*

Seismic body waves (Shear and Pressure waves) generated within the earth radiate in all directions, and when they reach the earth's surface they reflect most of that energy back into the earth. But some of this energy is dissipated at the density boundary interface between the crust and the atmosphere to create complex surface waves known as Love and Rayleigh waves (Fowler, 1990, p. 80). These surface waves form short-lived landforms (giant rapidly moving ripples) that can rearrange the earth's surface in minutes by creating landslides, liquifaction and altered drainages (Bolt, 1993). The physical morphology of these fleeting landforms is not well understood, but considering that few places on earth have been exempt from earthquakes, it is surprising that they have not been addressed in greater detail.

Endogenous energy is important in the larger scheme of landscapes and geomorphic processes. All uplift is in response to endogenous processes such as plutonism and isostasy that generate greater potential energy in the landscape that later is converted to kinetic energy via exogenous processes. In fact, without the endogenous input and subsequent uplift, landscapes would have long ago eroded away. Scheidegger (1998) notes the importance of endogenous processes in the Chinese Himalayan landscape and laments over the lack of respect these processes have been given.

2. *Microscopic surfaces*

Geomorphologists can benefit from the close examination of microtopography because unique environmental signatures are often scribed on these surfaces. For example, thermal spalling of quartzites form a unique fracture signature as seen on SEM microphotographs (Willard, 1968). Mahaney *et al.* (1996) found that the microtexture on quartz grains from Antarctica can be used to differentiate till transported over long distances under thick ice from thinner outlet glaciers traveling over shorter distances. Micromorphology of sand and silt grains using SEM from the Lower Cambrian sediments in Estonia was studied by Kurvits *et al.* (2000). They were able to construct transport history that indicated eolian and/or fluvial suspension was dominant.

3. *Ocean floor*

The ocean and the ocean floor are the last frontiers of earth exploration. Because ocean water obscures our view of 70 percent of our planet, we know more specific detail about the surfaces of Mars and Venus than we do of Earth. This is because the Mars Global Surveyor satellite provided imagery of the Martian surface with resolutions about one meter (http://nssdc.gsfc.nasa.gov.html). On Venus the Magellan satellite radar penetration through the thick Venetian atmosphere has given us less than 300 meter object resolution. On Earth, satellite radar cannot penetrate ocean water and we are relegated to interpreting the ocean floor from radar altimetry of the ocean surface that gives us about a 1 to 2 km resolution. Gravity variations, due to the distribution of submarine topography, mold the seawater surface to reflect an approximation of the ocean floor thousands of meters below. This is another example of a surface interpretation from a sympathetic boundary. At present, modern side-scan sonar imagery with sub meter resolution has covered less than a few percent of the ocean floor surface. If the ocean floor has as much diversity as the land, it follows that we have an extensive information gap to close.

CONCLUSIONS

The purpose of this paper is to break down the inherent, or perhaps unintended, limits of geomorphic study by focusing on boundary surfaces, their adjacent media, and the fundamental forces driving geomorphic processes. Geomorphic studies should have no scale limits. By defining a geomorphic surface as simply an interface between two media, a few basic concepts are revealed: 1) earth surface morphology evolves from the transfer of mass in 3-d space, 2) at mega- and mesoscopic scales gravity is the dominant force driving geologic processes to shape the landscape, 3) at molecular scales gravity plays a minor role compared to the electromagnetic/strong forces holding matter together and 4) sympathetic boundaries found with the primary surface of study can add insight to the nature and origin of both surfaces. The boundary concept can be expanded to the study of both continental-scale, as well as, molecular-scale surfaces. Geomorphology viewed in this larger context then becomes a subject of study that should be the cornerstone of all Earth system curricula.

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