# The state of interactions among tectonics, erosion, and climate: A polemic

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Since Dahlen and Suppe (1988) showed that erosion can affect the tectonics of the region undergoing that erosion, geodynamicists, tectonic geologists, and geomorphologists have joined in an effort to unravel the interrelationships among not only erosion and tectonics but also climate, which affects erosion and is affected by tectonics. The fruits of this effort grow continually, as shown in part by the attraction that this subject has for students and young scientists. Yet, it seems to me that progress has been limited by a misconception that has stimulated this polemic. Much effort seems to be expended in trying to understand what "controls" erosion, tectonics, or climate, or what "drives" erosion, "rock uplift," climate, and so forth. Although these questions are not meaningless in all cases, enough are.

My thesis is that erosion, climate, and tectonics interact with one another in a state that is usually and in most regions approximated as quasi-equilibrium. "Usually," because even if we ignore major storms, which are short-lived on any geologic time scale, climate changes continually with orbital pacing, and tectonic processes also change, though more slowly. "Most regions," because there always is a place where the unexpected occurs. "Quasi-equilibrium," because in a system as nonlinear as either climate or erosion, if not tectonics too, equilibrium cannot be sustained for long, and geologic time is long on the time scales of changing climate and erosion, if not tectonics.

An equation of state describes equilibrium. A good example is the perfect gas law:

$$PV = nRT. \tag{1}$$

$P$ is pressure, $V$ is volume, $n$ is the number of moles of a gas, $R$ is the gas constant, and $T$ is absolute temperature. An equation of state, and likewise an equation of equilibrium, does not assign cause or effect, and hence does not attribute a controlling factor or driver to any of its elements, but simply expresses a balance. Of course, if one changes the pressure, then at least one of volume, temperature, and conceivably the number of moles of gas must change. Here it might make sense to ask what "controlled" the change in those quantities, or what "drove" them. The occurrence of change, external to "equation (1)," transforms questions that concern drivers or controls from being ill posed to well posed.

In the earth sciences, perhaps no concept illustrates better a state of quasi-equilibrium than isostasy. Isostasy is not a process; it exists. On short time scales (thousands of years), viscous deformation can retard the inexorable trend toward isostatic equilibrium, as is illustrated well by the rebound following the melting of Pleistocene ice sheets. Thus, on such time scales, one might understand pressure differences in the asthenosphere as "driving" the overlying lithosphere and surfaces of Canada or Fennoscandia upward. On longer geologic time scales, however, isostasy is maintained as a state of equilibrium; like the perfect gas law, "isostasy," therefore, does not drive anything, much as traffic laws do not "drive" cars.

Dahlen and Suppe (1988) considered the state of stress within a wedge of sediment obeying Coulomb friction and the equilibrium cross sectional shape of that wedge. It seems unlikely that erosion would suddenly excavate a divot from a fold and thrust belt, but it is easy to imagine that erosion rates could change relatively quickly on geologic time scales, for instance because of some change in climate (e.g., more typhoons). Dahlen and Suppe's work predicts that the deformation field would respond comparably rapidly to maintain the cross sectional shape of the wedge, so as to maintain a state of quasi-equilibrium.

Suppose we recognize that steep terrain offers its erosive agents more energy to do their job than gentle terrain, that more precipitation will remove more material (erode faster) than less precipitation, but that the stormier the climate the faster the erosion, and that tectonics can elevate terrain, which then is subject to erosion. I offer the following mnemonic:

*__P__recipitation rate × __V__ertical component of velocity = __n__umber of floods per annual precipitation × __R__ock removal rate × __T__ectonic movement.* (2)

Here, the ***Precipitation** rate* is some average, such as mean annual precipitation, a measure that can distinguish wet from arid environments. The ***V**ertical component of velocity* refers to movement of rock relative to base level, and might be called "rock uplift rate" except that that term is usually used without a clearly defined reference frame. The ***n**umber of floods per*

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*annual precipitation* would characterize the recurrence interval of some kind of typical flood, such that a small number means that most of the precipitation comes during a few floods, and a large number would imply little variability in precipitation. The ***R**ock removal rate* is the erosion rate or, perhaps mnemonically better, the *e**R**osion rate*. To be consistent with how it is commonly used in geomorphology, ***T**ectonic movement* is intentionally vague, but refers to processes that elevate the earth's surface, either by crustal thickening or by the alteration of mantle structure. Note that (2) is a mnemonic, not an equation to be solved.

Nevertheless, (2) captures much of the common sense statements that began the previous paragraph. With no changes to climate ($\boldsymbol{P}$ or $\boldsymbol{n}$) and to erosion ($\boldsymbol{R}$), tectonic movements ($\boldsymbol{T}$) scale with the rate that rock goes up ($\boldsymbol{V}$). In the absence of tectonics ($\boldsymbol{T}$) or climate change ($\boldsymbol{P}$ or $\boldsymbol{n}$), because of isostasy, the erosion rate ($\boldsymbol{R}$) will scale with the rate that rock goes up ($\boldsymbol{V}$). All else being equal, increased precipitation ($\boldsymbol{P}$) will be proportional to the erosion rate ($\boldsymbol{R}$). Moreover, if that precipitation (same $\boldsymbol{P}$ in each case) occurs in rare storms (small $\boldsymbol{n}$), erosion will be faster (big $\boldsymbol{R}$) than if precipitation is steady (large $\boldsymbol{n}$ and small $\boldsymbol{R}$). Of course, the mnemonic is imperfect, not just because it ignores glaciers. For instance, according to (2), in the absence of erosion ($\boldsymbol{R}$) and tectonics ($\boldsymbol{T}$), precipitation ($\boldsymbol{P}$) would scale inversely with the rate of vertical movement of rock ($\boldsymbol{V}$), which is nonsense (if, however, increasing $\boldsymbol{V}$ might, via orographic precipitation, call for an increase in $\boldsymbol{P}$). Anyhow, if (2) were perfect, wouldn't that be a gas?

Most of the preceding words are meant to urge geodynamicists, tectonic geologists, and geomorphologists to be more careful in how they view the interactions among tectonics, climate, and erosion. Yet, an exciting part of these subjects lies where equilibrium does not apply. For instance, to what extent does the relief that prevented elephants from reaching Rome or that challenges mountaineers reflect a transient state, and perhaps one that is decidedly not in equilibrium, because changes in erosion rates induced by climate change occur faster than the landscape can evolve? Moreover, there is a difference between (1) and (2) that should not be overlooked. The beauty of (1) lies in the state that it describes, and in that context, each of $\boldsymbol{P}$, $\boldsymbol{V}$, $\boldsymbol{n}$, $\boldsymbol{R}$ (especially), and $\boldsymbol{T}$ need not, individually, make for interesting study. In (2), beauty is in the mind of the beholder, and real progress may come more from understanding each of $\boldsymbol{P}$, $\boldsymbol{V}$, $\boldsymbol{n}$, $\boldsymbol{R}$ (again, especially), and $\boldsymbol{T}$ independently of the others, than from studying the interactions among them.

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## REFERENCE CITED

Dahlen, F. A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts, *in* Clark, S.P., Burchfiel, B.C., and Suppe, J., eds., Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper 218, p. 161–178.