On the implications of low spatial correlation of tectonic and climate variables in the western European Alps

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Vernon et al. (2009; p. 859 in this issue of *Geology*) address the issue of tectonic versus climatic influences on vertical displacement in the western European Alps by applying spatial correlation methods to diverse data sets that may serve as proxies for various forcings. Indications of time-dependent variations in sedimentation and exhumation rates in the Alps (Kuhlemann et al., 2002), together with a broad array of recently acquired high-precision data, have fomented a plethora of widely divergent interpretations of the causative factor of vertical displacements in the western European Alps, ranging from mantle kinematics to the fluctuating climate in which isostasy plays a major role (Champagnac et al., 2007; Korup and Schlunegger, 2009).

Given the general acceptance of Archimedes' work, the fact that an isostatic response occurs related to the erosional removal of rock is in itself not too surprising, but the nature of the load and the relative role of climate-driven isostasy in orogenic processes have remained hotly debated. If any mountain belt demonstrated clear correlation of climatic driving forces with vertical displacement, then the western European Alps, with its recently formed remnant crustal root and current low horizontal strain rates (Delacou et al., 2004), would be an excellent candidate. However, rigorous statistical correlation of nonstationary temporal and spatial series of this coupled system presents a serious challenge. The complex stew of irregular sampling frequencies, thermal characteristic scales of fission tracks, and elastic-versus-anelastic deformation scales will severely test any statistical analysis. At first glance, notable features of the Kendall statistical analyses employed by Vernon et al. (2009) are the strong spatial heterogeneity of all the variables and the low correlation among all the various relationships tested, with the exception of an association of modern vertical displacements with long-term exhumation rates (see their Table 1 and Table DR2). Some of the poor correlations derive from inadequate data coverage and are insignificant, but some of the correlation weakness contains important information on those variables that control surface evolution, and reinforce our presently accepted view of erosional controls.

Part of the reduced correlation of exhumation with "tectonic driving forces" arises from the difficult and ambiguous identification of tectonic driving forces within any orogen in which buoyancy and horizontal far-field plate displacements (= plate-driven forces) contribute to the pattern of strain. Vernon et al. use a 41 yr instrumental seismic record as a proxy for tectonic driving forces. As noted by Sue et al. (2007), the instrumental record has captured little of the magnitude of the geodetically predicted strain release, leaving uncertain the relative role of seismic and aseismic strain in the area. The more extensive, ~1000 yr, historical seismicity record of Switzerland identifies total seismic strain release originating from combined buoyancy-driven and plate-driven strain.

While the instrumental record of seismicity does not capture the predicted magnitude of strain release, the orientations of strain and stress axes extrapolated from the seismicity analysis do fit surprisingly well with the geodetic information available (Delacou et al., 2004). Where vertical measurements are not available (i.e., the non-Swiss part of the study area), the strain and stress analyses over the predictably buoyant regions of northwestern Italy display the characteristic buoyancy signal of extension in the core (σ_1 [maximum principal stress] is approximately vertical) and contraction on the edges (σ_1 is approximately horizontal), and appear to illuminate a region of buoyancy-driven unroofing. As discussed by Sue et al. (2007) and Delacou et al. (2004), most, but certainly not all (Persaud, and Pfiffner, 2004), of this strain appears to be related to buoyancy forces and therefore is not identifiable as tectonic in the sense of being driven by horizontal relative plate motion.

The Swiss western Alps are globally notable for the very high observational precision available over a relatively long time (Kahle et al., 1997; Schlatter, 2007), which permit us to view what are quite low rates of vertical uplift when compared to the maxima found in active convergent belts (~10 mm/yr) or those associated with glacial rebound (~50 mm/yr). Although these high-precision measurements are remarkably widely distributed in the main valleys of Switzerland, comparable measurements are absent over most of the western European Alps (see Vernon et al., their figure 2D). Consequently, correlation is indeterminate of short- and long-term uplift in the internal massifs (Sesia, Dora Maira, etc.) which are characterized by high- and ultra-high pressure history, and that are currently exhibiting extension in the core and contraction along the edges (Delacou et al., 2004).

Regarding the correlation of long-term exhumation with other variables, the western European Alps are characterized by heterogeneous surface geology ranging from weak shales to highly cohesive plutonic rocks that are being acted on by a spatially (and temporally) variable climate. If our understanding of multivariant control of erosion rates as a function of both rock material properties and climate (water, ice, wind) agents (e.g., Syvitski et al., 2005) is generally correct, then correlation of exhumation under heterogeneous conditions with a single factor is unlikely. In this respect, the western European Alps differ from more homogeneous active mountain belts, acted on by simpler, orographic climate regimes (e.g., the Southern Alps in New Zealand; Taiwan; the Cascades in Washington, United States) where erosion rates correlate more obviously with precipitation (e.g., Koons, 1989; Dadson et al., 2003; Reiners et al., 2003).

One potentially important correlation not tested by Vernon et al. was that of erosion rates and rock material properties. Korup and Schlunegger (2009) have demonstrated that relative rock weakness plays a significant role in erosion rates in eastern Switzerland, and appears to be a critical factor in the relatively high uplift rates in eastern Switzerland that can override the influence of precipitation on erosion rates. The influence of rock strength on erosion resolves an apparently anomalous short wavelength correlation in Valais of southwestern Switzerland, where low precipitation is associated with high modern rates of uplift and young apatite fission-track ages (Vernon et al., their figure 2F.; ~120 km due east of Geneva). Using the ~1000 yr seismicity record, the Swiss Seismological Service has produced a measure for strain release in Switzerland in the form of predicted ground accelerations in which the maximum predicted accelerations lie in Valais (Giardini et al., 2004). Ground accelerations can provide a robust proxy for seismic material damage, which exerts an important influence on erosion rates (Molnar et al., 2007). If erosion rates in the Valais are driving uplift rates, and erosion rates are a function of the seismic strain release, then this rapid-uplift region of southwestern Switzerland

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represents positive feedback between unloading and strain that can lead to tectonic aneurysm behavior (Koons et al., 2002).

A temporal window in an orogen's evolution exists, when both horizontal strain–generated forces and mantle-derived buoyancy forces are small, in which erosion-driven isostasy is a dominant process, and the record of spatial variance in uplift rates reflects and records the spatial and temporal variance of erosion (climate and material parameter distribution). Parts of the western European Alps appear to currently lie within this window. The erosion-driven uplift pattern in the western European Alps, however, remains partly obscured by potentially significant uplift signals derived from glacial rebound (Persaud and Pfiffner, 2004), lower crustal flow (Westaway and Bridgland, 2008), and the unknown contribution of mantle buoyancy. The latter remains the most problematic component in the isostatic balance because of its omnipresence, limited resolution, and potential magnitude. Unwrapping mantle contributions when mantle differential buoyancy and kinematics are subtle remains a critical obstacle in sorting out the influence of climate change on vertical displacements.

IMPLICATIONS

The limited correlation among individual variables in Vernon et al.'s (2009) study actually represents a very positive outcome. In an orogen in its decaying stages, not dominated by net horizontal convergence or divergence, where differential mantle buoyancy is not great, earth response should reflect the multiple dependence of erosion rates on the mix of rock materials and climate parameters. The fact that parts of Switzerland with very different precipitation regimes have similar long-term exhumation rates and modern uplift rates reinforces a working theoretical framework of multiple rock and climate controls on erosion.

The obvious spatial heterogeneity identified in Vernon et al.'s study, as well as elsewhere (e.g., Alaska; Larsen et al., 2005) means that our mechanical models based on spatially extensive one-dimensional and two-dimensional approximations that were tenuous when our measurement density was low (<1:50×50 km) are completely inadequate where surface and deep processes demonstrably vary at the short wavelengths indicated here. Similarly incomplete in the presence of a buoyancy-influenced stress state is the widely used equilibrium critical wedge formulation, with its foundation assumptions (Terzaghi, 1943) that 1) the topographic slope is defined by the ratio of vertical shear stress and vertical normal stress, and 2) the entire orogen is at a critical state.

Modern observations of strain, erosion, and climate are producing a far more interesting image of Earth, with a great deal of information about its surface evolution. The newly observed, high-frequency temporal and spatial variations require that both our physical formulations and the solution density of time-space discretization must incorporate more of our modern geological knowledge of Earth materials and the physics of Earth deformation before they can substantively contribute further to understanding the coupled climate and tectonic systems.

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