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Effect of erosion on topographic evolution process: periodical instability of stratified non-linear and linear viscous fluid

Youichiro Takada[1]; Peter Molnar[2]

[1] Earth Sci., Oxford Univ; [2] Geol.Sci., Univ. Colorado

Many consider the effect of erosion on topographic evolution on a geologic time-scale to be large, but the quantitative, physical understanding of this effect remains limited, partly because topography itself is complex. In this study, we examined effects of surface erosion on the growth of periodic instabilities (e.g., folding, boudinage) under regional compression, because these phenomena can be treated semi-analytically, which allows a direct physical interpretation.

To understand topographic evolution, it is necessary to examine this when topography starts to grow. In addition, the macroscopic behavior of the crust and mantle behaves as non-linear viscous fluid obeying power-low creep on a geologic time-scale. Considering these points, we constructed the following 2-D model by which we numerically calculate the effect of surface erosion on the growth of periodical instability formed by the uniform shortening. We represent the crust-mantle structure as two layered medium consisting of the surface layer with large stress exponent n and a substratum with small n. This model is applicable to various problems associated with existence of low viscosity layer as rock salt, lower crust, and asthenosphere. The boundary conditions are as follows: (1) surface loading due to the surface uplift and subsidence, (2) continuity of displacement and stress across the layer interface, (3) no displacement at the bottom of the substratum. When averaging a periodical instability subject to partial erosion and sedimentation over one wave length, the average density contrast between the crustal material and its surrounding material is smaller than that between the crustal material and air. To treat the effect of erosion in this manner, we multiplied the density contrast in the boundary condition at the surface by a parameter D, which scales the magnitude of the erosion rate. Small D corresponds to the large erosion rate, and D=1 means no erosion. Given the uniform background flow at a constant rate created by regional compressive stress, we described the stress and strain rates as the summation of those associated with background flow and perturbation to the background. Since the perturbation is very small relative to the background deformation, we used the linearized constitutive equation of the perturbations derived by Smith (1977).

Given small perturbation to the surface and the layer interface at t=0, we calculated the mode, wavelength, and growth rate of the perturbation, and examined the effect of erosion by changing D. The time derivative of perturbation amplitude vector is represented as a product of a square matrix by the perturbation amplitude vector. We obtained growth rates and modes of the perturbation by calculating eigenvalues and eigenvectors of the square matrix.

The modes of instabilities were folding or inverse boudinage (mullions). When the erosion rate gets larger, the growth rate usually gets larger, because the effect of gravity suppressing crustal uplift/subsidence is weakened. However, when the surface layer has very strong non-linearity, the growth of instability is not affected by erosion, but the effective viscosity of the surface layer limits growth. As the erosion rate gets larger, the wavelength gets larger. In general, the longer the wavelength of deformation is, the larger the effect of gravity is. However, the fast erosion weakens the effect of gravity, which helps the long wavelength perturbation grow.

The behavior of the whole system strongly depends on the viscosity contrast between two layers. When the viscosity contrast is small, both layers couple. When the viscosity of surface layer is far larger than that of the substratum, the surface layer behaves as a plate. The effect of erosion on the growth of instability has strong viscosity contrast dependence.