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Transient cnoidal waves can explain fault-damage zones

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The principal-slip zone (PSZ) of faults is usually surrounded by a wide zone of secondary deformation bands called fault-damage zone (FDZ). The non-linear decrease in deformation-band density perpendicular to the PSZ and the asymmetric distribution of secondary deformation structures around the PSZ are commonly explained with the inherently non-linear and asymmetric distribution of deviatoric stresses in the stress lobes at the tips of propagating faults and asperities along the PSZ, or in geometrically complex zones of fault interaction. However, existing mechanical models for FDZ based on deviatoric stresses alone cannot predict exactly where deformation bands form. Moreover, they fail to explain why FDZ in, for example, porous siliciclastic rocks often exhibit dramatic differences in geometry from bed to bed on the cm-scale. Here, we present a new model for the formation of FDZ based on transient cnoidal waves, which addresses both shortcomings.

The important physical novelty of our model is that it accounts for inelastic volumetric deformation of deforming rocks coupled to diffusive internal mass transfer processes. Darcy flow, partial melting, grain crushing, or dehydration reactions constitute typical geological examples of diffusive internal mass transfer. Recently, studies of stationary cnoidal waves demonstrated that strictly periodic volumetric instabilities can form in rocks with internal mass transfer under two conditions: the solid skeleton relaxes a pressure load about ten times faster than the weak phase; and it obeys a viscoplastic power-law volumetric rheology with a stress exponent $n > 1$.

Fault slip imposes a sudden time-dependent pressure load on the surrounding rock. Moreover, it is generally accepted that deformation bands generally nucleate as volumetric instabilities (for example, as mode-I fractures or inelastic compaction bands). Therefore, we hypothesise that FDZ can be explained with transient cnoidal waves. In this context, deformation bands nucleate as decaying-periodic volumetric instabilities in the wake of a viscoplastic p-wave. Deformation-band growth and interaction are then controlled by the following deviatoric wave.

We first present general properties of numerical solutions to the transient cnoidal wave. It is discussed how three important physical parameters control the spatial expression of instabilities: the speed of the viscoplastic p-wave, the stress exponent of the volumetric rheology of the solid skeleton, and a modified compaction length. Then, we show that the cnoidal model can reproduce the spatial distribution of deformation bands within a natural FDZ in porous siliciclastic rocks. Moreover, independent measurements of rock transport and mechanical properties fit the best-fit cnoidal model. Hence, transient cnoidal waves may provide new means for the deciphering of fault history and the inversion of material properties from geometrical measures of the FDZ.