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Do foliation refraction patterns around buckle folds represent finite strain?

M. Frehner (1) and U. Exner (2)

(1) Geological Institute, ETH Zurich, Switzerland (marcel.frehner@erdw.ethz.ch), (2) Department of Geodynamics and Sedimentology, University of Vienna, Austria

Buckle folds in the field commonly feature a characteristic syn-deformational foliation, which is sub-parallel to the fold axial plane; hence it is called axial plane foliation. As the foliation is not perfectly parallel to the axial plane, it may exhibit either a divergent or convergent fan around the fold. Convergent fans most commonly occur in the stronger rocks (the folded layer) while divergent fans rather occur in the mechanically weaker rocks (the matrix). The foliation orientation is usually thought to reflect the long axes of the finite strain ellipses, a hypothesis that we investigate in our study.

To study the strain distribution around folds, we use the finite-element method to simulate two-dimensional single-layer viscous buckling. The numerical simulations allow to calculate the strain evolution during the folding process and to visualize its distribution and orientation around the fold. We use different measures of strain: (1) the finite strain (recording the strain history from the beginning of the simulation until the end), (2) the infinitesimal strain (capturing only the very last moment of the simulation), (3) the incremental strain (recording the strain history from a certain shortening value during the simulation until the end), and (4) initially layer-orthogonal passive marker lines. The shortening value, from which the incremental strain is calculated, can be anything between the beginning and the end of the simulation. The first three strain measures are tensor fields that are used to calculate and visualize the orientation of the long axis of the strain ellipses around the fold.

We find that all strain measures result in a divergent fan in the mechanically weak matrix at the outer arc of the fold and that this divergent fan has almost the same geometry for all strain measures. Also, for the case of the incremental strain, the divergent fan does hardly depend on the moment from which the incremental strain is calculated. This observation leads to the conclusion that the geometry of the divergent fan does not reflect the orientation of the long axes of the finite strain ellipses, but can reflect anything from finite to infinitesimal strain. However, the convergent fan in the mechanically strong folded layer takes very different shapes for the different strain measures. The convergent fan is well developed in the case of the finite strain and the passive marker lines, but it is strongly influenced by the migration of the neutral line through the fold in the case of the incremental and the infinitesimal strain.

We compare the described strain orientations with foliation refraction patterns in outcrop-scale folds near the village Luarca (Asturias, NW Spain). Generally we observe that the foliation is much better developed in the mechanically weak layers than in the strong folded layers. In the latter, the foliation often has the appearance of fractures and exhibits a nice convergent fan. Therefore, we conclude that the foliation roughly reflects the long axis of the finite strain ellipse or even corresponds to initially layer-orthogonal lines, which rotated passively during folding. This could be explained by a very early formation of the foliation. The foliation in the weak layers, which exhibits divergent fans, may also have developed later in the folding history. In one particular fold, we observe a strong orientation change of the foliation along the axial plane trace. In the numerical models, we observe a similar orientation pattern of the long axis if the incremental strain is used. We conclude that such patterns can be explained by the superposition of two or more generations of axial plane foliation, which developed at different stages of the folding process.