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Folding of Nodular Layers – Insights from Field Observations and Numerical Modeling

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Formation of the fold and thrust belt in the Oslo Region involved deformation of a sequence of alternating nodular limestone layers and shales. The nodules were formed prior to the deformation by local dissolution of continuous limestone layers (Bjørlykke, 1973). The nodules are aligned and exhibit various sizes and shapes ranging from spherical to discoidal. Folding and thrusting of the whole sequence affected the morphology of the individual nodules. The question arises when the transition from isolated inclusion behavior to orchestrated behavior as one effective (nodular) layer takes place. The deformation of the nodular layers and the shape evolution of the nodules are the subject of this study.
To gain a basic understanding of the behavior of nodular layers under shortening, we study a simplified physical model, where a single layer composed of numerous nodules embedded in a weak matrix is subjected to layer parallel compression. We examine the relative importance of different parameters: 1) viscosity ratio, 2) fraction of nodules in the layer, 3) distribution of nodule sizes, 4) shape of nodules, and 5) number of nodules forming the layer. The Stokes equations, which describe slowly creeping flow, are solved numerically using the finite element method solver MILAMIN (Dabrowski et al., 2008).
The numerical results show that the nodular layer undergoes folding for a sufficiently large number of layer-forming nodules. The folding behavior is promoted by high viscosity ratio between the nodules and the matrix, high fraction of nodules (over 60%), and small diversity of nodule sizes. The shape of inclusions affects the fold shapes, e.g. the presence of elongated nodules leads to the formation of chevron-like folds. Additional insight is obtained by relating the folding of the nodular layer to the shortening of a continuous layer, which is well understood. The relationship between the models is established through the effective properties of the nodular layer and the initial perturbation of the layer envelope, which is determined by the size distribution of nodules. The effective isotropic/anisotropic viscosity is approximated using a differential effective medium scheme based on the first four parameters from the list above.
Folding of the nodular layer is accompanied by displacement, rotation, and shearing of the individual nodules. Nodules with high aspect ratio experience more intense folding. The interaction of nodules at high concentrations results in the development of complex shapes.
Finally, we study the case of a multilayer stack made up of weak homogenous layers and stronger nodular layers, which is more relevant to the analysis of the field observations from the Oslo region. The additional parameters comprise: 6) number of nodular layers, 7) distance between layers, and 8) relative thickness of the nodular layer to the thickness of the weak layer. Various models exhibit strong similarity to the structures observed in the field.

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