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Numerical models diapiric structures – analysis of the finite strain distribution

L. Fuchs[1], H. Schmeling[1]
[1] *Goethe-University, Institution of Geoscience, Frankfurt am Main, Germany*
lfuchs@geophysik.uni-frankfurt.de

Introduction Diapirs, both magmatic and salt diapirs are generally important structures in geology. Internal deformation structures may provide information about the dynamics of the process and prevailing simple rheological conditions, like the viscosity contrast. By analyzing the finite strain in such structures, on the one hand, the deformation processes taking place within it will be better understood and secondly, a statement can be made, how the strains are distributed in two layers each. In a few analog models [1] and numerical models [2] the finite deformation was analyzed for certain conditions inside diapiric structures, but there are no systematic analysis done so far. In the study conducted here, the strain was analyzed for two different models. First, the model of a classical Rayleigh-Taylor instability [3], which is mainly important for magmatic diapirs, the other is the down-building model [4], which is especially important for salt diapirs where the rise is driven by differential sediment loading.

Governing equations and model set up The equations of conservation of mass, momentum, and composition are solved by a 2D finite difference code (FDCON) based on a stream function formulation in combination with a marker approach based on a predictor-corrector Runge-Kutta 4th order scheme. The Rayleigh-Taylor model corresponds to the model of van Keken et al. [5] with the intention to extend the benchmark with the information of the distribution of the finite strain. Two series of different viscosity contrasts $m = \frac{\eta_{buyont}}{\eta_{top}}$ and different thicknesses were calculated for each $h_{buoyant}$ with both no slip and free slip boundary conditions at the top and bottom. The down-building model corresponds to the model of Fuchs et al. [6], whereby the amplitude and the wavelength is chosen to be constant and only the sedimentation rate and the viscosity contrast were varied. In Fuchs et al. the viscosity contrast was chosen close to the limit of a stiff subsiding sediment layer, with the result high deformation within the salt and no deformation in the ambient sediments. In addition, new models with a viscosity contrast approaching weak sediments have been carried out, in which the deformation is partitioned between the salt and the sediments. The finite deformation was measured using the algorithm of McKenzie [7] calculated centered in time and in space, where the information of the deformation matrix is advected with the markers in the model. In addition to the local analysis of the strains in each layer, the strain partitioning is considered on the entire surface of the two layers. Therefor the maximum shear strain [8] is integrated in each layer and forms the ratio S_r between the integrated values of the upper and lower layer. This ratio provides information on how the strain is distributed between the two layers.

Model results Locally the finite strain is concentrated within the diapir during the pillow stage of the no slip models. The maxima are found at the bottom of the model and in the center of the pillow where the stain is decreasing to the interface. For a higher or lower viscosity the maximum values are decreasing and increasing, respectively. The strain at the boundary depends strongly on the viscosity contrast, so one can find always a higher strain in the softer material. During the ascent, the strain is concentrated within the stem of the diapir. Inside the head though there are regions which undergo little or no more finite stretch, both for soft and hard layer. In the overburden layer above the head, however, there is a region with stronger strains which are always greater than the strain within the head. This is favored by the constraints of the model so that the upper layer is continuously stretched while the rising source layer is destrained as it approaches the top of the model. During the phase of lateral spreading of the diapir head mainly the upper layer is thinned and stretched, whereby inside the diapir the strain is essentially rising within the stem. In principle the free slip models show a similar behavior of finite strains, but the strains due to the boundary conditions at the top and bottom of the model disappear. As a result, the strain above the head of the diapir is distributed on a larger area throughout the ascent. The maximum values are remarkably smaller than in the no slip case. Due to the free slip boundary conditions also the thinner layers get more stretched than the thicker ones. Varying the thickness of the layer, the finite strain is distributed over a larger area and the maximum values are slightly smaller. However, the spatial distribution of the finite strain is essentially similar for different source layer thicknesses. It is found in the strain partitioning that the strain in the softer layer is always larger. However, surprisingly the ratio is significantly smaller than the viscosity contrast. Thus, analyses of strain partitioning in natural scenarios may only give limited information about viscosity contrasts. The down-building models show an interesting effect so far. Due to the subsidence of sediment basins on the side of the evolving diapir head we find an enhanced internal circulation within the diapir. This amplification leads to several overturns during the early phase of ascent.

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