Control of rheology on the development of structures in layered gneissic rock

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Abstract

This thesis presents an integrated investigation into the deformation mechanisms of layered metamorphic rocks within the Chhotanagpur Granite Gneissic Complex, employing a combination of field observations, analogue experiments, and advanced numerical modelling. The study critically examines the evolution of complex structures—including boudinage structures, folding, and flanking features—in order to elucidate the interplay between rheological contrasts, mechanical anisotropy, and strain partitioning under diverse tectonic regimes.

The work begins by exploring the development of segmented, elongated boudinage structures that serve as natural strain markers. This study investigates the influence of viscosity on the formation of rectangular torn boudins, categorized based on the curvature of their exterior and face margins. Finite Element Method-based numerical simulations using Maxwell viscoelastic materials were conducted in ANSYS, exploring seven viscosity combinations among boudin, inter-boudin, and matrix materials. The findings highlight that the relative viscosity of the inter-boudin material critically affects boudin morphology. Bone-shaped boudins form when the inter-boudin is more competent than the boudin, with enhanced development when the matrix is also stronger than the boudin but weaker than the inter-boudin. In contrast, when boudins are stiffer than the inter-boudin, barrel- or fish-head shapes with concave faces emerge. Straight margins are observed when the boudin is more rigid than the matrix or when viscosity contrasts between boudin and inter-boudin are minimal. Thus, field-based boudin shape analysis can provide qualitative estimates of relative viscosity contrasts.

The investigation then turns to the processes underlying fold formation in layered rock under layer-parallel compression. Folds in layered rock systems are key to understanding deformation history and rheological behaviour. This study uses finite element modelling to examine fold development in such systems, emphasizing how thinner layers influence the folding of adjacent thicker layers. Results reveal that initially harmonic folds may evolve into polyharmonic or disharmonic patterns due to complex strain interactions within the contact zones of thinner layers. The geometry of resulting folds is strongly shaped by the mutual influence between thinner and thicker layers, where folding in one layer initiates deformation in the other. These interactions often diverge from outcomes predicted by simpler models, as noted in previous research. The study also suggests that higher-order fold geometries may serve as qualitative indicators for estimating relative viscosity contrasts between layers and the surrounding medium.

Subsequently, the research addresses the deflection of pre-existing fabrics adjacent to cross-cutting elements. By focusing on the mechanisms by which linear and planar fabrics are dragged and reoriented in response to local perturbations, the study distinguishes between open and closed flanking geometries within layered gneissic rocks. Using two-dimensional finite element modelling, the effects of cross-cutting element (CE) orientation, kinematic vorticity number (W_k), and anisotropy factor (δ) were analysed. Results show that the geometry, offset, and drag patterns of flanking structures are strongly influenced by anisotropy, particularly by the CE's orientation relative to stress axes and anisotropy pole. CE shape, offset magnitude, and tip displacement serve as qualitative indicators for estimating mechanical anisotropy in deformed layered rocks. The analysis further demonstrates that an increase in the degree of simple shear, as well as variations in the anisotropic factor, systematically alters both the normalized aspect ratios and offset lengths of these features, thereby providing deeper insights into the kinematic implications of shear-induced deflections in heterogeneous media.

Overall, the thesis advances our understanding of deformation processes in high-grade metamorphic rocks by systematically linking microstructural observations with rigorous numerical analyses. The integrated approach adopted herein provides a comprehensive framework for interpreting the interdependence of material properties, strain conditions, and structural evolution in tectonically active regions.

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