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Transtensional Flanking Structures

Franziska Mayrhofer[1], Bernhard Grasemann[1], Martin Schöpfer[1], and Marta Adamuszek[2]
[1]Department of Geology, University of Vienna, Austria
[2]Polish Geological Institute-National Research Institute, Poland

Flanking structures are deflections of an existing planar fabric (e.g., foliation) alongside a cross-cutting element (e.g., a vein) that can develop in a wide range of rock types, ranging from eclogites to unconsolidated sediments, and also glacier ice, which deforms in temperate glaciers dominantly by dislocation creep and can be considered as a monomineralic metamorphic rock analogue. The finite geometry of flanking structures depends on several factors, such as initial orientation of the cross-cutting element (CE) relative to the shear zone boundary and the kinematic vorticity of the shear zone flow. However, nearly all published examples of flanking structures are interpreted to have formed either under simple shear or transpressional general shear, although in theory flanking structures should also form under transtensional general shear. Here we describe the geometry and development of transtensional flanking structures in glacial ice of the Pasterze, Austria's largest alpine valley glacier. Mapping was carried out with the aid of high-resolution drone photography and the structures' attitudes were determined using traditional field techniques. The studied flanking structures develop in an area situated on the orographic right side of the glacier tongue and downstream of a transverse crevasse field. The CEs are closed crevasses containing granular ice and rotate clockwise (when viewed from above), consistent with the large-scale flow field of the glacier. The penetrative foliation, which is regionally parallel to the glacier's flow direction, is locally deflected alongside the CEs, forming a- (antithetic) and s-type (synthetic) flanking structures. The variability of the cross-cutting elements' orientation systematically decreases downstream as they rotate into a stable position. We compare the mapped flanking structures with model results of a semi-analytical modified Eshelby solutions for a frictionless CE embedded in an isotropic linear viscous matrix. The model results demonstrate that a variety of a- and s-type flanking structures form under transtensional shear flow for a broad range of kinematic vorticity numbers and initial orientations of the CE but also show that shear bands do not form a stable structure. On the other hand, s-type flanking folds may be diagnostic for transtension because they form stable structures (but still accumulate displacement) when the CE has been rotated parallel to the fabric attractor, which is oblique to the shear zone boundary under transtension. Because of the abundance of shear bands and the lack of s-type flanking structures in natural rocks we speculate that transtensional ductile shear zones rarely occur in nature.