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Upright folding during extensional and transtensional tectonics

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Upright folds are common structures that develop in response to horizontal shortening in layered material, for example in foreland basins that surround orogens. While the contractional nature of these folds is not in doubt, interpretation of their tectonic setting needs careful consideration. Here we focus on two examples: (1) folds developed in transtension; and (2) folds developed during the flow of deep crust in response to lithospheric extension. In both cases we consider folding of nearly horizontal layers that are either primary (bedding) or secondary (foliation). Strain theory inspired by John Ramsay's work makes predictions for the behavior of material lines and planes as well as strain axes (instantaneous, finite) during transtensional deformation. Results show: folds can form in transtension; fold hinges rotate toward the direction of divergence (and not the shear zone boundary as they do in transpression), providing unique insight into ancient plate motions; fold tightness is controlled by the obliquity of divergence and not finite strain; hinge parallel stretching is always greater than hinge-perpendicular shortening, resulting in constriction strain and boudinage of fold hinges. Taken together these results provide a rigorous framework for interpreting field observations where structures are complex and boundary conditions unclear. These principles are applied to various tectonic settings ranging from active tectonic regions of oblique divergence in western North America to ancient folding that developed during oblique extension of the Western Gneiss Region, deposition of Devonian basins, and exhumation of ultrahigh-pressure rocks in the Norwegian Caledonides.

The other class of upright folds that form during extension may require revision of the tectonic interpretation of structural overprints in orogenic cores, for example in gneiss/migmatite domes. Dynamic modeling of extension of thick/hot crust predicts a positive feedback between extension of shallow crust (low-angle detachment system) and flow of low-viscosity (partially molten) deep crust. As the low-viscosity crust converges toward the zone of extension, it forms two crustal-scale upright to slightly inclined folds that eventually, in three dimensions, define two elongate domes. These contraction structures develop while the lithosphere undergoes extension. As it flows toward the zone of extension, deep crust material is incorporated into a contractional domain located directly beneath the zone of shallow crust extension, forming two domes of foliation separated by a high strain zone. This double-dome and high strain zone accommodate rapid exhumation of the deep crust, which then enters a domain of extension as it reaches the base of the shallow crust. Therefore, structural and metamorphic history indicates that high-pressure contraction is overprinted by low-pressure extension under nearly isothermal conditions. Geologic observations, for example in the Montagne Noire double dome (Massif Central, France), indicate that upright folds in the core of domes formed during extension of the units that mantle the dome. These folds/domes have significant exhuming power since eclogite that crystallized at the onset of extension is found in blocks and pods in the migmatite dome, indicating > 30 km of exhumation.