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Complex fold patterns developed by progressive deformation

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Folds arise from shortening instabilities in rocks containing layers with contrasting viscosities or bearing mechanical anisotropies. A complete understanding of this fact requires a three-dimensional approach, because of the variable geometrical relations between strain and kinematic tensors and the surfaces subjected to folding. This is especially common in progressive non-coaxial flow, under which folds become unstable, leading to fold hinge curvature, axial surface curvature or both. The resulting complex fold patterns generated by progressive folding can be morphologically indistinguishable from interference patterns produced by the superposition of two fold systems, and a detailed 3-D analysis is needed to distinguish between them.
This study is focused on complex fold shapes arisen from progressive single deformations. Examples can be grouped into: (i) non-cylindrical (or non-cylindroidal) folds and (ii) folds with non-planar axial surfaces (or non-plane folds). In both cases, hinge lines and axial surfaces can display up to a 180º curvature. Hinge line curvature leads to the development of sheath folds, while axial surface curvature leads to the development of polyclinal folds, being these cylindroidal if the hinges remain straight. The two end-member situations (sheath folds and polyclinal folds) are illustrated using examples from the Variscan Cap de Creus massif (Eastern Pyrenees).

Fold Hinge rotation and development of sheath folds
In simple shear zones, folds commonly nucleate with hinges at a high angle to the shear direction and progressively rotate towards parallelism with the shear/extension direction, giving rise to sheath folds. Axial surfaces also change in attitude with increasing strain, becoming parallel to the shear plane.

Development of polyclinal folds with strongly curved axial surfaces
A peculiar complex fold pattern consists of strongly curved axial surfaces but straight hinges. This folding type is opposed to sheath folds where axial surfaces are planar or slightly curved while hinges are strongly curved. A detailed analysis of such polyclinal folds evidence that they are not the result of superimposed folding, but they arise from a progressive deformation event. Factors accounting for the development of these patterns are: (i) folds nucleate with hinges in close parallelism with the extension direction, (ii) thickened short limbs and hinges behave as rigid bodies and rotate synthetically, causing local strain partitioning, (iii) axial surfaces are unstable and can rotate antithetically with regard to the shear component, and (iv) rock softening during progressive folding enhances strain localization.

The two cases described here, sheath folds and polyclinal folds, imply area reduction on the fold profile. This should not be necessarily correlated with constrictional regimes. Moreover, alignment of hinges parallel to the shear/ extension direction impedes unfolding during progressive deformation.