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Patterns of fold interference: influence of early fold shapes

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Abstract—Model experiments were specifically designed to test the effect of different profile shapes of early folds on refolding patterns. Comparison of natural examples with experimental results and analogy with engineering information on buckling of fold shapes suggest that, when layers are mechanically active during refolding, the profile shape of the early folds markedly affects the patterns of fold interference. Open rounded folds tend to refold to form dome and basin patterns of interference whereas isoclinal folds tend to refold by folding their axial plane, forming type 2 patterns of interference. Hence, the dimensions and shape of the profile of the early folds control the preferred buckling mode during refolding.

INTRODUCTION

IN Julivert & Marcos' (1973) excellent description of the superimposed folds in the Cantabrian Mountains of NW Spain, one of the most striking features of the patterns of interference is the difference in pattern between the superposed folds on earlier tight antiforms and the superposed folds on the earlier open synforms. Basins (type 1 patterns, Ramsay 1967) form on the open folds, whereas the axial planes of the tight folds are folded, forming type 2 (Ramsay 1967) patterns of interference.

Ghosh & Ramberg (1968, p. 102) noticed in their model experiments that, even in two different bulk strain conditions, the superposed folds were predominantly type 2 patterns of interference when the early folds were isoclinal. Skjernaa (1975, p. 269) noted that superposed folds of the first type may ride over open early folds, but vanish when they meet well-developed isoclinal early folds.

This paper suggests that the fundamental mechanical control on the patterns of interference described in the above papers is a form of buckling anisotropy: that is the shape of the early fold profile dictates the preferred axes of buckling of the subsequent superposed folds. The concept of preferred axes of buckling is drawn from analogies with engineering analyses of elastic buckling of isolated fold shapes (Chajes 1974). The concept is demonstrated with further model experiments designed to specifically isolate this control from other controlling factors on shapes of interference patterns, such as bulk strain orientation and boundary conditions (Ghosh & Ramberg 1968, Watkinson 1977). Further geological examples are given where it appears that the predominant control on the shape of the interference patterns is the fold profile shape of the earlier folds.

GEOLOGICAL EXAMPLES WITH MODEL DEMONSTRATIONS

Model work has shown that very large bulk strains markedly affect the finite shape of folds (Cobbold & Quinquis 1980) and of patterns of fold interference (Watkinson 1977).

Therefore, it would seem that the best areas to observe the predominant mechanical effects of early folds on later folds are areas that do not have markedly high strain values: that is away from areas, such as ductile shear zones or deep level interior zones of orogenic belts, where bulk strain effects may predominate.

Folded rocks of low grade metamorphism commonly show bedding plane slip features and therefore the bedding appears to have a strong mechanical control on the folding. One such area is in the Cantabrian Mountains in NW Spain, where large-scale interference patterns exist. Overlapping fibrous calcite growth on bedding plane surfaces indicates two predominant directions of movement corresponding to the two phases of folding (P. R. Cobbold, pers. comm.). From the maps of Julivert & Marcos (1973), it appears that the wavelengths of the superposed folds are of the same magnitude as those of the early folds. The marked feature of the interference patterns is that open synforms have refolded to form basin patterns of interference (type 1) whereas the tight antiforms have refolded with folded axial surfaces to form type 2 patterns of interference.

Similar changes of patterns of interference exist in the low grade Brioverian rocks of Douarnenez Bay in West Brittany (Darboux *et al.* 1975). Here, however, the change

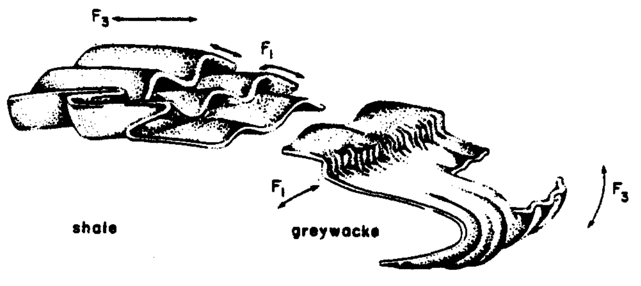

Fig. 1. Patterns of fold interference from Douarnenez Bay, Brittany (see Carte Geologique 1:50,000 Douarnenez IV-18, p. 9). The tight F_1 folds are in shale units, the rounded-profile F_1 folds are in greywacke units.

in pattern is not between tight anticlines and open synclines but between open, rounded folds in competent greywacke sequences and tight, angular folds in less competent shale sequences (Fig. 1). Figure 2 shows small-scale, superposed folds riding over a rounded-profile, open, early fold in a greywacke layer to form a type 1 pattern of interference (Ghosh & Ramberg 1968). The ratio of wavelengths between the early and late folds is approximately 10:1.

To demonstrate the control exerted by early fold shapes, a multi-layer model system was constructed and deformed to form folds of an alternating cusp and concentric nature. The multilayer was embedded in a soft matrix so that the cusp structures occurred at the matrix–multilayer interface. The cusp-shaped folds formed the anticlines and the concentric-shaped folds formed the syclines. The folds were then refolded by compression acting parallel to the early fold hinge directions. A section of the model is shown in Fig. 3(b) and is compared with the natural shapes of the fold from the Cantabrian Mountains in Fig. 3(a). The resemblance is striking with the tight antiforms refolding into type 2 patterns and the open synforms refolding into basins.

A further test was made by producing an early fold in a single layer embedded in a soft matrix. The profile shape changed from an open, concentric profile at one end of the fold to a tight, angular profile at the other end. Such variation of fold profile shape is frequently observed in examples of complete three-dimensional exposures of folds (Dubey & Cobbold 1977). Figure 4 shows the resulting interference pattern after compression along the early fold hinge direction. Again the open, rounded fold forms type 1 patterns whereas the tight, angular profile forms predominantly type 2 patterns.

DISCUSSION

When compression is applied in a direction parallel to the hinges of early folds superposed fold patterns will develop. In Ghosh's (1970) analysis of patterns of interference it is assumed that the later folds ride over the early folds without folding the early fold axial plane (cf. Fig. 2), thus developing domal patterns of fold interference. The analysis predicts that the length of arc of the later superposed folds depends on the original radius of curvature of the concentric folds.

However, it appears from the model work and from the geological examples that, when: (a) the curvature of the early folds is very high; (b) the early folds have long limbs and small hinge zones and are tight to isoclinal; or (c) the superposed folds are of sufficiently long wavelength, there will be a fundamental change in the mode of buckling. The pattern becomes one of folding the early fold axial plane, forming a predominantly type 2 pattern of interference.

Engineering concepts of buckling of open cross-section columns provide an analogy from which the mechanical principles are evident. The analysis of buckling of thin-walled, open cross-section columns has been summarized by Chajes (1974). For a cross-sectional column shape with two axes of symmetry there are three modes of buckling possible: pure flexural buckling about either of the two symmetry axes; or a pure torsional buckling. In general, the preferred mode is about the weak axis, or the axis about which the moment of inertia, I, is lowest. A singly symmetric cross-section can buckle either by bending in the plane of symmetry or by a combination of twisting and bending. The buckling mode that predominates depends on the dimensions and shape of the column cross-section (Chajes 1974, p. 210).

In a geological context, and assuming the beds to have active mechanical properties, we have to consider the following constraints.

(1) The early folds are not isolated column shapes but are part of a wave train, or at least bounded by the rest of the layer. One exception may be detached intra-folial folds.

(2) The early folds are surrounded by matrix or other layers which have a confining effect.

(3) The twisting mode of buckling tends to be suppressed by an infinite or large plate unless the fold shape is isolated. Some field examples of intrafolial folds have been found that appear, at least geometrically, to be compatible with formation by flexure plus twist (Fig. 5).

(4) Pure flexural modes for type 2 patterns are not possible due to accommodation and compatibility constraints (Ramsay 1967, p. 547, Ghosh 1974) unless the fold is, or becomes, isoclinal (Mukhopadhyay 1965).

(5) The direction of bulk flow during the superposed deformation with respect to the early folds may influence the predominant mode of buckling (Ghosh & Ramberg 1968, p. 99, Watkinson 1977).

These three-dimensional, confined, finite amplitude constraints make rigorous analysis intractable but the results of the model work suggest that, analogous to the engineering buckling, the shape and dimensions of the early fold cross-section determine the predominant mode of deformation. Isoclinal folds tend to buckle about a single axis, presumably the weak axis, producing a type 2 pattern. Open concentric folds, comparable with buckled cylindrical shells (Timoshenko & Gere 1961, p. 457), tend to buckle in the plane of symmetry of the cross-section producing type 1 patterns. Folds intermediate in cross-section shape will, depending on the cross-section shape, buckle either into a type 1 mode or a more complex mode involving both components across and within the axial surface. The concept is easily demonstrated with a sheet of paper. If the sheet is folded isoclinally and compressed in a direction along the fold hinge, the sheet folds into a type 2 pattern. In contrast, if the sheet is folded into an open concentric fold and compressed, the dominant mode is a type 1 pattern.

In this context we can now understand, as for example, in Skjernaa's (1975) models and in field observations, why type 1 patterns may die out as they approach early isoclinal folds. The isoclinal fold will act as a natural 'internal' boundary because it has a high resistance to refolding into a type 1 pattern.

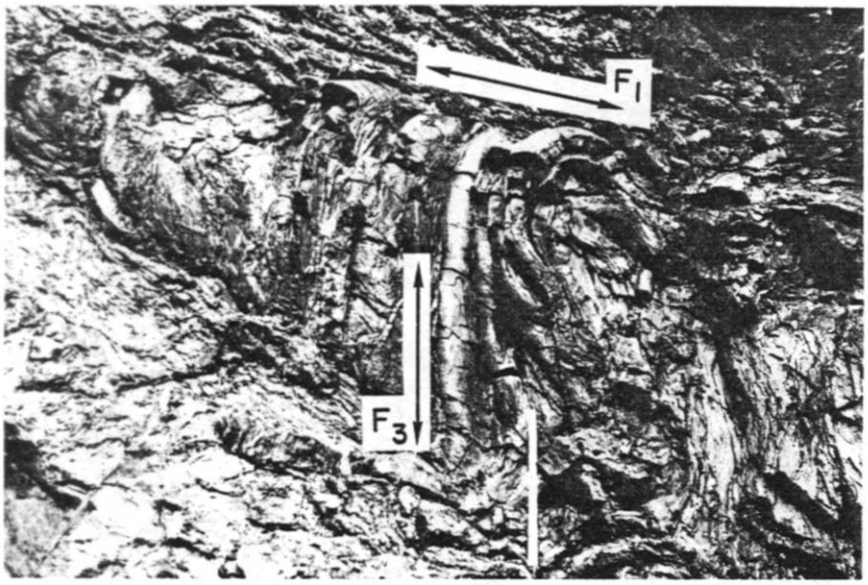

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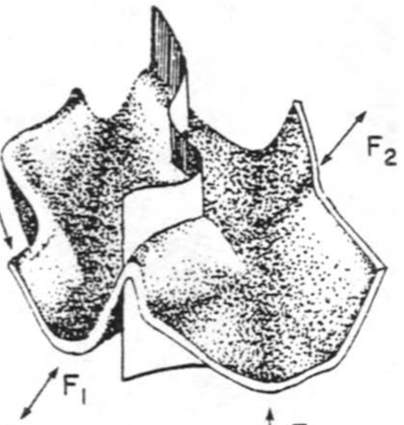
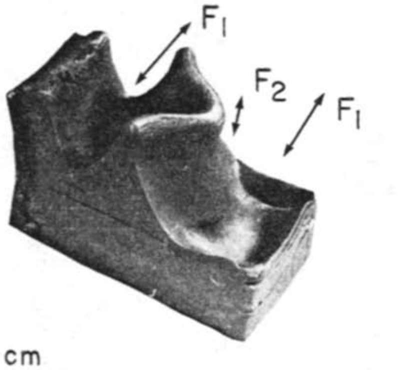
Fig. 2. Mesoscopic F_1 fold in a greywacke layer from Cameros, Douarnenez Bay, with later folds, (F_3), forming a type 1 pattern of interference.



3(a)



1 cm

3(b)

Fig. 3. (a) Cantabrian refolds (Julivert & Marcos 1973, p. 374). (b) Model experiment with type 1 patterns of interference on open synforms and type 2 patterns on tight anticlines.

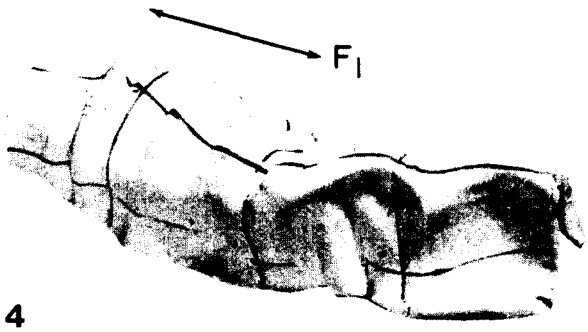


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Fig. 4. Section of a folded single-layer fold (removed from the softer matrix). The open-end forms type 1 patterns, whilst the tight-end forms type 2 patterns.

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Fig. 5. Isolated intra-folial folds, refolded, with a 'flexure and twist' component. The axial surface of the early folds is now non-planar. Example from Ruidhe Buidhe, Loch Hourn, Scotland.

CONCLUSIONS

From the results of model work it appears that the early fold-profile shape markedly affects the pattern of interference of folds when the layers are mechanically active. While it is difficult to assess quantitatively the exact change-over from one buckling mode to another, by analogy with engineering concepts the buckling mode is determined by the shape and curvature of the early fold profile. Open rounded folds tend to refold into type 1 patterns. Tight angular folds tend to refold into type 2 patterns. Such variations have been observed in natural examples of refolding.

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