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Near-orthogonal foliation development in orogens: meaningless complexity, or reflection of fundamental dynamic processes?

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Abstract

Orogenic belts are geometrically complex owing to repeated deformation. Within this complexity, there is evidence that may suggest a common pattern of sequential steeply dipping and gently dipping foliations. Seven possible explanations are presented for the sequential development of these foliations, which can probably be reduced to four of general importance: (1) the passage of thrust sheets over flats and ramps; (2) switching of the maximum and minimum compressive stress orientations during orogenesis; (3) reversal of structural development owing to strong rheological anisotropy; and (4) back-rotation of crenulation hinges during crenulation cleavage development. It is suggested that all four of these reflect fundamental dynamic processes at work to build an orogen, and therefore that sequentially overprinted steeply- and gently dipping foliations also reflect such fundamental processes. This illustrates that detailed geometrical analysis at the meso- and microscales can provide valuable input to dynamic models of orogenesis. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

One of the ultimate goals of a structural geologist is to work backwards from geometries and kinematics to determine the underlying forces, or dynamics, at work to shape an orogenic belt. However, the evolution of orogenic belts involves a large number of physical and chemical processes, some of which (e.g. deformation) are repeated many times in the same rock volumes. The final geometrical result is generally so complex that it must be greatly simplified before it can be incorporated into dynamic models. Yet, within the complexity are geometrical patterns that may provide insights into fundamental dynamic processes. This paper discusses the evidence for sequential development of steeply- and gently dipping foliations in orogenic belts, and asks two questions: (1) how does the near-orthogonality arise; and (2) does this pattern provide insights into fundamental dynamic processes in developing orogenic belts? I offer several possible answers to the first question, and suggest an answer of ‘yes’ to the second.

2. The evidence

Near-orthogonality of sequential foliations has been described in numerous studies (e.g. Zwart, 1979; Helmstaedt and Dixon, 1980; Beutner et al., 1988; Bell and Johnson, 1989; Sandiford, 1989; Johnson, 1990, Johnson, 1999a; Bell et al., 1992; Hayward, 1992; Aerden, 1994, 1995; de Roo and van Stall, 1994; Johnson and Vernon, 1995; Johnson and Moore, 1996). At the mesoscale, it presents itself as overprinting foliations and associated refolded folds (Fig. 1a). At the microscale, the evidence comes in the following four forms: (1) near-orthogonal overprinting foliations, at least the last of which is generally a crenulation cleavage (Fig. 1b); (2) near-orthogonal relationships between different growths of fibrous quartz–chlorite in pressure fringes around opaque minerals (Fig. 1c); (3) near-orthogonal inclusion-trail sets preserved in metamorphic porphyroblasts (Fig. 1d); and (4) near-orthog-

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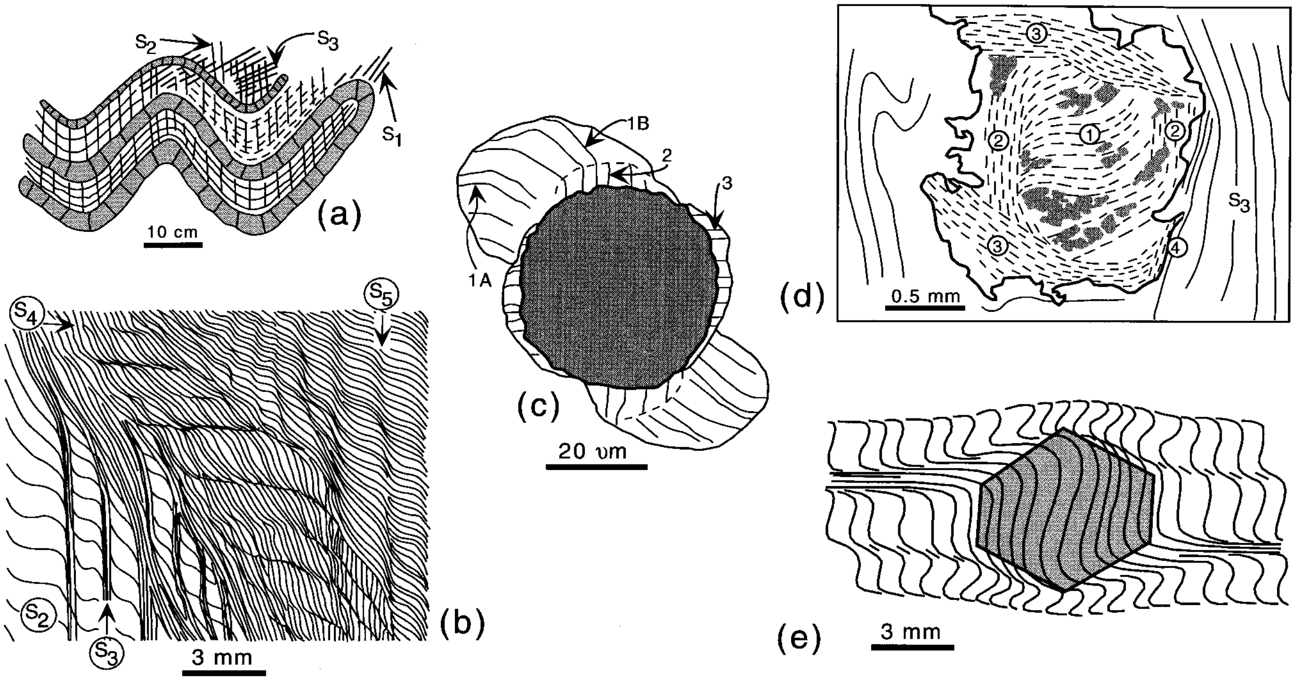

Fig. 1. Examples of near-orthogonal foliations, or evidence that suggests near-orthogonal foliation development. (a) Mesoscale example in which S_1 and S_3 are gently dipping, whereas S_2 is steeply dipping; after Helmstaedt and Dixon (1980, fig. 5). (b) Microscale example in which S_2 and S_4 are gently dipping, whereas S_3 and S_5 are steeply dipping; after Hayward (1992, fig. 2). (c) Example of three sets of quartz fibers growing from a pyrite framboid; after Beutner et al. (1988, fig. 4). (d) Example of four sets of near-orthogonal inclusion trails preserved in a garnet porphyroblast. Set 2 and 4 (the external foliation) are steeply dipping, whereas Sets 1 and 3 are gently dipping; after Hayward (1992, fig. 5). (e) Example showing steeply dipping inclusion trails in a prophyroblast that are continuous with a matrix foliation that is overprinted by a gently dipping crenulation cleavage.

onal relationships between porphyroblast inclusion trails and a surrounding crenulation cleavage that developed during or after porphyroblast growth (Fig. 1e).

In most examples of the above relationships, orthogonality is defined by overprinting of steeply- and gently dipping foliations, although two steeply dipping foliations that intersect at high angles have also been described (e.g. Fyson, 1980; Passchier and Speck, 1994). This paper is concerned mainly with the former.

3. The explanations

Below, seven possible explanations we offered for alternating steeply dipping and gently dipping foliations.

1. Foliations superposed at high angles to one another appear to be fairly common in thrust environments (e.g. Helmstaedt and Dixon, 1980; Mitra and Yonkee, 1985; Beutner et al., 1988). Beutner et al. (1988) presented a model whereby gently dipping foliations form when the hanging wall rocks are positioned above a flat during thrusting, and steeply dipping foliations form when the rocks undergo layer-parallel shortening as they move over a ramp, which is consistent with geometrical and intuitive models (e.g. Sanderson, 1982; Knipe, 1985).
2. Another, more general thrust-related model, involves vertical shortening during what is sometimes referred to as 'thrust loading', 'sheet collapse' or 'footwall collapse' (e.g. Gray, 1995; Camilleri, 1998). This is a localized form of gravitational collapse, which is driven by the increased gravitational potential energy and thermal relaxation that results from crustal thickening during thrusting. This explanation is particularly relevant to thrust environments where monotonous stratigraphy does not promote the development of multiple ramp–flat geometries (e.g. Gray, 1995; Johnson, 1999a).
3. Bell and Johnson (1989) suggested that an orogenic belt undergoing horizontal shortening and vertical thickening develops a steeply dipping foliation, and that during the life of the orogen it enters several phases in which the thickened pile becomes gravitationally unstable and undergoes vertical shortening, resulting in a gently dipping foliation that overprints the steeply dipping one. Though they did not explicitly say so, their model implies that the vertical compressive stress (σ_3) exceeds the horizontal compressive stress (σ_1) during vertical shortening

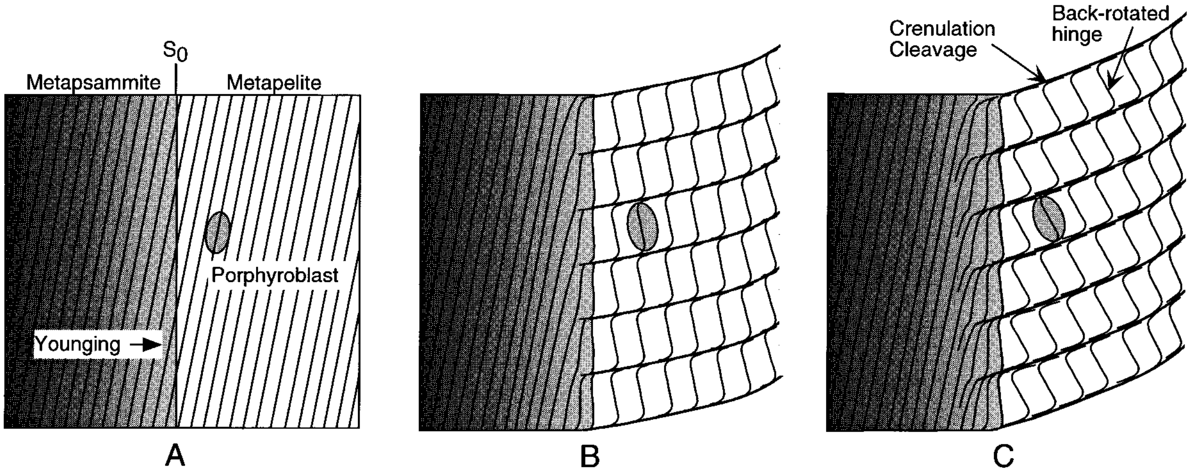

Fig. 2. Three-stage sequential diagram showing the process of back-rotation of crenulation hinges during the development of a crenulation cleavage. Back-rotation proceeds until the two foliations are nearly orthogonal. The porphyroblast shown rotates with the hinge, and has inclusion trails that are also near-orthogonal to the new cleavage. After Johnson (1999b, fig. 8).

phases, owing to crustal overthickening. Alternative mechanisms, such as changes in plate convergence velocities (e.g. Willett et al., 1993), may lead to the same result. Bell and Johnson (1989) suggested orogen-wide vertical shortening events that drive thrusts on the orogen margins. However, such events may also be localized around thermally perturbed areas, occurring in different places at different times [e.g. explanation (2) above].

4. Means (1987) suggested that if the condition $\sigma_1|\dot{e}_1| < \sigma_3|\dot{e}_3|$ could be met in a rock with a well-developed foliation oriented subperpendicular to σ_1 and subparallel to σ_3, the rock may experience what he called 'retrodeformation', which may cause a new foliation to form approximately orthogonal to the pre-existing one. Revisiting his earlier idea, Means (1999) suggested that the observations documented by Bell and Johnson (1989) may not require a reversal in the directions of maximum and minimum compressive stresses. Instead, the gently dipping foliations may form if the rate of vertical shortening multiplied by σ_3 exceeds the rate of horizontal shortening multiplied by σ_1, which would require vertical shortening rates to be higher than horizontal ones (i.e. rapid collapse stages of short duration). This model depends on the rock becoming strongly anisotropic during the development of the steeply dipping foliation. The retrodeformation, or 'bounce' of Means (1999) serves to weaken the anisotropy, which allows forward structural development to continue (i.e. development of a new steeply dipping foliation).
5. Johnson (1999b) showed that 'back-rotation' of crenulation hinges, relative to crenulation limbs, occurs during the development of crenulation cleavage in some graded metaturbidites (Fig. 2), and suggested that crenulation hinges in these examples have a tendency to attain near-orthogonality with the developing cleavage seams. Interestingly, porphyroblasts in the crenulation hinges of these rocks grew prior to, or during crenulation-cleavage development (Johnson and Vernon, 1995), and show inclusion trails parallel to the hinge foliation (Fig. 2). If the crenulation hinges back-rotated and the porphyroblasts grew before or during crenulation-cleavage development, the porphyroblasts must also have rotated with the hinges. Thus, the porphyroblast inclusion trails also end up nearly orthogonal to the crenulation-cleavage. This process can explain relationships like those in Fig. 1(e), and repeating the process one or more times may result in geometries similar to Fig. 1(d).
6. In areas affected by plutonism, the question may arise as to whether or not gently dipping foliations are emplacement related, forming above rising diapirs. The Pyrenees is an illustrative example of an area where a gently dipping crenulation cleavage overprints a steeply dipping foliation above and around several of the granite- or orthogneiss-cored massifs (e.g. Zwart, 1979; Soula, 1982; Pouget, 1991; Vissers, 1992; Aerden, 1994). Some workers have interpreted the dome-shaped enveloping surface of the crenulation cleavage over the massifs as indicating vertical shorting caused by their diapiric rise (e.g. Soula, 1982; Pouget, 1991), whereas others attribute the cleavage to vertical shortening around the massifs during more widespread orogenic collapse (e.g. Vissers, 1992; Aerden, 1994). The gently dipping crenulation cleavage in the Pyrenees apparently formed during peak low-pressure, high-temperature metamorphic conditions (e.g. Gibson, 1991; Aerden, 1994), and so the elevated tempera-

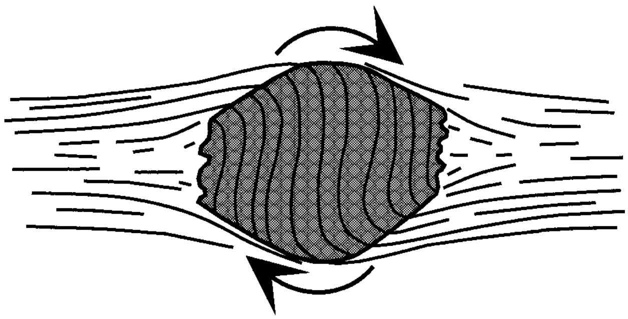

Fig. 3. Diagram showing clockwise porphyroblast rotation owing to a shear couple with the single external foliation. The porphyroblast stops rotating when the inclusion trails are approximately orthogonal to the external foliation. The reason why the porphyroblast stops, or if such a process is even realistic, is unclear.

tures may have helped to trigger vertical shortening by thermally induced strain softening (e.g. Collins and Vernon, 1991; Sandiford et al., 1991; Willett et al., 1993). Thus, plutonism may have had an indirect, rather than direct, effect on the development of such foliations.

7. It may be possible that approximately orthogonal relationships preserved in some porphyroblasts result directly from porphyroblast rotation relative to a foliation fixed to the flow plane of simple shear (Fig. 3). This issue has been discussed by Hayward (1992) and Johnson (1993), but neither author offered explanations for why rotations might occur in approximately 90° increments. If this explanation is indeed valid, then the mechanisms involved in crenulation cleavage development [explanation (5) above] may play an important role in controlling porphyroblast rotation, even in areas where the direct evidence for crenulation cleavage development has been partially or wholly removed by intense deformation.

4. Discussion and conclusions

The two questions posed in this paper are: (1) how does near-orthogonality arise; and (2) does this pattern provide insights into fundamental dynamic processes in developing orogenic belts? In answer to the first question, I suggest that the seven explanations listed above can be reduced to four of general importance, as follows. (1) In thrust belts where stratigraphy allows the development of multiple flats and ramps, sequential overprinting of steeply- and gently dipping foliations may be a direct result of thrust-sheet propagation over these features. (2) In higher-grade parts of orogenic belts, and in thrust belts where monotonous stratigraphy precludes the development of multiple ramps and flats, sequential overprinting of steeply and gently dipping foliations reflects a balancing act between (a) forces related to convergence of tectonic plates, and (b) gravity. If gravity decisively prevails, wholesale orogenic collapse results. (3) In these same areas, sequential overprinting of steeply- and gently dipping foliations may instead reflect a balancing act between the forward development of structures and their reversal, which may be driven by the degree of rheological anisotropy attained by the affected rock volume. (4) Where overprinting foliations are not initially at high angles to one another, back-rotation of crenulation hinges (and porphyroblasts located there) can result in near-orthogonality. This explanation still requires sequential overprinting of foliations, although they may initially lie at moderate angles to one another.

The second question is difficult to answer with confidence. Though the evidence listed in this paper has been found in many orogenic belts, it is much easier to discover in some than in others. In addition, many of the examples cited above are microstructural, and it may be a big jump to infer orogen-scale processes from such small-scale observations. Nevertheless, I will venture a cautious answer of ‘yes’; these observations do reflect fundamental dynamic processes, regardless of which of the four general explanations is preferred for a given area. Thrusting (general explanation 1) obviously reflects fundamental processes, but perhaps more important in the context of this paper, so do any large-scale balancing acts between driving forces or directions of structural development (general explanations 2 and 3). Many examples of near-orthogonality show the types of evidence in Fig. 1(d and e) and Fig. 2, and so in some instances they may be a product of back-rotation during crenulation cleavage development (general explanation 4), rather than overprinting of initially near-orthogonal foliations. However, these examples may be important because crenulation cleavages are widespread in orogens, and so the back-rotation process may reflect a widespread balancing act between the need for rock volumes to deform, the need for strain compatibility during this deformation, and the constant constraints placed on these volumes by the surrounding stress field.

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