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Reversed structures and bounce structures: are they recognizable? Are they real?

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Abstract

This note poses two related questions about structural evolution in rocks. How easy is it to recognize structural features that have reversed their sense of development over time? Are there circumstances in rock deformation where early intensification of structure sows the seeds for a later, more or less inevitable, diminution of intensity? It is suggested, as a partial answer to the first question, that there is an irreversibility principle inherent to most structural development, such that even if bulk strain is reversed, the structural changes that accompanied 'forward' structural development will not be completely reversed when the strain is reversed. Where this principle applies, it should always be possible to recognize structural reversals, by sufficiently close observation of the final state. It is suggested, as a partial answer to the second question, that where energy is stored by forward structural changes, this energy can often be expected to drive further structural changes, and these further changes may sometimes cause the original structure to 'bounce' back to a less intense state. These questions may have some bearing on developing a firmer basis for kinematic analysis, and for understanding overprinting structures in orogens. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Have you ever wondered, at an outcrop with folds, whether the folds were still tightening, or perhaps *opening*, during the last part of the folding process? Have you ever wondered, when looking at a garnet schist in thin section, whether the garnets were still growing, or perhaps *shrinking*, when they were last changing size? For most of us, the answer to questions like these is no. We recognize folds or large garnets as products of a *forward* process (fold tightening, garnet growth) and do not much care whether these processes were reversed a little at the end. After all, when the rates of deformation or metamorphic processes drop to zero, at the end of tectonic events, odd things are bound to happen, which tell us little about the main activity earlier on. Studying late-stage processes and their signatures in rocks is as futile as scrutinizing the pallor of a corpse, if what we really want to know is how the person *lived*.

The above dismissal of processes that *deintensify* structures in rocks is probably shortsighted in two ways. First, processes like opening of folds and shrinkage of porphyroblasts are not necessarily just late-stage processes, or processes unimportant in establishing the main features we now see in outcrops or thin sections. All that a fold indicates is more tightening than opening. All that a porphyroblast indicates is more growth than shrinkage. In fact the *main* part of a history (the longest interval of time) can be occupied by 'backwards' structural changes that deintensify structural features and may ultimately remove them. This is of course what ordinarily happens to primary structures like bedding, which may become completely obscured by the time an originally bedded sequence is converted into a para-gneiss. Flinn (1962) recognized many years ago that secondary structures can be deintensified, when he explained how a layer can be shortened (folded) then lengthened (unfolded), even during a single progressive deformation. Secondly, whether or

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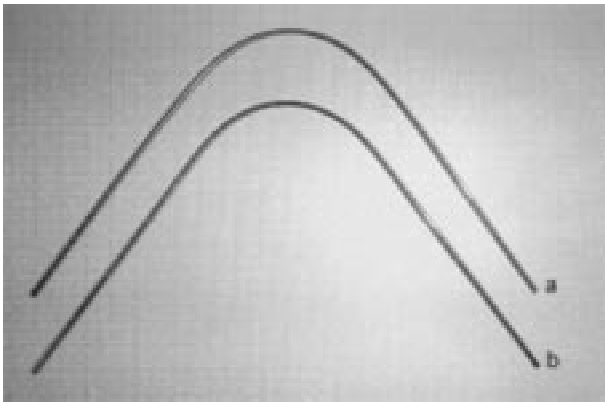

Fig. 1. Wires, folded by different histories, with subtly different fold shapes. Wire *a* was buckled monotonically, from its original length of 30 cm to a length of 20 cm, measured normal to its 'axial plane'. Wire *b* was buckled more strongly, to form an isoclinal fold, then pulled apart to the same 20 cm final length as wire *a*. The fold in wire *b* is an example of a reversed structure.

not deintensification of secondary structures is a common thing, thinking about it brings us face-to-face with two fundamental problems of our science: what is the relationship between the geometry we see and the processes that were changing this geometry? And what is the relationship between the structural state at an instant and the *sense* of structural change at that instant?

2. The irreversibility principle

What I call the 'irreversibility principle' here is the idea that whenever forward, bulk deformation and development of large-scale structure is accompanied by local changes in structure that influence local mechanical properties, unless all the local changes are themselves completely reversible, reversal of the bulk deformation will not be accompanied by perfect reversal of the large-scale structure. Fig. 1 shows an example.

Fig. 1(a) shows a 30 cm length of annealed copper wire that I folded by forcing its ends together with my fingers, until the distance between the ends of the wire, measured normal to the 'axial plane', was 20 cm. Fig. 1(b) shows an identical length of wire that I first buckled to the same shape as wire *a*, then shortened further, to an isoclinal state, then pulled apart until the distance between the ends was the same as for wire *a*. The bulk deformation parameter that is identical for the two pieces of wire is the 33% net shortening of the distance between the ends of the wires. If the large-scale structural change in wire *b*, between the time it was shaped like wire *a* and the time it was isoclinal, was completely reversible, the final shape of wire *b* would be exactly like that of wire *a*. This is not the case. Fold *a*, with the monotonic history of fold-closing, has a broader distribution of curvature around the hinge, and shorter segments of its limbs that are straight. Fold *b* has a sharper hinge and longer straight segments on its limbs. The reason for these differences in final structure is easy to understand. During forward folding of both wires, there was strain-hardening of the copper crystals in the hinge region. This was especially true in wire *b*, taken to higher hinge-strains. During unfolding of wire *b*, the hardened hinge region resisted reverse-straining more than regions just outside the hinge, so the hinge unfolded less than that which would have been necessary to precisely reproduce the hinge shape of fold *a*.

For irreversibility of structure in any material, forward deformation has to be accompanied by some kind of local structural change in the material that influences the resistance to deformation, and these small-scale structural changes have to be themselves imperfectly reversible if straining is reversed. In the copper wire, the small-scale structural features that presumably changed during forward deformation were dislocation densities and configurations. Dislocation products of crystal–plastic deformation may be expected to account for irreversibility of larger-scale structure in many rock situations too, but *any* small-scale structural change that influences rheology can be expected to have a similar effect.

A corollary of the irreversibility principle is that structures in materials with local mechanical properties influenced by straining will always be deformation-path dependent, not simply finite strain dependent. This is the basis for using structure to distinguish coaxial from non-coaxial deformation paths. It is also the basis for expecting non-zero structural changes at zero finite strain, so long as there have been excursions away from zero strain.

3. Recognition of structural reversals

In some geological situations, structures that are being reversed or deintensified are easy to recognize and are already quite familiar. For example in many multiply deformed terranes, folds that are opening are strongly indicated where there is a later foliation that cuts both limbs and crenulates their axial plane foliation. Here the structural reversal is accompanied by a prominent, new, mesoscopic structure (the cross-cutting cleavage). But in other cases, no equally prominent new structure is introduced during unfolding, for example in folds which fold and then unfold by flexural slip. Here the unfolding strain should still be recognizable, if close enough attention is given to slip-sense indicators on the slip surfaces, or to such microscopic features as calcite twin orientations within the layers. On the field scale, Lloyd and Whalley (1998) describe a geometrical technique which they have used in an area where upright folds have been deformed by later, horizontal shearing, which reveals that some of the folds have been opened. Reversals of movement sense on faults are very familiar, as for example where early normal faults have become reactivated as thrust faults (see Gutierrez-Alonso and Gross, 1997, and references therein for techniques for recognizing reversal of slip-sense on faults).

But what about the more difficult problem of recognizing structural reversals where *migrating* planar structures are involved? This is the situation when a garnet porphyroblast changes size. The migrating structural feature here is the 'phase boundary' that separates the garnet from its matrix. What criteria do we have for recognizing reverse growth (shrinkage) of porphyroblasts? Shrinkage is easy to detect where retreat of the garnet's boundary is recorded by a chlorite pseudomorph, the outer edge of which indicates the former extent of the garnet. But what about a garnet that grows by replacement of quartz and mica, then shrinks by regrowth of surrounding quartz and mica? How cryptic could such a structural reversal be? Conventionally, one might expect a growth-only garnet to be idioblastic, and a garnet that grew and then shrank again to have more irregular, perhaps embayed, boundaries. But the basis for this kind of interpretation has been weakened recently by Daniel and Spear (1998), whose maps of garnet zoning suggest that garnets can be irregularly shaped even when they are growing. It seems to me that it should ultimately be possible, by close examination of present geometry or chemistry on some scale, to distinguish between present porphyroblast boundaries that were migrating away from or toward the oldest part of the grain when they were last in motion. The basis for this expectation is that the processes of attachment or detachment of atoms from the surface of a crystal *must* be different in some way, so that at least a cryptic signature of each process should be present in the structure of the porphyroblasts or its matrix near the migrating boundary. Does this seem right: that where there is a difference in process, there will always be *some* difference in structure? And are the processes of attachment (actually where more atoms are attaching than detaching) and detachment (more atoms detaching than attaching) always sufficiently different as to leave distinct signatures? What about the situation where atoms are being transferred *along* a boundary, so that one segment of a boundary is moving toward the oldest part of a grain while another segment is moving away from it? This might occur during an interval where the porphyroblast as a whole is neither gaining nor losing atoms, just becoming more idioblastic.

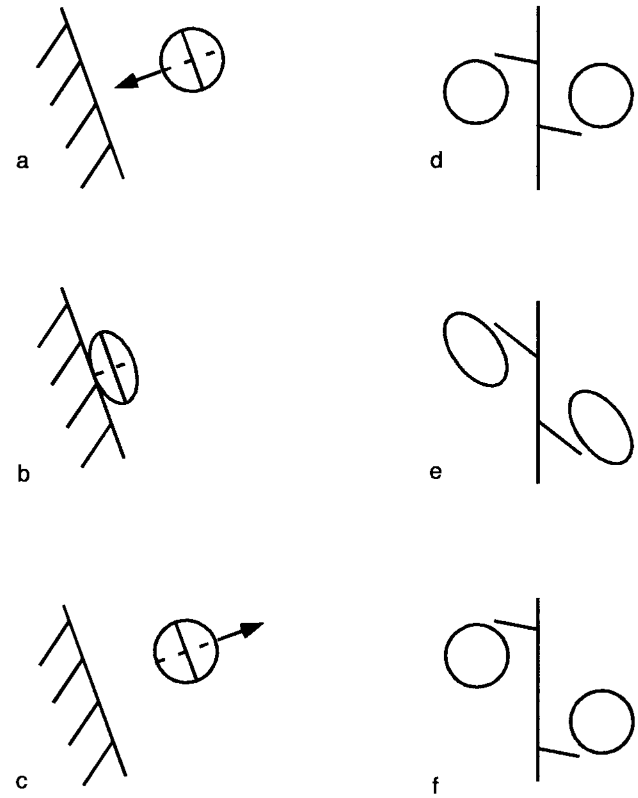

Fig. 2. Elastic bounce effects. A ball strains on impact (a, b) and reverses the strain when it rebounds (b, c). The internal structural changes at impact are also reversed on rebound. A locked fault region strains under tectonic stress (d, e), then reverses the strain when slip occurs (e, f). The structural change in bond-lengths within the grains, as well as in the angle between the previously offset marker and the fault, are both reversed during rebound. The strains are greatly exaggerated in the drawing.

4. Bounce structures

To this point, I have been considering reversal or deintensification of structure without implying any causative link between intensification (e.g. fold tightening) and deintensification (fold opening). But could there be such a link? Can folding or foliation development or other 'forward processes' sometimes lead causally to circumstances that produce reverse processes such as unfolding or foliation weakening? Is structural change sometimes inherently unstable and self-reversing? I imagine there is a class of such processes, where forward structural change stores energy, either internally or by virtue of elevation in the gravity field, which drives later structural change that deintensifies certain structural features. I call the resulting, deintensified structures 'bounce structures'.

When a ball bounces, part of the kinetic energy at impact is stored as elastic strain energy, which is then converted back into kinetic energy as the ball rebounds

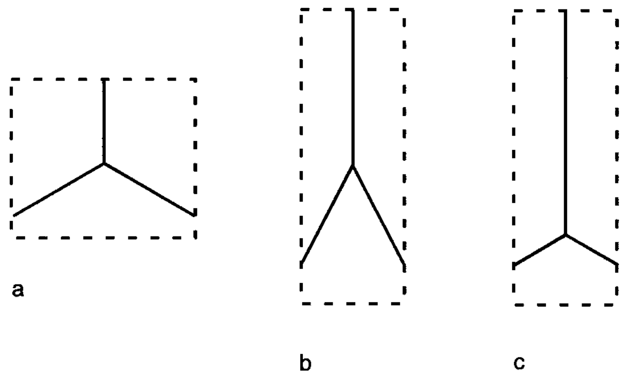

Fig. 3. Bounce effect without strain reversal. A triple junction between three grains is strained plastically (a, b), then returns to its original 120° configuration by grain boundary energy-driven grain boundary migration. The structural change between a and b is reversed between b and c, but not the strain.

(Fig. 2). The rebound occurs because the strain at impact (Fig. 2b) is unstable when the velocity of the ball has dropped to zero, so strain reversal occurs, accelerating the atoms of the ball away from the impacted surface. During the interval b–c the internal structure of the ball changes. Bonds that were extended in b become shorter again in c, and vice versa. The structural change from b to c is linked to and driven by, the previous structural change from a to b.

The closest analogy in rocks to the linked strain and structural reversal in the bouncing ball is the elastic rebound process adjacent to faults that slip episodically (see Suppe, 1985, p. 296). Under shear stress, fault wall rocks become strained and the structure changes in two senses. Bonds in the mineral grains are extended or shortened slightly, and the angle between a marker offset by previous slip and the fault is changed slightly (Fig. 2d and e). When fault slip occurs between e and f in Fig. 2, the bonding structure returns to something like its geometry in d, and the structure defined by the intersection angle between the marker and the fault also returns to more or less its pre-slip value.

In the elastic rebound case above, the strains and structural changes are very small. Are there examples of bounce structures that involve large and permanent structural changes? I think there are, and that they come in two varieties: one where the reverse structural change occurs without reversal of the strain, and one where the structural change and the strain are both reversed.

The clearest example of structure-reversal I can think of that is self-driven by the forward structural change but not accompanied by strain reversal, is the grain-scale process discussed by Bons and Urai (1992) and illustrated in Fig. 3. A triple junction formed by three grain boundaries making 120° angles with each other is distorted by crystal–plastic deformation of the three grains. The resulting, forward structural change is the change in angles between the boundaries (Fig. 3b), assumed here to be moving passively with the material of the grains. Energy is stored by the deformation, partly in the form of grain boundary energy associated with an increase in the total length of the boundaries. This energy is then available to drive migration of the two inclined grain boundaries and propagation of the vertical boundary, such that the structural change between a and b is reversed and the original 120° angles are restored in c, even though the strain is not reversed. For structural change to occur this way, unstably oscillating between two different states (a, c and b) instead of settling for a stable, steady, compromise state, there has to be a threshold driving force below which the structure-reversing process cannot keep pace with the forward structural change, and above which the structure-reversing process runs faster than the forward structural change. It is not clear whether such threshold driving forces exist in steady-state flow at low natural strain-rates, i.e. whether *local* behavior is oscillating or steady-state. It seems to me that on a sufficiently local scale, oscillating behavior is always to be expected. Consider for example, a dislocation-rich region on one side of a grain boundary which eventually acquires enough dislocation-energy to 'suck' the grain boundary through itself. As the boundary passes, the atoms in the region become reorganized into a relatively good crystal structure, with low dislocation density and low resistance to renewed build-up of dislocations. This material region has thus 'bounced' from a state of high dislocation density to a state of low dislocation density, and can be expected to repeat this structural oscillation several times, even if the polycrystal as a whole is in steady-state flow (constant bulk resistance to flow at some constant bulk strain-rate).

An example of bounce structure where the reverse structural change is driven by the forward structural change and accompanied by strain reversal, is provided by the model of Bell and Johnson (1989) to explain certain patterns of inclusion trails in porphyroblasts. In this model, horizontal shortening in parts of an orogenic pile is accompanied by development of vertical foliations which become more intense (i.e. stronger preferred orientation of planar fabric elements) as deformation proceeds. Then, by virtue of stored gravitational potential energy (stored by upward displacement of upper parts of the rock mass), there is gravitational collapse (i.e. vertical shortening). This can happen if the stress-difference building the pile decays for some reason and the horizontal stress (original σ_1) becomes less than the vertical stress (new σ_1). It can also happen, in principle at least, without any switch in the orientations of σ_1 and σ_3. If the previous structural change, to produce the vertical foliation, renders the rock rheologically anisotropic enough, it may become possible to switch from horizontal to vertical shortening, even if σ_1 remains horizontal and σ_3 remains vertical. All that is necessary is that the product of σ_3 times the vertical shortening-rate must exceed the product of σ_1 times the horizontal extension-rate, so that the net rate at which work is done on the rock volume remains positive (Means, 1987). This in turn requires that the vertical shortening-rate somewhat exceeds the horizontal extension-rate, as it might do if a subhorizontal crenulation cleavage forms with *volume-decrease* while the old vertical foliation is being weakened.

5. Concluding remark

My inclination to expect reversed structures in rocks is partly a bias from watching microstructure evolve in experiments on analog materials. There, it is common experience to see a structure that is prominent locally at one moment, become indistinct a little later. Whole grains for example may grow for a while, then shrink and perhaps be fully consumed by their neighbors. Or slip-surfaces that are marked at one moment may be indistinct the next, and later gone altogether. But in these analog experiments there are vigorous *migration* processes at work which are certainly not so important or perhaps totally unimportant to the development of the outcrop-scale or map-scale structures studied by field geologists, particularly in rocks deformed at low temperature. On the other hand, in metamorphic rocks that bear multiple generations of mesoscopic structures, it is common knowledge that the earliest structures are often obscured or removed altogether by development of later ones. So early-formed mesoscopic structures *do* commonly become weakened as an orogeny proceeds, and in this sense, reversed structures are also very common on the mesoscopic and map scales. It is a nice reflection on our human nature that we have always taken more interest in the rise of new structures than in the demise of old ones.

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