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A fundamental problem with the kinematic interpretation of geological structures

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Abstract

Non-steady flows are ubiquitous in nature. Not only do imposed boundary conditions vary with time and rock rheology change during the course of deformation but also deformation is generally heterogeneous and all of these conditions lead to non-steady flow histories.

In modern kinematic analysis, flow apophyses, the instantaneous stretching axes and the vorticity vector, collectively referred to as the 'eigen directions' of deformation, are used in place of Bruno Sander's kinematic axes. For deformation with a steady flow history, this practice is well justified and has led to great advances in structural geology. But for non-steady flow histories, the geometrical relationships among eigen directions (flow pattern) vary with time. This makes it inappropriate to correlate an association of structures and fabrics with certain 'time-invariant' flow patterns and hence raises the question: How should we interpret geological structures and fabrics kinematically, without the assumption of homogeneous and steady deformation? We suggest that the answer lies primarily in forward-modeling of deformation, based on a knowledge of rock properties.

1. Introduction

The kinematic information about an area is critical in deciphering large scale tectonic processes and movements. Since the work of Bruno Sander (e.g. Sander, 1930, 1948, 1950) reconstruction of the kinematic history of structures has usually been based on the geometry and fabric of the structures themselves. The two most important concepts in Sander's theory and methodology that remain relevant today are the concepts of the movement picture and the symmetry principle (Sander, 1930, 1948, 1950; Paterson and Weiss, 1961; Turner and Weiss, 1963; Lister and Williams, 1979). The concept of movement picture is now best described by the geometry of the flow ('flow pattern' of Passchier and Trouw, 1996). In place of Sander's kinematic axes, structural geologists now use rigorously defined terms, such as flow apophyses (Ramberg, 1975), the instantaneous stretching axes (ISA) and the vorticity vector, collectively referred to as the 'flow eigen directions'. The description of a flow is dependent on the reference frame used. Astarita (1979) and Means et al. (1980) independently show that objective mathematical description of a homogeneous flow is possible by using a reference frame that is fixed with respect to the ISA.

Flow of rocks leads to strain accumulation. The strain can be infinitesimal, but mostly we are concerned with finite strain. A strain state is described by the strain ellipsoid with three principal strain axes. The geometry of natural structures and fabrics is commonly interpreted using the flow eigen directions and the principal finite strain axes (e.g. Ramsay, 1967; Ramsay and Graham, 1970; Ramberg, 1975; Bobyarchik, 1986; Passchier, 1990, 1997; Simpson and De Paor, 1993; Means, 1994; Passchier and Trouw, 1996; Jiang and Williams, 1998, in press; Lin et al., 1998). For example foliations have been considered to be coincident with the finite strain axes (e.g. Ramsay,

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1967; Ramsay and Huber, 1983; see Hobbs et al., 1976, 1982; Williams, 1976; Williams et al., 1977; Lister and Snoke, 1984; for discussion). Crystallographic fabrics, shear band cleavages and various kinematic indicators in shear zones have been related to the flow apophyses, the vorticity vector and the ISA (e.g. Ghosh and Ramberg, 1976; Lister and Hobbs, 1980; Bobyarchik, 1986; Passchier and Simpson, 1986; Passchier, 1987, 1990; Hanmer and Passchier, 1991; Simpson and De Paor, 1993; Passchier and Trouw, 1996). As pointed out, for finite deformation, by Williams et al. (1977) and Hobbs et al. (1982), and for instantaneous deformation by Lister (1982), all the above axes are *spatial orientations*, not generally attached to material lines. Once the deformation history is non-steady, the flow pattern (the geometrical relationships among the flow apophyses, the ISA and the vorticity vector) varies with time.

2. The ubiquity of non-steady deformation

A flow can be described in an external reference frame by its velocity gradient tensor **L**, which, following Cauchy–Stokes decomposition (Truesdell and Toupin, 1960, p. 362) and the decomposition of Astarita (1979) and Means et al. (1980), can be decomposed as follows (see Jiang, 1999 for details):

$$\mathbf{L} = \mathbf{D} + \mathbf{W} + \mathbf{\Omega} = \bar{\mathbf{L}} + \mathbf{\Omega}, \tag{1}$$

where **D** is the stretching tensor, **W** is the internal vorticity—the vorticity measured with respect to the ISA, the principal directions of **D**, $\mathbf{\Omega}$ is the spin tensor—the vorticity appropriate for the spin of the instantaneous stretching axes in the external reference frame used to describe the flow (Means et al., 1980), and $\bar{\mathbf{L}}$ ($= \mathbf{D} + \mathbf{W}$) is the velocity gradient tensor of the flow described in the ISA frame.

In the context of structural geology, when we speak of steady flow or steady deformation history, what is meant is that the kinematics of the flow at a given material particle is not varying with time. This is a reference-frame-independent quality of the flow. A definition of steady flow can be made mathematically as follows (Jiang, 1999): a flow is steady in the vicinity of a material particle if $\bar{\mathbf{L}}$ does not vary with time (t) in that vicinity:

$$\frac{\mathrm{D}\bar{\mathbf{L}}}{\mathrm{D}t} \equiv 0. \tag{2}$$

Most natural deformations are non-steady. There have been many papers emphasizing the significance of heterogeneous and non-steady deformation including Lister and Williams (1983), Twiss et al. (1993), Jiang (1994a,b) and Jiang and White (1995). The ubiquity of natural non-steady deformation is widely acknowledged in discussion amongst structural geologists. However, deformation is generally treated as homogeneous and steady because the mathematical description becomes too complex otherwise. The principal reasons for believing that deformation is generally non-steady can be summarized as follows:

1. Imposed boundary conditions are generally variable: Both the rate and direction of plate motion vary with time and the geometrical configuration of the volume of rock that accommodates the motion is constantly varying. As a result, the immediate boundary conditions of the deformation that causes structures to develop, varies with time. Variability in the imposed boundary condition necessarily means that the deformation of the volume of rock bounded by the boundary is non-steady.
2. The rheological properties of rocks generally change during deformation: During the course of deformation, both physical and chemical changes are likely to take place. The composition, microstructure, anisotropy and deformational conditions of the rock evolve with time. This progressively alters the rheology and hence the response to tectonic forces, thus deformation is likely to be non-steady.
3. Heterogeneous deformation is generally non-steady: If the heterogeneous deformation is divisible into domains of homogeneous deformation, then this is similar to situation 1 because the boundary condition of each domain of homogeneous deformation varies because of heterogeneity. If the heterogeneity is mathematically more smooth, the deformation is still generally non-steady (Jiang, 1994a). This point is clearly demonstrated by the following equation:

$$\frac{\mathrm{D}\bar{\mathbf{L}}}{\mathrm{D}t} = \frac{\partial\bar{\mathbf{L}}}{\partial t} + \bar{\mathbf{v}} \cdot \left(\frac{\partial\bar{\mathbf{L}}}{\partial \mathbf{x}}\right)^T, \tag{3}$$

where $\bar{\mathbf{v}}$ is the velocity with the spin-related component removed, and $\mathbf{x}$ is spatial location.

For a homogeneous flow ($\partial\bar{\mathbf{L}}/\partial\mathbf{x} = 0$), it is steady ($\mathrm{D}\bar{\mathbf{L}}/\mathrm{D}t = 0$) if the flow field is constant ($\partial\bar{\mathbf{L}}/\partial t = 0$). A general heterogeneous flow ($\partial\bar{\mathbf{L}}/\partial\mathbf{x} \neq 0$) is non-steady even if $\partial\bar{\mathbf{L}}/\partial t = 0$. A Ramsay and Graham (1970) shear zone is an exception where the flow can be heterogeneous in the direction perpendicular to the shear zone boundary but the flow is still steady so long as $\partial\bar{\mathbf{L}}/\partial t = 0$. This is because for the special velocity field of simple shear, $\bar{\boldsymbol{v}} \cdot (\partial\bar{\mathbf{L}}/\partial\mathbf{x})^T \equiv 0$. There are other exceptions, however, in view of the general applicability of conditions 1–3, listed above, and we believe that steady deformation must be an exception rather than the norm (e.g. Lister and Williams, 1983; Jiang, 1994a,b; Jiang and White, 1995).

3. The consequences of non-steady deformation

Where the deformation is steady, as is often assumed in the literature, the eigen directions have fixed orientations with respect to the ISA. It is then possible to consider the development of structures or fabrics in terms of the flow eigen directions. For example, one can say that materially defined fabric elements such as mica flakes may rotate during deformation towards the extensional flow apophysis and give rise to a schistosity. But what if we consider more realistic cases in nature where the deformation is generally non-steady?

Flow apophyses, the instantaneous stretching axes and the vorticity vector still exist for non-steady flow histories, but their geometrical relationships (flow pattern) vary with time. For layered rocks with competence contrast undergoing plane-strain deformation, the spin of the eigen directions is much faster and/or is opposite in sense to the spin of material lines (fig. 7 of Jiang, 1994b). The eigen directions therefore coincide with different material lines as deformation progresses. Thus one arrives at an erroneous conclusion in attempting to reconstruct the flow history, if a constant flow pattern is assumed, when it is in fact non-steady. It follows then that we cannot generally interpret structures in terms of unique flow patterns. This in turn means that structures cannot be used to uniquely interpret regional tectonic movements, such as the emplacement direction of an allochthon.

Taking the example of the allochthon a little further, assume a ductile thrust in which a horizontal mylonite zone deforms by simple shear. The shear plane is horizontal and assumed constant in orientation. The flow in the zone however, is non-steady because during emplacement of the nappe we assume that the direction of shear changes progressively from top-to-the-north to top-to-the-west. A stretching lineation that tracked the principal finite stretch direction would initially trend north and would gradually change direction towards the west. Depending on details of the history, it might finally trend, say, northwest. If a steady-flow history was assumed, normal analysis would determine that the thrust was towards the northwest and would be wrong. If the lineation was a steady-state shape fabric, the final trend might be west, which would give an equally wrong interpretation of the history.

4. The future of kinematic studies

In view of our conclusions we have to ask the question: is there any future in studying kinematics? It is of course an interesting study in itself, but the question that we wish to address is whether it has any useful application in geology or not. In a somewhat negative way we believe that it does! It seems to us that in interpreting the history of an area it is better to be cognizant of all the possibilities even if the corollary is an inability to give a unique answer. In other words it is better to say we cannot determine the history, but the following interpretation or interpretations are reasonable, rather than assert incorrectly that a given history is the correct one. We can usefully build hypotheses on uncertainties but not on incorrect 'definitive' conclusions. For example, in the interpretation of an area, it is better to realize that the movement on a major shear zone cannot be determined from the observed structure alone, rather than have the regional interpretation constrained by an incorrect conclusion concerning the movement on the shear zone.

Better understanding has increased the possibilities for interpretation. At one time it was generally believed that stretching lineations in shear zones definitively indicated the direction of shear. We now have a better understanding and believe that the lineation can lie anywhere between parallel and perpendicular to the shear direction (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Robin and Cruden, 1994; Jiang and Williams, 1998; Lin et al., 1998). Thus, for example, when faced with a situation where there is a major mismatch in markers (indicating that the displacement is large) across a shear zone, and a vertical stretching lineation, but no change in metamorphic grade from one side to the other, we are able to interpret the shear zone as transcurrent, despite the vertical lineation. Similarly when it was realized that axial plane foliations generally developed in non-coaxial flow and therefore did not generally track a principal plane of strain, it became possible to explain the observed shear parallel to the foliation (Williams, 1976). Prior to that, ad hoc explanations were necessary that enabled interpretation of the shear as only apparent, despite cogent evidence to the contrary in some examples.

Kinematic indicators are used extensively by non-specialists without a clear understanding of their limitations. It is critical to realize that sense of shear, sense of vorticity and sense of non coaxiality are different concepts of instantaneous flow (Jiang, 1999). In addition it is also critical to distinguish them from their finite counterparts such as sense of displacement and sense of rotation (Jiang, 1996). Strictly speaking snowball garnets and rotated porphyroblasts indicate sense of vorticity which can be different to the sense of shear of the shear zone.

The problem is not restricted to shear zones. Any deformation that can occur in a shear zone can, at least theoretically, occur outside of a shear zone. This general situation is even harder to analyze since one advantage of studying shear zones is that we generally have a better idea of boundary conditions than in the more general situation.

In our opinion the most fruitful approach to studying kinematics is likely to be forward-modeling based on a sound understanding of the mechanical behavior of rocks and the theory of flow. Such an approach will enable us to understand how various structures can develop. However, because of the complexity of natural deformation we do not expect to be able to reverse the process in general to arrive at unique solutions from observation of natural structures. The best we can hope for is to place constraints on kinematic interpretations which can then be weighed in light of other evidence. Thus the down side is that it becomes even more difficult to find unique interpretations for our observations. However, looking at it more positively, the recognition of complex kinematics opens up additional possibilities for interpreting complex geometry and increases our chances of arriving at correct, albeit scant, conclusions.

If we can accurately model the mechanisms available in a deforming rock in the way, for example, that has been attempted for deforming quartzite (e.g. Lister and Hobbs, 1980; Wenk et al., 1989) then for a given set of conditions we may be able to model the development of the resulting structure and fabric. This approach has been quite successful for quartz fabrics in monomineralic quartzites so that in ideal cases we believe that we now have a reasonable basis for interpreting natural fabrics (for a cautionary note however, see Wenk and Christie, 1991). This type of forward-modeling leads to a whole series of new avenues for us to explore and would seem to be the most promising approach to understanding the structures produced by non-steady flow.

In summary since flow pattern varies for non-steady histories, we should not assume constant eigen directions and interpret structures in terms of them. Instead we should investigate the stretching and rotation history of different material lines or other fabric elements. To do so requires knowledge of the deformation paths, which at this stage cannot be determined retroactively but can be explored by forward-modeling of various geological deformation conditions. For a given deformation path, the development of structures and fabrics can then be analyzed in terms of the rotation and stretching history of material lines in the flow field (Elliott, 1972; McKenzie, 1979; Jiang and Williams, in press). Considering the allochthon example, although we cannot determine the kinematic history from the observed structures due to non-steadiness (see above), if we know the history of relevant plate movement we can forward-model the kinematic history. This can then be used to model the development of the resultant fabric and compared with the observed fabric. A good correlation would *suggest* that the model represents a sound interpretation and that the assumed plate movements were correct. However, consistency is still not proof that the interpretation is correct since there may be other kinematic histories that could produce the same end result. Nevertheless we believe the forward-modeling approach comprises a large and potentially fruitful area of research and one that needs further exploration if we are to contribute significantly, as structural geologists, to the study of tectonics.

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