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Structural Geology: where have we come from and where might we be going next?

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Abstract: This talk will present a review of certain topics in structural geology and will analyse what the speaker considers were some of the major advances in their development. It may come as a surprise to many younger workers what high standards of observation and mathematical analysis of these observations characterized many publications over 100 years ago. One of our current problems is that researchers, not having easy access to these publications, keep "rediscovering the wheel". There exists a strong case for republishing some of these works much in the way that the AAPG has produced volumes of the classic papers on faulting.

Keywords: finite strain, progressive deformation, fold geometry, folding mechanics, structural geology.

Finite strain and rock deformation fabrics

During the middle and late 19th century several British geologists began investigations into the significance of slaty cleavage and schistosity. They realized the difference between cleavage and jointing and began an intensive study of strain using deformed objects found in the rocks. The results of Sharpe, Phillips and Sorby showed that slaty cleavage was related to the finite strain state of deformed rocks and formed perpendicular to the principal finite shortening. In 1885 Harker produced a complete summary review "On slaty cleavage and allied rock structures" in which he discussed the significance of the finite strain ellipsoid, the effects of volume changes and explained the significance of cleavage refraction. Many of the characteristic strain equations were assembled and should be an eye-opener to many modern structural geologists.

Of course there was some opposition to these views and Laugel (1855) suggested that cleavage was related to planes of maximum finite shear, a view supported later by Becker (1905) who used laboratory experiments with paraffin wax, to back his views. All these ideas were incorporated by Leith (1906) in a memoir suggesting that there were both types of cleavage "flow cleavage" and "fracture cleavage" were possible. Today's view, based on more data, suggests that fracture cleavage is more related to brittle jointing than persuasive rock flow. Although there followed an idea that cleavage was related to dewatering of wet sediments by Maxwell (1962) this has generally been discredited because it could neither explain cleavage passing from a sedimentary rock matrix through lithified pebbles in conglomerates nor explain the presence of cleavage developed in volcanic rocks.

There are still many aspects of cleavage open to research. More work needs to be done in explaining how cleavage develops in situations of rotational finite strain, how volume changes affect the development of cleavage and what are the contributions of mineral rotation and new mineral growth in slates and schists.

Progressive deformation

The state of finite strain is built up by the progressive superposition of incremental strains. These can be superposed coaxially (pure shear), non-coaxially (simple shear or general shear) depending on the stress state that exists at different times throughout the deformation history and the rock rheology at the time of development. Ramberg (1959) and Flinn (1962) were the first to really appreciate the significance of progressive deformation in the sequential development of folds and boudinage and Ramsay (1967) showed how different types of incremental sequences arriving at identical finite strains could develop very different structural sequences in layered materials.

Unfortunately, in most rocks there are no techniques which might be used to determine accurately the different types of progressive strain. However, in certain situations where mineral veins or pressure shadows are developing (usually in anchimetamorphic rocks or green-schist facies), some techniques have been developed to use the geometry of fibrous new crystalline material to determine the changing directions of incremental extension (Durney and Ramsay, 1973; Ramsay and Huber, 1983).

There has been much further study on the implications of progressive deformation on crystal fabrics (Passchier and Trouw, 1996) and in showing how certain geometries are indicative of certain types of rotational incremental strain. This has led to the idea of using certain types of geometry to indicate the sense of shear in rocks. Such shear sense indicators are useful but they have to be used with care because in some circumstances they can give ambiguous results. In particular, in regions of successive superposed deformation phases where there are several differently oriented deformation sequences and it is not always an easy task to separate the different shear sense imprints.

There has also been some theoretical work on different types of deformation sequences building on the notion of vorticity of the deformation (which might be thought of as the relative proportions of pure shear vs. simple shear in the increment sequence or the relations between the incremental distortional strain axes and the rates of rotation of these axes). Most theories have been built on the concepts of two-dimensional strain with a constant vorticity number to each deformation sequence, a concept of steady state increments which I find difficult to accept as a realistic situation in natural deformations. However, the concept of progressive deformation is clearly of great importance in ductile flow of rocks and much more theoretical, experimental and practical work needs to be carried out. In view of the essential three-dimensional nature of most geological deformations, such investigations will be for the future.

Fold geometry and folding mechanics

Folding of layered rocks has always exerted a strong fascination for structural geologists. The first attempts at describing fold geometry were made by Van Hise (1894) who was the first to separate folds in which the layers keep relatively constant orthogonal layer thickness (now usually termed parallel- or concentric-folds) from those showing limb thickness reductions relative to the thickness of layers at the fold hinge (usually known as similar-folds). It should be pointed out that none of these names is really self-evident in a Euclidian geometric sense. At high crustal levels, the fold geometry is usually controlled by the most competent rock layers and in a classic book Busk (1929) developed a geometric analysis based on the condition that all layers keep their orthogonal thickness. The "Busk construction" was much used in the oil industry to extrapolate fold continuity at depth from surface dip measurements. However, it clearly contains many assumptional errors. Any geologist working in rocks from the middle crust is aware that severe limb thinnings are frequent in competent layers while different rock layers show differing geometric forms: there is no unique name to describe the fold geometry of a layer stack. Ramsay (1967) used measurements of orthogonal thickness of successive layers to try and find a classification scheme that was based on geometry, was non-genetic and was of practical application. The scheme was based on layer curvature and curvature differences in two dimensional fold profiles, and the technique of drawing dip isogons through any structure revealed these differences very quickly. Like much geometric study these analyses are essentially two dimensional and, although they are not inappropriate for many fold rock situations they are in no ways of universal application. The future of geometric analysis will have to employ three dimensional analytical methods based on three-dimensional analysis of layer curvature and the Keynote talk by Richard Lisle will show the way how such methods might develop.

All the forgoing analysis is based on geometry. Such ways are an anathema to some who believe that our starting point should be based on the principles of mechanics. I do not subscribe to the view that one is better than the other. Both should be integrated and it is my opinion that much of the mechanical analysis of the past has tended to decry the practical usefulness of the geometric approach. The prime investigators of fold mechanics have been made by Ramberg (1960) and Biot (1961) considering the behaviour of a compressed single layer of competent rock in an infinite matrix of incompetent material, both being linearly viscous materials. Although these analyses are of great geological interest they have their limitations: they were essentially 2D and considered only the initial fold perturbations (assumed to be sinusoidal). In fact, very little has been directly investigated into the truly mechanical development of large finite folds in which the layers become anisotropic (i.e. develop cleavage) or considered realistic 3D models where the layers might be inclined to the overall shortening directions or where the bulk strains are not of plane strain type or where volumetric changes might take place. All of these later conditions are of great practical interest to the structural geologist. I am not suggesting that such a complete mechanical analysis will be easy. The researcher will have to be a top-grade mathematician as well as (hopefully!) a very good field geologist with a great deal of practical experience. For example, the problems that occur in situations of superposed folding (perhaps the predominant feature of middle and lower crustal orogenic deformation) seem an almost insoluble problem at present. Yet the field geologist has to find solutions and these are currently based on careful field observations on well exposed examples. But perhaps, as with most structural geology, this is not a bad way to press forward research.

Conclusions

We need to base all our research on sound field observations, taking many measurements and producing accurate maps. We need to be more aware than has been done in the past that our subject is a three-dimensional one. We need more careful mathematical analysis of kinematics and mechanics and we need to integrate field work more closely with mathematical analysis and with modelling (both physical and computer based) checking out the modelling results with natural situations. Finally, we need to be more aware that a great deal of accurate research has been done by past workers and we should attempt to integrate our own research with past publications. Please, no more papers with references to only the past 10 years of research!

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