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Strain and stress

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Abstract

Structural analyses of specific features in naturally deformed rock consist of geometric observations (e.g. shape), kinematic measurements (e.g. strain), and dynamic models (e.g. stress). Although analytical definitions clearly distinguish strain and stress, common usage of the terms tends to blur the conceptual difference. Strain and stress do not have a simple cause-and-effect relationship. The fundamental difference between strain and stress is that strain terms reflect *descriptive* interpretations of what movements produced a structure, while stress terms reflect *genetic* interpretations of why the structure formed. This descriptive vs genetic distinction has several implications. First, kinematic analysis is less speculative and more directly related to observations than dynamic analysis. Second, kinematic analysis is less computationally and analytically intensive than dynamic analysis. Third, kinematic analysis is amenable to more intuitive, but shallower, understanding than dynamic analysis. The most useful terminology communicates this conceptual framework through clear and accurate use of terms for strain, stress, and related concepts. A variety of examples illustrate the descriptive and genetic usage of strain and stress terminology. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The systematic application of continuum mechanics has transformed structural geology from a qualitative field into a largely quantitative one. This is perhaps clearest in undergraduate texts. Structural geology texts from the first half of the Twentieth Century were mostly devoid of equations (e.g. Willis, 1923: equations only in final chapter on geometric problems and in appendix on shear stress; Nevin, 1931: no equations; Billings, 1942: six equations apart from discussion of geophysical methods), whereas modern treatments tend toward the analytical (e.g. Suppe, 1985; Twiss and Moores, 1992; Davis and Reynolds, 1996; van der Pluijm and Marshak, 1997). The terminology of strain and stress is elemental to continuum mechanics. In its simplest form, strain is defined as the change in length or rate of length change of a line divided by its original length (i.e. we wish to simultaneously consider incremental and finite strains); stress at a point is the force per unit area operating on an infinitesimal surface at that point (e.g. Means, 1990). Alternative definitions exist that require explicit reference to the tensorial character of these parameters. However, our objective in this contribution is conceptual clarity rather than analytical generality, so we prefer to use simple definitions. Although geologists readily agree that strain fundamentally differs from stress, the conceptual distinction is often lost among the equations. Worse still, the usage of strain and stress terminology in the context of observation and interpretation of natural structures frequently fails to communicate a clear conceptual framework. Many specific examples of this problem are discussed in the second half of this article.

The modern conceptualization of structural analysis was initiated early in the Twentieth Century by Bruno Sander (1970), whose ideas were elaborated by Knopf and Ingerson (1938) and by Turner and Weiss (1963), among others. While we do not advocate a return to the limited techniques of that era, the conceptual underpinnings of modern structural analysis can be

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traced to that time. At issue is the analysis of specific natural structures for which only the final state is known, as opposed to general mathematical models or laboratory experiments that focus on processes. In particular, we are concerned with the analysis of field data. Structural analysis of rock (e.g. Turner and Weiss, 1963; Davis, 1984; Twiss and Moores, 1992) comprises geometric analysis (descriptive analysis of Davis, 1984), kinematic analysis, and dynamic analysis (mechanical analysis of Twiss and Moores, 1992). These analyses respond respectively to the questions: What are the structures? What motions/displacements produced the structures? Why did the structures form in the way they did? Geometric analysis is the description of locations, shapes, sizes, and orientations of structures. Kinematic analysis addresses the pattern of motions and/or displacements within material (e.g. translation, rotation, strain) that produce structures, without regard to associated stresses. As pointed out by Jaeger (1962, p. 1) and Ramsay (1967, p. 50), kinematic analysis is essentially a problem in geometry. Dynamic analysis concerns the pattern of forces within material (e.g. stress) and the relationship between strain and stress during the development of structures.

More precise (and correct) classifications of structural analysis have been articulated that distinguish between incremental motions and finite displacements (e.g. van der Pluijm and Marshak, 1997); however, the simpler classification introduced above, in which strain analysis is subsumed under kinematic analysis, is sufficient for the current purposes. It also should be pointed out that the term 'dynamic analysis' has another significantly different meaning. In the contexts of mechanics, dynamic analysis refers to the study of bodies that are not at equilibrium (i.e. the complement of static analysis).

The purpose of this paper is to compare and contrast kinematic and dynamic analyses, especially with regard to the terminology of strain and stress. We argue that, at a conceptual level, the difference between strain and stress does not lie in the form of quantification or in the need for interpretation, nor are strain and stress simply related as effect and cause. Rather, strain terms are fundamentally *descriptive* whereas stress terms are fundamentally *genetic* (as explained in the following section). This distinction has significant implications for their relationships to observations, the manner and uniqueness of problem solution, and their suitability for intuitive understanding. The most useful terminology reflects these differences.

2. Comparison and contrast

Strain and stress share many characteristics. Both are most generally expressed in analytical terms as symmetric second-order tensors associated with three mutually orthogonal principal directions; both can be represented graphically by ellipsoids and Mohr circles; and both may vary in space and through time (e.g. Means, 1976). Strain (or strain rate) and stress are intimately related during deformation by material rheology, as idealized by constitutive equations that depend on material properties and deformation conditions. Neither strain nor stress in rock are fundamentally observable quantities, at least not in the sense that the shape and size of an object is observable. One can observe the final shape of an object and compare it with the assumed original shape, but the change in shape cannot be observed apart from special circumstances such as earthquakes (i.e. both initial and final states are observable). Instead, both strain and stress must ultimately be interpreted from observations by reference to assumptions and calculations. The character of such interpretation, as we discuss in detail below, is quite different for strain and stress.

Strain is conventionally regarded as a consequence of stress, such that stress and strain are associated in a one-way cause-and-effect relationship. However, no logical fallacy results by considering strain to be the cause of stress, such as in a displacement boundary-value problem. This is exemplified by the fact that the following two statements are equally reasonable. First, displacements imposed at the boundaries of a body cause stress within the body. Second, forces applied at the boundaries of a body cause strain within the body. Strain and stress are allied in constitutive equations, which attribute primary importance to neither. This point of view is analogous to that of Edelman (1989). So what *is* the conceptual distinction between strain and stress?

The character of interpretation required for structural analysis of specific natural deformation features (as opposed to generic models of deformation processes) fundamentally distinguishes strain and stress as descriptive and genetic concepts, respectively. This distinction differs from a cause-and-effect relationship, in as much as cause-and-effect refers to one phenomenon unilaterally driving the other in *nature* whereas the distinction between descriptive and genetic concepts lies in how we *think* about the phenomena. Geometric observations constitute the foundation of all structural analysis. Strain, representing the relative motions and/or displacements associated with structure development, can be completely specified in geometric terms without reference to stresses and dynamics. Kinematic analysis consequently interprets geometric observations and appeals to geometric assumptions. For example, brittle fault striae are assumed to mark the relative motion and/or displacement of fault bounded bodies, and an ellipsoidal ooid is assumed to have been spherical before deformation. To the extent that geometric features provide a record of movement, kinematic analysis descriptively interprets the development of structures. By contrast, stress represents the forces at work during structure development, and *cannot* be inferred from rocks without reference to kinematics. This does not mean that a complete kinematic analysis is prerequisite to dynamic analysis, but dynamic analysis of geometric features made without an intervening kinematic analysis must rely (at least implicitly) upon kinematic interpretations of the geometric features. Dynamic analysis consequently interprets kinematic descriptions (from analysis or assumption) by virtue of appeals to rheological and environmental assumptions. For example, brittle fault striae are interpreted kinematically as the slip direction, which in turn is assumed to represent the direction of shear stress resolved on the fault plane at the time of slip. Similarly, a calcite crystal is assumed to twin when shear stress resolved on the twin plane exceeds some threshold. To the extent that kinematic interpretations and rheological assumptions are valid, dynamic analysis genetically explains structures.

In summary, strain and all other kinematic quantities descriptively interpret what movements produced the structures; stress and all related dynamic quantities genetically interpret why the structures formed. These conclusions conform to the thinking of Sander (1970, p. 12): "... conscious separation of the pure kinematic description [from forces establishes]... the best possible foundation for the genetic dynamic consideration of [structure]...." This is perhaps clearest in instances of non-constant deformation histories. Varying incremental strains superposed through time produce a physically meaningful finite strain. Without knowledge of the progressive strain increments, a finite strain measurement does not provide a complete portrayal of deformation but the finite strain is nonetheless valid, reliable, and useful. The same cannot be said for any stress determined from this finite strain in the absence of an understanding of the strain increments, because stresses do not superpose in time, only in space. Because descriptive interpretation of kinematics (if not of strain then of individual geometric features) is prerequisite to genetic interpretation of dynamics, we prefer to write strain before stress when alluding to the pair.

The distinction between the descriptive interpretations of kinematics and the genetic interpretations of dynamics holds a variety of ramifications. The genetic understanding of structure provided by dynamic analysis is deeper than the descriptive understanding that results from kinematic analysis, but this deeper understanding comes at a price. The assumptions of kinematic analysis of specific natural structures are fewer and more testable than those of dynamic analysis. The results of kinematic analysis are therefore less speculative and more directly related to observations than are those from dynamic analysis. Kinematic problems about specific natural structures (e.g. based on field data), as opposed to generic questions of deformation processes, are typically solved as forward problems (e.g. strain measurement). However, analogous dynamic questions must be posed as inverse problems (e.g. stress inversion) unless highly restrictive assumptions are made (e.g. coaxial strain and stress). As a consequence, kinematic analysis of a specific natural structure is less computationally and analytically intensive than dynamic analysis. Indeed, graphical methods often are sufficient (e.g. Wojtal, 1989; Marrett and Allmendinger, 1990). Additionally, kinematic solutions to problems are typically unique (e.g. slip in a particular direction on a fault produces a unique infinitesimal strain) whereas dynamic solutions are usually non-unique (e.g. many different stress states can cause a fault to slip in a particular direction). This difference in uniqueness makes kinematic analysis more amenable to intuitive insight and understanding than is commonly the case for dynamic analysis.

3. Terminology

Confusion in the terminology, and possibly the philosophy, of dividing strains and stresses is widespread. For example, *extension* is a strain term (e.g. Ramsay, 1967, p. 52) and *compression* is a stress term (e.g. Ramsay, 1967, p. 23), yet it is common for 'extensional' and 'compressional' to be used as opposites in signifying tectonic settings and structures. This might appear to be a meaningless subtlety or a careless error. Careless terminology is, however, dangerously close to confused thought.

One aim of this paper is to emphasize that strain terms connote kinematics (in the general sense of 'kinematic analysis'), and are most useful for description and classification of structures. Stress terms connote dynamics, and are most useful for: (a) mechanical modeling (mathematical or physical) of structures, where stress is an explicitly controlled variable; or (b) genetic interpretation of structures, where the forces and material response during deformation are of primary interest. Below we address the use and misuse of a variety of structural terms and highlight their descriptive and genetic implications.

3.1. Extension and contraction, tension and compression

Extension and *contraction* signify the strains that occur in most materials along the loading direction under the stress states of uniaxial *tension* and *compression*, respectively. An example of the usage of this terminology is given by Ramsay and Huber (1987,

p. 668), who "connect positive tensile stresses with positive strain elongations and negative compressional stresses with negative contractional elongations". Another term for contraction is *shortening* (e.g. Ramsay and Huber, 1983, p. 8).

Although structural geologists acknowledge the difference between strain and stress, it is very common to see strain terms applied to stresses and vice versa. Some recent examples of 'extensional' and 'compressional' being used as opposites include:

1. deformation or tectonic phases (Applegate and Hodges, 1995; Reiter, 1995; Vigneresse, 1995; Zelt and White, 1995; Cohen and McClay, 1996; Martin and Mercier, 1996);
2. tectonic regimes (Celerier, 1995);
3. deformation styles (Richardson and Coblentz, 1994);
4. shear (Demoulin et al., 1995) or loading (Jeyakumaran and Keer, 1994);
5. faulting (Sibson, 1993; Kargen and Pozio, 1996) and fault motion (Carey-Gailhardis and Mercier, 1992);
6. fault oversteps and bends (Biddle and Christie-Blick, 1985);
7. wedges (Xiao et al., 1991);
8. folds (Mitra, 1993); and
9. structures in general (McBride et al., 1995; Robinson et al., 1996).

The strain term 'extensional' has been used for stresses by Yeh et al. (1991), Decker et al. (1993), Lacombe et al. (1993) and by Borgia (1994), and for force by Zoback (1992). The stress term 'compressional' has been applied to faults and fault bends by Wolfe et al. (1993), Mitra and Islam (1994) and by Johnston and Phillips (1995), to folds by Stewart and Coward (1995) and generally to structures by Kline (1994). Similarly, the name *pressure solution cleavage* is a stress term commonly used to describe a structure.

Other examples are the so-called *P*- and *T*-axes ('pressure' and 'tension'; e.g. Kasahara, 1981, p. 39) of fault-plane solutions, which are simple descriptions of fault-slip kinematics but are at best indirectly related to stress states. The *P*- and *T*-axes are not stress axes, but rather are the principal axes of the incremental strain tensor for fault movement (e.g. McKenzie, 1969; Marrett and Allmendinger, 1990). Paleostress (dynamic) analyses of fault-slip data (e.g. Angelier, 1984) are feasible but have a variety of limitations; Wojtal (1989) and Marrett and Allmendinger (1990) describe some simpler kinematic alternatives.

This confusion in the use of strain and stress terms not only involves the terminology but suggests confusion in what is being addressed. Are the structures or the inferred stresses being characterized? It is preferable to use strain terms to describe and classify geological structures, as strains are more directly measurable than stresses. Tectonic events should not, therefore, be described as 'compressional' if what is being measured is a *contractional strain* in the horizontal plane. Stress terms are inappropriate for field descriptions, and should only be used for: (a) genetic interpretation of natural structures, (b) mechanical analysis in mathematical models, or (c) mechanical analysis of laboratory experiments. Furthermore, the procedure used for the analysis (i.e. techniques, assumptions, relation between kinematics and dynamics) needs to be provided.

3.2. Stress from petrofabrics

The orientations and magnitudes of stresses can, under certain circumstances, be determined from dislocation density, sub-grain diameter and dynamically recrystallized grain size. A good overview of these *piezometric* methods is given by Passchier and Trouw (1996). To take one example, calcite twin lamellae can be used to directly determine stress magnitudes, the assumptions being made that stress was homogeneous at the grain scale and the deforming material was isotropic. Passchier and Trouw indicate, however, that because lamellae represent a deformation, the quantity measured is really a strain (i.e. technique of Groshong, 1972). This view was echoed by Burkhard (1993), although most previous work (e.g. Jamison and Spang, 1976; Laurent et al., 1990) was aimed at paleostress determination. The assumptions of paleostress analysis can be violated in any number of common ways (Burkhard, 1993). In addition, the piezometric methods are still not very precise, with calibration for temperature dependence and grain size being inadequate (Burkhard, 1993).

3.3. Special problems with tension

The stress term *tension* is often used synonymously with the strain terms *extension* or *dilation*. For example, the term 'tension gash' is often used to describe veins (e.g. Lacombe et al., 1993), while normal faults are often discussed as forming 'in tension'. These structures, however, usually form under compression in all but the uppermost few hundred meters of the crust (Rubin, 1993). Current dynamic interpretations of most veins and dikes hold that the structures are usually opened by fluid pressures exceeding the least compressive stress (Rubin, 1993), commonly under *effective* tension. Most extensional structures, such as veins, form in *effective* tension, not true tension (e.g. Gross and Engelder, 1995). The term *effective tension fracture* would be a more appropriate but unwieldy genetic term than *tension fracture*. Because veins and dikes can be more directly related to their deformational effect, it is simpler to call them *extension fractures*. It seems unnecessary, and potentially misleading, to refer to a vein as a 'tension fracture' (e.g. McGrath and Davison, 1995) when the structure is simply a vein.

3.4. Fracture propagation

The terminology of fracture propagation modes (modes I, II and III) concerns the propagating tip of a fracture (Pollard and Segall, 1987), and does not refer to the geometry of the resultant fracture. For example, veins are referred to as 'mode I fractures' by McGrath and Davison (1995), although the veins are merely inferred to have propagated under mode I conditions. Indeed, the genesis of fractures is quite complex and not necessarily obvious from their final geometries. Experiments suggest that faults ('mode II/III cracks') propagate, at least at the microscopic scale, through the development and coalescence of extension fractures ('mode I cracks') (Scholz, 1990, p. 26). It seems unnecessarily complicated to describe and classify fractures in terms of the tip propagation mode (i.e. genesis) when the propagation mode is interpreted from the final geometry of the fracture. Fracture mode terminology is only appropriate when fracture propagation and rock mechanics are addressed. The terminology should not be used as a geometric description or for field classification.

3.5. Transtension and transpression

The terms *transtension* and *transpression*, as defined by Harland (1971) and by Sanderson and Marchini (1984), are misnomers because the words refer to stress but are defined by states of strain. The terms are often used vaguely to describe strains or structures formed under transpressional or transtensional stress conditions (e.g. Jones and Tanner, 1995; Krantz, 1995; Peacock and Sanderson, 1995; Stanley et al., 1996). Strain terms that could be used to describe structures formed under transpressional stress include *oblique contraction*, *convergent transcurrence*, or *prolate transcurrence*. Strain terms that could be used to describe structures formed under transtensional stress include *oblique extension*, *divergent transcurrence*, or *oblate transcurrence*. As with any description of strain, it is important to state the orientations of the strain: e.g. to what is the deformation oblique, and in what plane is the deformation described?

4. Conclusions

Strain and stress are fundamentally different quantities, which do not share a simple cause-and-effect relationship. Strain is a change in length per unit original length, while stress is a force per unit area. Strain terms are closely related to observations and consequently are most appropriate to *describe* the *movements* associated with natural structural development, while stress terms are best suited to *inferences* about the *genesis* of natural structures. Strain (kinematic) analyses have the following advantages over stress (dynamic) analyses: (a) they are more directly related to observed structures; (b) they are less computationally and analytically intensive; and (c) they are more intuitive (but shallower). Stress (dynamic) analyses should only be used when inferences are being made about the genesis of natural structures, when mathematical models of mechanics are considered, or when forces are effectively measurable, as in laboratory experiments.

Inappropriate use of strain and stress terminology is widespread, belying poor conceptual understanding of the relationship between kinematics and dynamics. For example, whereas 'extensional tectonics' and 'compressional tectonics' are both meaningful phrases, they are not the opposites implied by an abundant literature. The use of *tension* to describe such structures as veins, dikes and normal faults should be particularly avoided because these structures almost always form in a compressional state of *effective* tension. Use of fracture propagation mode terminology is also inappropriate for the field description and classification of structures, as it adds an unnecessary level of complexity and mixes description with genetic interpretation. *Transtension* and *transpression* are stress terms, so it is confusing to use them to describe structures. Strain terms such as *oblique extension/contraction* or *oblate/prolate transcurrence* would be better for description because they refer to measurable aspects of movement.

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