PERGAMON

Journal of Structural Geology 22 (2000) 1359–1367

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Strain and stress: Discussion

David D. Pollard

Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA

Received 26 January 2000; accepted 25 April 2000

The three sections of the paper by Marrett and Peacock consider, respectively, the historical development of structural analysis, the conceptual role of strain and stress in the mechanical analysis of structures, and the use of these (and related terms) in the literature of structural geology (Marrett and Peacock, 1999). In keeping with the spirit of the 20th Anniversary Special Issue as described in the Preface (Evans and Treagus, 1999), Marrett and Peacock have presented both factual information and opinions about these topics. Some of these opinions are challenged in this discussion, which also seeks to correct a few misleading statements and to advocate a research methodology that integrates geometry, kinematics, and dynamics.

1. History revisted

Marrett and Peacock assert that "the modern conceptualization of structural analysis was initiated early in the Twentieth Century by Sander (1970), whose ideas were later elaborated by Knopf and Ingerson (1938) and by Turner and Weiss (1963)" ... and that "the conceptual underpinnings of modern structural analysis can be traced to that time". Not only do these statements inflate the importance of the contributions made by Sander and his followers (Knopf and Ingerson, 1938; Sander, 1948, 1950, 1970; Turner and Weiss, 1963), they fail to acknowledge the contributions made by others who played seminal roles in the initiation and development of modern structural analysis. While the intentions of Marrett and Peacock clearly were not to write a history of structural analysis, their limited summary of this history is biased to favor the points of view they espouse later in the article.

An informative historical account up to 1963 of the concepts and methods attributed to the Sander school is found in the book by Turner and Weiss (1963) (see especially pages 3–11). There one reads:

> "Sander and his followers have demonstrated that a high degree of geometric order commonly pervades a body of deformed rock. This order has found expression in the concept of a tectonite fabric. More particularly the orientation patterns of the individual elements, whether macroscopic or microscopic, tend to conform to a common symmetry. Sander's emphasis on symmetry as the fundamental property of a naturally deformed rock is perhaps his most original and significant contribution to structural geology. His interpretation of rock structure—necessarily a speculative field—is based on the assumption that the symmetry of the structure is influenced by the respective symmetries of structural anisotropy in the parent rock and of the forces, stresses, and internal movements involved in deformation." (Turner and Weiss 1963, p. 4)

There can be no argument that the demonstration of geometric order in bodies of deformed rock, especially metamorphic rocks that have experienced multiple phases of deformation, was a significant achievement for the disciplines of structural geology and tectonics. Furthermore, a variety of techniques (e.g. stereographic projections, down-plunge views, etc.), developed during this time to enhance field descriptions and laboratory studies of such rocks, occupy important places in the toolkits of modern structural geologists. However, invocations that symmetry is the fundamental property of naturally deformed rock are rarely heard today, and symmetry principles have not proven to be effective means to interpret forces, stresses, and movements during deformation.

PII: S0191-8141(00)00048-1

1.1. The microscopic scale

This is not an appropriate forum to review structural analysis in the Twentieth Century in order to demonstrate the demise of the Sander symmetry method, and indeed others have done this quite effectively with respect to deformation textures in rock at the microscopic scale. For example, Wenk and Christie point out that:

> "fabric analysis blossomed under the direction of Bruno Sander in Innsbruck and Walter Schmidt in Berlin (Sander, 1911, 1923, 1930; Schmidt, 1912, 1932). These two scientists made the first serious attempts to interpret the development of crystallographic preferred orientation in deformed rocks, but each approached the problem with an entirely different philosophy. ... Sander ... maintained that an empirical-comparative approach was necessary because of the enormous complexities which preclude an analytical solution. Schmidt, on the other hand ... insisted that any interpretation needs to be based on physical principals." (Wenk and Christie, 1991)

Wenk and Christie offer the opinion that Schmidt's approach should prevail because deformation is governed by physical processes, but lament the fact that geologists have taken so long to accept the contributions of the material scientists and physicists whose methodology was consistent with that of Schmidt. On the other hand, Sander chose to ignore developments in polycrystalline plasticity (Taylor, 1938), and the concept of the dislocation (Orowan, 1934; Taylor, 1934), which have proven to be powerful tools to understand the physical basis for deformation textures. After a thorough review of the state of fabric analysis to 1991, Wenk and Christie emphasize that "future work on texture development of rocks should be based on rigorous physics rather than ingenious intuition, in accordance with an old recommendation of Walter Schmidt" (Wenk and Christie, 1991).

The past decade has witnessed considerable research activity that seems to heed that recommendation. Of the more than 20 sessions on structural geology and tectonics at the Geological Society of America 1999 Annual Meeting, one focused on "Deformation Mechanisms, Fabrics, and Strain". In the keynote address for that session, Tullis provided a current perspective on the three regimes of dislocation creep in experimentally deformed quartz aggregates and the distinctive microstructures associated with each regime (Tullis et al., 1999). Within the session of 15 abstracts, only one makes a direct reference to symmetry, in that case the triclinic symmetry of a shear zone. Instead, research on the use of crystalline fabrics in naturally deformed rocks to quantify and understand the kinematics and dynamics of deformation have largely turned, for example, to the thermodynamics and diffusion of lattice vacancies, the mechanics of dislocation motion, and the energy of grain boundary migration and sliding (Hobbs et al., 1976, ch. 2; Poirier, 1985). The notion of a symmetry principle is not even mentioned in a recent book on the microstructures and fabrics of rock (Passchier and Trouw, 1996).

In a paper also published in the 20th Anniversary Special Issue, Jiang and Williams point out how research on flow fabrics has evolved since the work of Sander, and address the consequences of non-steady deformation (Jiang and Williams, 1999). While perhaps providing a more sympathetic interpretation of Sander's contributions, these authors concur with Wenk and Christie with regard to an approach based on a rigorous physics:

> "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." (Jiang and Williams, 1999)

1.2. The mesoscopic and macroscopic scales

Although Sander developed his procedure to investigate microscopic fabrics, he later expanded its application to mesoscopic and macroscopic structures, particularly to folds and systems of folds (Turner and Weiss, 1963, p. 529). Because mesoscopic and macroscopic structures have been the focus of this author's research as well as that of Marrett and Peacock, and because others have addressed microscopic fabrics, the remainder of this Discussion will dwell on structural analysis at these larger scales.

In a postscript to their 1963 book on metamorphic tectonites Turner and Weiss make a rather sweeping prediction regarding the future of Sander's contributions.

> "But in spite of inevitable extension, modification, and revision of the kind just envisaged, the basic foundation of structural analysis can be expected to survive—just as it has in the decades immediately past—the test of future observation and experiment. In particular we emphasize three facets of this foundation, all initiated and developed by Sander: The material appropriate for structural analysis will continue to be defined and limited by the subtle concept of the statistically homogeneous tectonite fabric. Interpretation of tectonites to the fullest possible degree will still be framed in terms of the movement

> picture. And the prime criterion by means of which a tectonite fabric can be correlated with movement, strain, or stress will continue to be its symmetry." (Turner and Weiss, 1963, p. 530)

A brief evaluation of these "facets" in the light of research progress in structural geology during the second half of the Twentieth Century helps one to understand why they have not stood the test of time.

The limited view of a deformed rock mass as separable into regions of statistically homogeneous fabric is necessitated by the inability of Sander's method to deal with spatial variations in any of the relevant physical quantities. Thus, the only choice for Sander was to focus on deformation at a point, or of a small enough volume such that the deformation is homogeneous within tolerable errors. This predicament followed, in general, from the absence of calculus in Sander's method and, in particular, from the absence of partial differential equations that define physically possible spatial variations in displacement or velocity. Interestingly, such equations were available for application in Sander's day. For example, the equations of compatibility of Saint-Venant (Fung, 1969, pp. 121–125) place explicit constraints on how the infinitesimal strain components can vary from point to point across a region of small, non-homogeneous strains. For finite strains the equations are more complex, but they have been defined (Green and Zerna, 1954). An analogous set of partial differential equations, referred to as the conditions of integrability, constrain the spatial variations of the rate of deformation from point to point across a region of non-homogeneous flow (Fung, 1969, pp. 121–125).

There is no necessity to limit one's view to a region of statistically homogeneous fabric or deformation. On the other hand, this does not mean that the study or investigation of such a region is without merit. Indeed, most students are introduced to physical quantities such as strain and stress by considering their definitions in terms of cubical elements across which these quantities are uniformly distributed (Means, 1976, 1990). Furthermore, a variety of useful methods have been introduced to characterize and quantify homogeneous finite strain in deformed rock masses (Ramsay, 1967). On the other hand, the concept of heterogeneous strains in structures such as shear zones has been introduced in modern textbooks in structural geology (Ramsay and Huber, 1983, pp. 33–54), and a variety of tools to investigate heterogeneous deformation have been available in the introductory textbooks of continuum mechanics for several decades (Bird et al., 1960; Fung, 1969; Timoshenko and Goodier, 1970; White, 1974). The limitation imposed by Sander's viewpoint is unnecessary and counterproductive.

Instead of adopting the basic kinematic vector quantities of displacement and velocity, and then using the well-known kinematic equations to relate partial derivatives of these quantities to one or the other measures of strain or deformation rate (Fung, 1969; Means, 1976), Sander conceived the 'movement picture', a vague and qualitative concept that apparently encompasses the translations, rotations, and relative motions of formal kinematics, but fails to provide the relationships among these quantities necessary to treat them quantitatively. Sander's method attempts to replace the differential equations of kinematics with symmetry principles. Thus, according to Turner and Weiss, kinematic analysis can proceed in one of two ways: use symmetry principles to infer the strain state for a region of statistically homogeneous fabric; or compare the observed final state with an assumed initial state to calculate the strain (Turner and Weiss, 1963, p. 9). The second method is disparaged by these authors because so few geological materials (e.g. well-known fossil species) provide an unambiguous initial state. That may be true, but from the perspective of nearly 40 years of research in structural geology, the second method has attracted many adherents and produced numerous successful case studies (Ramsay and Huber, 1987). In contrast, deducing strain or stress from symmetry principles and the 'movement picture' has attracted few adherents and produced few convincing case studies in this same period of time.

If the Sander school followed an unproductive path, to whom might one attribute the modern conceptualization of structural analysis? Again, this is not the forum for an inclusive historical review, but a few names come immediately to mind. Certainly that "great engine of research" G.K. Gilbert (Pyne, 1980) would be on the list along with E.M. Anderson (Anderson, 1951), and M.K. Hubbert (Hubbert, 1972). These structural geologists understood the advantages of integrating careful field observations with the fundamental constraints of continuum mechanical principles. Others would be D.T. Griggs (Griggs and Handin, 1960), J. Handin (Handin and Hager, 1957, 1958), and H. Ramberg (Ramberg, 1967) who championed the role of laboratory experimentation, both to measure the material properties of rock and to investigate scaled models of tectonic processes. In short, these researchers avoided the trap of focusing too narrowly on the geometry, kinematics, and symmetry of structures at the expense of the inclusive physical principles.

In his classic report on the Henry Mountains, G.K. Gilbert set the example by showing how theoretical constructs should be used to guide field investigations (Gilbert, 1877). He formulated the conceptual model for laccoliths in the first few days of field work and then constructed a simple mechanical model based on static equilibrium conditions. The solution to this theoretical problem in mechanics indicated that the diameter of the model laccolith should vary linearly with overburden thickness. From this result Gilbert posed the hypothesis that the size of laccoliths should correlate with stratigraphic position, and he set out to test this hypothesis by measuring the stratigraphic section, identifying the position of laccoliths in this section, and measuring the diameters of the exposed laccoliths in the Henry Mountains.

Both the interplay of field observations and theoretical constructs, and the reliance on physical principles that can be traced to Newton's Laws of Motion (Newton, 1687), were abundantly evident in the sessions on structural geology and tectonics at the Geological Society of America 1999 Annual Meeting. In contrast, for example, in the three sessions focusing on folding, there were few if any references to symmetry principles, nor are such principles mentioned in a recent book on folding (Johnson and Fletcher, 1994). Apparently, this "most original and significant contribution to structural geology" has all but dropped from sight. On the other hand, the methodology demonstrated by Gilbert, has stood the test of time, and the same goes without saying for the physical principles of newtonian mechanics. These methods and principles should at least be mentioned when referring in a historical context, as Marrett and Peacock do, to the "conceptual underpinnings of modern structural analysis".

1.3. Turning newtonian mechanics upside-down?

Marrett and Peacock would have us believe that the one-way cause and effect relationship between stress and strain does not exist, and indeed "no logical fallacy results by considering strain to be the cause of stress, such as in a displacement boundary-value problem" (Marrett and Peacock, 1999). There is no doubt that the mathematical equations expressing constitutive relationships among the components of stress and strain can be rearranged to place either the stress components or the strain components alone on the left-hand side, where one would think of them as the dependent variables. Similarly, it is possible, for example, to use either tractions or displacements as boundary conditions for problems in elasticity theory. However, the possibility of these mathematical manipulations is not a good reason to abandon the physical concepts embodied in Newton's Laws of Motion.

Newton's own position is clearly stated in a recent English translation, where one reads the first and second laws as follows:

> "Every body preserves in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed.
>
> A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed." (Newton, 1687, p. 416)

Forces cause accelerations in particle dynamics. Stresses, being the manifestation of forces within a material body, cause deformation in solids and flow in liquids in continuum mechanical systems (Bird et al., 1960; Fung, 1969; Timoshenko and Goodier, 1970; White, 1974). In their book on rock mechanics, Jaeger and Cook state it this way:

> "The fundamental concept of continuum mechanics is that of the displacement of all particles of the material. The initial position x,y,z, of every one of these is supposed to be known, and the forces applied to the system cause it to be displaced to a final position." (Jaeger and Cook, 1979, p. 33)

2. Purity versus completeness

As reiterated by Marrett and Peacock, a "complete structural analysis of a body of deformed rock thus falls into three phases—geometric, kinematic, and dynamic" (Turner and Weiss, 1963, pp. 8–10; Marrett and Peacock, 1999). Sander advocated a clean separation between the geometric/kinematic phases and the dynamic phase.

> "The kinematic description and study of fabrics brings out the purely geometrical aspect of state and events, and is concerned with their typification. This is done in theory without reference to the forces which cause the movements in the physical sense, and without going into the dynamics. Such conscious separation of the pure kinematic description and its nomenclature from the discussion and representation of engendering forces will be maintained as far as is practicable in fabric studies, and has established itself as a basic principle." (Sander, 1970, p. 12)

Sander's point of view is further emphasized by Turner and Weiss who caution that "it is generally somewhat hazardous to attempt reconstructions of forces and stresses" and "dynamic analysis of rock structure remains correspondingly controversial and speculative."

Turner and Weiss suggest that their reticence for dynamic analysis is based on the lack of data on the rheological properties of rock (Turner and Weiss, 1963, p. 8). While this was a valid concern in 1963, it did not dissuade others working at this same time (e.g. Ramberg, 1967; Hubbert, 1972) from using elementary constitutive laws, such as linear elastic or linear viscous, to model particular structures approximately, in order to gain physical insight. Furthermore, the past four decades have witnessed numerous laboratory studies that provide data on constitutive properties of rock under a wide variety of conditions (Paterson, 1978; Hobbs and Heard, 1986; Atkinson and Meredith, 1987; Duba et al., 1990). While the abundance and precision of rheological data certainly could be improved, the scarcity and imprecision of these data are not credible excuses for avoiding dynamic analysis.

Marrett and Peacock take a stand on separating the three phases of structural analysis based not on the lack of rheological property data, but rather on the philosophical distinction that geometric analysis is 'descriptive' whereas dynamic analysis is 'genetic'. Apparently this distinction also can be traced to Sander:

> "Gefügekunde der Gesteine (structural analysis) involves two philosophically distinct procedures. First is the study and description of a rock body in its present state—a study as free as possible from inference and extrapolation, except to the extent imposed by limitations of poor exposure in the field. Then comes genetic interpretation of the descriptive data, an attempt to reconstruct the structural evolution of the body in question" (Turner and Weiss, 1963, p. 7).

Marrett and Peacock position kinematic analysis somewhere between geometric and dynamic analysis in this philosophical spectrum by characterizing it as 'descriptive interpretation', whereas dynamic analysis is 'genetic interpretation'. One could dismiss this as harmless word play, but the adherents of this philosophy attach value to these distinctions and use them to advocate a particular research methodology—one that asserts that: "Geometric observations constitute the foundation of all structural analysis." (Marrett and Peacock, 1999).

An alternative, suggested here, is that the conservation laws of mass, momentum and energy, along with their elaborations into the governing equations of continuum mechanics, constitute the foundation of structural and tectonic analysis (Johnson, 1970; Hubbert, 1972; Turcotte and Schubert, 1982). With these quantitative physical relationships taken as fundamental, geometric observations are put in their proper perspective as data, some of which may be useful in the testing of refutable hypotheses concerning the evolution of structures (Popper, 1968).

2.1. Pure geometric analysis

What are the possible outcomes of a 'purely geometric' study? It would result in photographic-like descriptions of outcrops and the prescriptive recording of geometric data. In some cases this purity has been justified by asserting that it provides the best way to collect unbiased data in the field. Being free of questions or models or hypotheses concerning the origin of a structure, is seen as a prerequisite for observing structures in outcrop and for recording geometric data equitably. For some adherents of this philosophy, 'descriptive' is a code word for 'objective' and 'genetic' is a code word for 'prejudicial'. However, in the opinion of this author, entertaining physically based hypotheses with genetic implications, and even letting these guide field work, does not necessarily jeopardize the impartial collection of data.

Often overlooked by those who advocate a descriptive approach to field work, is the fact that the only meaningful hypotheses that logically follow from purely descriptive geometric studies are statements about the geometry itself. For example, from the suggestion of a girdle pattern of poles to bedding on a stereonet, one could hypothesize that the fold under investigation is, within some tolerable error, a cylindrical fold (Turner and Weiss, 1963, pp. 154–185). A test of this hypothesis would involve gathering additional strikes and dips until the data meet, or do not meet, some criterion of statistical significance for approximating a great circle. Such exercises have a place in structural analysis, but their role is properly valued as technical rather than as fundamental.

Although the logical outcomes of purely geometric studies are limited to the refinement of our knowledge about the geometry of structures, such studies have proven to be informative and useful. They have helped to establish a set of techniques for the systematic gathering of geometric data in the field (Ragan, 1973; Marshak and Mitra, 1988); they have provided supporting data bases for the taxonomic classifications of structures (Dennis, 1987); and they have played a central role in the elucidation of the hidden architecture of structures holding mineral and petroleum resources (McKinstry, 1948; Billings, 1972; Sheriff and Geldart, 1995).

As examples of descriptive field work that lacked the guiding hand of physically based hypotheses, Pollard and Aydin cite certain studies of joints during the middle part of the Twentieth Century (Pollard and Aydin, 1988). The structural geologists engaged in this activity measured thousands of joint orientations and plotted these data on stereonets and rose diagrams, thereby limiting their focus to relationships of orientation. In the opinion of Pollard and Aydin these data alone are of little value because they ignore, among other things, the spatial relations among the joints, the textures of the joint surfaces, the spatial distribution of aperture along these surfaces, and the displacement discontinuity near the joint tiplines. Measuring these additional geometric features in the field is motivated by physically based hypotheses with clear genetic implications that relate these measurements to the tectonic events responsible for the joints.

In summary, maintaining geometric purity unnecessarily isolates the field geologist from the other facets of structural analysis (kinematics and dynamics), and from the physically based hypotheses that provide a rationale, beyond description and taxonomy, for collecting data. Neither a meaningful interpretation of the geologic history of a region, nor an understanding of the tectonic processes that produced the structures are possible with such a narrowly prescribed methodology for field work.

2.2. Comparing kinematic and dynamic analyses

Marrett and Peacock compare kinematic and dynamic analyses and conclude that: kinematic analyses require fewer and more testable assumptions, and therefore are less speculative; kinematic calculations typically are posed as forward problems, whereas dynamic calculations must be posed as inverse problems, so kinematic analyses are less computationally intensive; and kinematic solutions typically are unique, whereas dynamic solutions usually are non-unique (Marrett and Peacock, 1999). Perhaps this one-sided comparison can be defended if one takes a very narrow view of kinematic and dynamic analyses. With a broader view, one that fairly represents (in this author's opinion) modern research activity in these two facets of structural analysis, each of these comparisons can be shown to be false for particular cases.

Kinematic and dynamic analyses come in several different forms in the literature of structural geology and tectonics. For example, some structural geologists have devoted considerable attention to a form of kinematic analysis that focuses on the analysis of strain in regions, as Sander prescribed, of statistically homogeneous deformation (Ramsay, 1967; Means, 1976). The technique utilizes samples that preserve fossils (or other components of the deformed rock) with known initial shapes and the same constitutive properties as the host rock (Ramsay and Huber, 1983). Strain is calculated from a geometric comparison of the initial and final states, and this strain is assigned to the surrounding rock mass. While eminently satisfying because the technique admits a direct calculation of strain from geometry, the scarcity of suitable strain markers means that this form of kinematic analysis has limited applications.

A second form of kinematic analysis postulates relationships between particular structures, for example faults, and a homogeneous strain field for the region containing those faults (Molnar, 1983; Marrett and Allmendinger, 1990, 1991). Given enough different fault sets, and a penetrative spatial distribution of the faults in all sets, measurements of fault attitude and slickenline rake can be used to calculate a homogeneous strain field. An alternative method for analyzing fault slip data seeks to calculate a homogeneous stress field (Michael, 1984; Reches, 1987; Angelier, 1989), and is referred to as a 'dynamic analysis' (Marrett and Allmendinger, 1990). It is in this context that Marrett and Peacock make the comparisons that favor kinematic over dynamic analyses. In both the first and second forms of kinematic analysis heterogeneous strain is addressed piecemeal, with no explicit connections among homogeneous domains.

A third form of kinematic analysis is not limited to regions of homogeneous deformation, but utilizes models that produce spatially varying strain or rate of deformation fields subject to certain kinematic constraints, such as no area change in two dimensions. Kinematic models of this kind include those for fault-bend and fault propagation folding (Suppe, 1983; Suppe and Medwedeff, 1990) and the trishear model for fault-propagation folding (Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998). This form of kinematic modeling has been applied to tectonic reconstruction (Woodward et al., 1989), petroleum exploration (Mount et al., 1989), earthquake hazards mitigation (Shaw and Suppe, 1996), and the comparative studies of computer-based and analogue laboratory models (Hardy and McClay, 1999).

A form of dynamic analysis that is not limited to homogeneous deformation is based on the boundary and initial value problems of continuum mechanics (Fletcher and Pollard, 1999). The recent literature of structural geology contains numerous examples for the deformation associated with fault slip (Bürgmann et al., 1994; Willemse et al., 1996; Strayer and Huddleston, 1997; Smart et al., 1999)—the same geological problem used by Marrett and Peacock to question the efficacy of dynamic analysis. One could argue that more assumptions are required for these dynamic analyses, because an explicit constitutive behavior must be chosen, but purely kinematic models usually include the implicit assumption of incompressible behavior. Since laboratory testing (Jaeger and Cook, 1979) has demonstrated that rock under upper crustal conditions is compressible, one has to wonder how Marrett and Peacock can conclude that purely kinematic analyses of incompressible materials are less speculative. Furthermore, this form of dynamic analysis for fault slip can be posed either as forward problems (Maerten et al., 1999) or inverse problems (Harris and Segall, 1987; Matthews and Segall, 1993). Finally, the uniqueness of solutions, for example to the linear elastic boundary value problem, has been proven analytically (Timoshenko and Goodier, 1970, pp. 269–271).

3. Terminology related to fracture propagation

Marrett and Peacock take issue with the terminology of fracture modes (mode I, II, and III) when used as a geometric description or field classification (Marrett and Peacock, 1999). This is ironic since the modes may be distinguished on the basis of the displacement discontinuity measured between the two surfaces of a fracture in the near-tip region (Lawn and Wilshaw, 1975, pp. 51–56). Thus, the mode is directly related to a purely geometric feature of natural fractures and requires no genetic interpretation. In this sense the mode is eminently suitable for the taxonomic classification and description of fractures in the field.

On the other hand, one could choose to defend the point of view that the measured mode prevailed as the fracture ceased propagating and became the static entity now observed in outcrop. In this case, by identifying the mode, one opens the possibility for understanding the genesis of the fracture and thereby determining its proper role in the tectonic history of the rock mass. The mode provides a direct and quantitative link between a geometric feature measured in the field and the kinematics of fracture. Furthermore, since each mode is related to a unique stress field in the near-tip region, a sound link to a dynamic investigation is assured.

In a related matter, Marrett and Peacock point out that veins and dikes are usually opened by fluid pressure that exceeds the least compressive stress, and suggest that these fractures form in effective tension, not true tension (Marrett and Peacock, 1999). Effective stress is a concept introduced by Karl Terzaghi for a fluid saturated porous material (Terzaghi, 1943). The fact that a vein or dike once contained a fluid is not a sufficient reason to invoke effective stresses. Was the surrounding rock mass saturated with this fluid? Certainly not in the case of a dike; perhaps not in the case of a vein.

The reason for characterizing veins and dikes using the displacement discontinuity, rather than strain or stress terms, is precisely because one cannot know from the geometry whether the remote normal stress acting perpendicular to the fracture was tensile or compressive. Furthermore, one cannot know from the geometry if the average deformation across the structure was an extension or a contraction. For example, internal fluid pressure in excess of the least compressive stress would cause a contraction in the adjacent host rock as the fracture opened. Marrett and Peacock argue for the kinematic term ‘extension fracture’ rather than the genetic term ‘effective tension fracture’ (Marrett and Peacock, 1999), but neither can be deduced from field observations (Pollard and Aydin, 1988). What one can measure directly in the field are the components of the displacement discontinuity vector, and these vectors are directly related to the fracture modes.

4. Conclusions

Stress and strain are physical quantities with distinct and important roles in structural analysis. Marrett and Peacock’s evaluation of these roles is divisive in that it favors ‘descriptive strain’ at the expense of ‘genetic stress’. A balanced view, expressed here, is that both quantities should be included in a complete analysis, one that explicitly links the two quantities through constitutive relationships. Marrett and Peacock’s philosophical argument limiting field methods to descriptive geometric and kinematic techniques would isolate structural geologists from the concepts, principles, and tools necessary to formulate meaningful and refutable hypotheses about geological history and tectonic processes. Such isolation is not necessary in order to collect field data with impartiality. Geometric observations do not “constitute the foundation of all structural analysis”. Instead, this foundation is constructed from the conservation laws of physics, and geometric observations are properly viewed as data, some of which may be useful for testing hypotheses. The contrasts drawn by Marrett and Peacock between kinematic and dynamic analyses artificially divide what should be an integrated investigation of structures based on a complete mechanics.

References

Allmendinger, R.W., 1998. Inverse and forward numerical modeling of trishear fault-propagation folds. Tectonics 17, 640–656.

Anderson, E.M., 1951. The Dynamics of Faulting and Dyke Formation with Application to Britain. Oliver and Boyd, Edinburgh.

Angelier, J., 1989. From orientation to magnitudes in paleostress determination using fault slip data. Journal of Structural Geology 11, 37–50.

Atkinson, B.K., Meredith, P.G., 1987. Experimental fracture mechanics data for rocks and minerals. In: Atkinson, B.K. (Ed.), Fracture Mechanics of Rock. Academic Press, London, pp. 477–525.

Billings, M.P., 1972. Structural Geology. Prentice-Hall, Englewood Cliffs, NJ.

Bird, R.B., Stewart, W.E., Lightfoot, E.N., 1960. Transport Phenomena. John Wiley and Sons, New York.

Bürgmann, R., Pollard, D.D., Martel, S.J., 1994. Slip distributions on faults: effects of stress gradients, inelastic deformation, heterogeneous host-rock stiffness, and fault interaction. Journal of Structural Geology 16, 1675–1690.

Dennis, J.G., 1987. Structural Geology, An Introduction. Wm. C. Brown, Dubuque, Iowa.

Duba, A.G., Durham, W.B., Handin, J.W., Wang, H.F., 1990. The Brittle–Ductile Transition in Rocks (The Heard Volume). Geophysical Monographs of the American Geophysical Union, Washington, DC, p. 243.

Erslev, E.A., 1991. Trishear fault-propagation folding. Geology 19, 617–620.

Evans, J., Treagus, S., 1999. Preface—20 years of the Journal of Structural Geology. Journal of Structural Geology 21, 893–894.

Fletcher, R.C., Pollard, D.D., 1999. Can we understand structural and tectonic processes and their products without appeal to a complete mechanics? Journal of Structural Geology 21, 1071–1088.

Fung, Y.C., 1969. A First Course in Continuum Mechanics. Prentice-Hall, Englewood Cliffs, NJ.

Gilbert, G.K., 1877. Report on the Geology of the Henry Mountains. U.S. Government Printing Office, Washington.

Green, A.E., Zerna, W., 1954. Theoretical Elasticity. Oxford University Press, London.

Griggs, D.T., Handin, J., 1960. Rock Deformation. Memoirs of the Geological Society of America, New York, p. 382.

Handin, J., Hager, R.V., 1957. Experimental deformation of sedimentary rocks under confining pressure: tests at room temperature on dry samples. American Association of Petroleum Geologists Bulletin 41, 1–50.

Handin, J., Hager, R.V., 1958. Experimental deformation of sedimentary rocks under confining pressure: tests at high temperature. American Association of Petroleum Geologists Bulletin 42, 2892–2934.

Hardy, S., Ford, M., 1997. Numerical modeling of trishear fault propagation folding. Tectonics 16, 841–854.

Hardy, S., McClay, K., 1999. Kinematic modeling of extensional fault-propagation folding. Journal of Structural Geology 21, 695–702.

Harris, R., Segall, P., 1987. Detection of a locked zone at depth on the Parkfield, California segment of the San Andreas Fault. Journal of Geophysical Research 92, 7945–7962.

Hobbs, B.E., Heard, H.C., 1986. Mineral and rock deformation. Geophysical Monographs of the American Geophysical Union, Washington, DC, p. 324.

Hobbs, B.E., Means, W.D., Williams, P.F., 1976. An Outline of Structural Geology. John Wiley and Sons, New York.

Hubbert, M.K., 1972. Structural Geology. Hafner Publishing Company, New York.

Jaeger, J.C., Cook, N.G.W., 1979. Fundamentals of Rock Mechanics. Chapman and Hall, London.

Jiang, D., Williams, P.F., 1999. A fundamental problem with the kinematic interpretation of geological structures. Journal of Structural Geology 21, 933–937.

Johnson, A.M., 1970. Physical Processes in Geology. Freeman, Cooper and Company, San Francisco, CA.

Johnson, A.M., Fletcher, R.C., 1994. Folding of Viscous Layers. Columbia University, New York.

Knopf, E.B., Ingerson, E., 1938. Structural Petrology. Geological Society of America.

Lawn, B.R., Wilshaw, T.R., 1975. Fracture of Brittle Solids. Cambridge University Press, Cambridge.

Maerten, L., Willemse, E.J.M., Pollard, D.D., Rawnsley, K., 1999. Slip distributions on intersecting normal faults. Journal of Structural Geology 21, 259–271.

Marrett, R., Allmendinger, R.W., 1990. Kinematic analysis of fault-slip data. Journal of Structural Geology 12, 973–986.

Marrett, R., Allmendinger, R.W., 1991. Estimates of strain due to brittle faulting: sampling of fault populations. Journal of Structural Geology 13, 735–738.

Marrett, R., Peacock, D.C.P., 1999. Strain and stress. Journal of Structural Geology 21, 1057–1063.

Marshak, S., Mitra, G., 1988. Basic Methods of Structural Geology. Prentice-Hall, Englewood Cliffs, New Jersey.

Matthews, M.V., Segall, P., 1993. Statistical inversion of crustal deformation data and estimation of the depth distribution of slip in the 1906 earthquake. Journal of Geophysical Research 98, 12153–12163.

McKinstry, H.E., 1948. Mining Geology. Prentice-Hall, New York.

Means, W.D., 1976. Stress and Strain. Springer, New York.

Means, W.D., 1990. Kinematics, stress, deformation and material behavior. Journal of Structural Geology 12, 953–971.

Michael, A.J., 1984. Determination of stress from slip data: faults and folds. Journal of Geophysical Research 89, 11517–11526.

Molnar, P., 1983. Average regional strain due to slip on numerous faults of different orientations. Journal of Geophysical Research 88, 6430–6432.

Mount, V.S., Suppe, J., Hook, S.C., 1989. A forward modeling strategy for balanced cross sections. American Association of Petroleum Geologists Bulletin 74, 521–531.

Newton, I., 1687. The Principia. University of California Press, Berkeley.

Orowan, E., 1934. Plasticity of crystals. Zeitschift für Physik 89, 605–659.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer-Verlag, Berlin.

Paterson, M.S., 1978. Experimental Rock Deformation—The brittle field. Springer-Verlag, New York.

Poirier, J.-P., 1985. Creep of Crystals, High-temperature Deformation Processes in Metals, Ceramics and Minerals. Cambridge University Press, London.

Pollard, D.D., Aydin, A.A., 1988. Progress in understanding jointing over the past century. Geological Society of America Bulletin 100, 1181–1204.

Popper, K.R., 1968. Conjectures and Refutations. Harper and Row, New York.

Pyne, S.J., 1980. Grove Karl Gilbert—A Great Engine of Research. University of Texas Press, Austin.

Ragan, D.M., 1973. Structural Geology: An Introduction to Geometrical Techniques. John Wiley and Sons, New York.

Ramberg, H., 1967. Gravity, Deformation and the Earth's Crust. Academic Press, London.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill Book Co, New York.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology, Volume I: Strain Analysis. Academic Press, London.

Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology, Volume II. Academic Press, London.

Reches, Z., 1987. Determination of the tectonic stress tensor from slip along faults that obey the Coulomb yield condition. Tectonics 6, 849–861.

Sander, B., 1911. Über zusammenhänge zwischen teilbewegung und gefüge in gesteinen. Tschermaks Mineralogie und Petrographie Mittelungen 30, 281–314.

Sander, B., 1923. Zur petrographisch–tektonischen Anlyse. Jahrbuch der Geologischen Bundensenstalt A23, 215.

Sander, B., 1930. Gefügekunde der Gesteine. Springer, Berlin.

Sander, B., 1948. Einführung in die Gefügekunde der geologischen Körper. Springer-Verlag, Vienna.

Sander, B., 1950. Einführung in die Gefügekunde der geologischen Körper. Springer-Verlag, Vienna.

Sander, B., 1970. An Introduction to the Study of Fabrics of Geological Bodies. Pergamon Press, Oxford.

Schmidt, W., 1912. Zum Bewegungsbild liegender Falten. Verhandlungen der Geologischen Reichsenstalt 3, 112–119.

Schmidt, W., 1932. Tektonik und Verformungslehre. Bornträger, Berlin.

Shaw, J.H., Suppe, J., 1996. Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California. Journal of Geophysical Research 101, 8623–8642.

Sheriff, R.E., Geldart, L.P., 1995. Exploration Seismology. Cambridge University Press, New York.

Smart, K.J., Krieg, R.D., Dunne, W.M., 1999. Deformation behavior during blind thrust translation as a function of fault strength. Journal of Structural Geology 21, 855–874.

Strayer, L.M., Huddleston, P.J., 1997. Numerical modeling of fold initiation at thrust ramps. Journal of Structural Geology 19, 551–566.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal of Science 283, 684–721.

Suppe, J., Medwedeff, D.A., 1990. Geometry and kinematics of fault-propagation folding. Ecologae Geologie Helvetia 83, 409–454.

Taylor, G.I., 1934. Faults in a material which yields to shear stress while retaining its volume elasticity. Proceedings of the Royal Society. Section A—Mathematical and Physical Sciences 145, 1–19.

Taylor, G.I., 1938. Plastic strain in metals. Journal of the Institute of Metals 632, 307–324.

Terzaghi, K., 1943. Theoretical Soil Mechanics. John Wiley and Sons, New York.

Timoshenko, S.P., Goodier, J.N., 1970. Theory of Elasticity. McGraw-Hill, New York.

Tullis, J., Heilbronner, R., Hirth, G., Stunitz, H., 1999. Progress in calibrating dislocation creep microstructures as indicators of deformation conditions. In: Geological Society of America Annual Meeting Abstracts with Programs. Geological Society of America, Denver, CO, p. A-57.

Turcotte, D.L., Schubert, G., 1982. Geodynamics: Applications of Continuum Physics to Geological Problems. John Wiley and Sons, New York.

Turner, F.J., Weiss, L.E., 1963. Structural Analysis of Metamorphic Tectonites. McGraw-Hill Book Company, New York.

Wenk, H.-R., Christie, J.M., 1991. Comments on the interpretation of deformation textures in rocks. Journal of Structural Geology 13, 1091–1110.

White, F.M., 1974. Viscous Fluid Flow. McGraw-Hill, New York.

Willemse, E.J.M., Pollard, D.D., Aydin, A., 1996. Three dimensional analyses of slip distribution on normal fault arrays with consequences for fault scaling. Journal of Structural Geology 18, 295–309.

Woodward, N.B., Boyer, S.E., Suppe, J., 1989. Balanced Geological Cross-Sections. American Geophysical Union, Washington, DC.