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Competitive macroscopic deformation processes

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Abstract

Macroscopic deformation mechanisms such as folding, fracturing–faulting and formation of rock fabrics compete with one another in a fashion similar to the competition among crystalline deformation mechanisms such as cataclasis, grain boundary sliding, dislocation creep and diffusive mass transfer. Many authors seek to develop a unique structural chronology for a given field area based on what are considered exclusive overprinting relationships between structures. In contrast the approach taken here suggests that relative changes in external or internal variables within a rock mass can cause significantly different 'dominant' types of macroscopic deformation to be developed in hand specimen and/or outcrop at the same time. Rather than representing distinct structural 'facies', observed dominant macroscopic features are waypoints in continuum processes. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Jamison (1992) suggested that there is a 'fundamental competition' between folding and faulting, and that variations in different variables may make one process or the other dominant at a particular place at a particular time. I extend that argument to include all of the major 'structural styles', namely folding, fracturing–faulting, and rock fabric development, and suggest that they can be best understood as competitive macroscopic deformation processes, similar to what we understand for competing deformation mechanisms.

Deformational studies commonly evolve from geometric and areal descriptions to inferring deformation processes and sequences. There is the common assumption that the geometric, areal, process, and sequence descriptors are relatively unique and independent. For example, fold geometries and folding processes are commonly described independently of grain-scale deformation processes (Donath and Parker, 1964; Ramsay, 1967; Johnson, 1977, 1980). Rock fabric evolution and strain studies are commonly discussed independently of either folding or faulting processes (Wilson, 1961; Wilson and Cosgrove, 1982;, Hobbs et al., 1976; Ramsay and Huber, 1985, 1987). Cataclasis is considered as a microscopic deformation mechanism, but its evolution from the initiation of fracturing is not considered in the evolution of folds. Faulted folds, and folding as the result of faulting are commonly discussed as mutually independent processes and without regard to either brittle or ductile rock fabric evolution (Willis, 1893; Dahlstrom, 1969, 1970, 1990; Suppe, 1983; Mitra, 1990; Fischer et al., 1992). When we compartmentalize rock structures into three fundamental types of macroscopic structures—folds, faults and rock fabrics (cleavage, foliation, lineation, etc.), or when we envision that the macroscopic processes of folding, faulting and the formation of foliations–lineations occur independently we miss the important relationships among these processes.

Fig. 1 illustrates an excellent field exposure in which all processes have occurred. The different features within the structure may have formed independently at different times. Equally likely, given smoothly varying external conditions, the different macroscopic processes compete with one another to accommodate bulk deformation in the most efficient fashion at the same time. In other circumstances one deformation process may

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Fig. 1. Quarry outcrop photograph of carbonate fold overlying a shallow thrust with a cleaved forelimb in the Hudson Valley fold and thrust belt, New York, USA (Penrose conference participants for scale). The co-occurrence of all of these features in a single outcrop or hand-specimen leads to the discussion of whether there is a time-sequence of different features, or if deformation features/processes in one part of a structure compete with or compensate for other features/processes elsewhere in the structure.

complement another. Rather than arguing over the sequence of folding vs faulting and fabric formation, I discuss the concept in this paper that spatial changes in lithology (% different minerals), stress concentration (structural position), strain rate, or other parameters, enable all processes to be operative simultaneously in different parts of the same outcrop or of the same larger area. Means (1993) suggested that the fundamental problem in structural geology is to understand the geometry of the processes of structural change; this should be extended to also include understanding the competitive processes that drive the changes we see in structural geometries.

Crystalline deformation mechanism (CDM) maps have been extremely useful tools to explain and understand the relationships among the ways minerals deform at the microscale (Elliott, 1973; Rutter, 1976; White, 1976; Knipe, 1989). They are created for individual minerals based on the assumption that each mineral has unique material properties (expressed as a rate law) at a given temperature, pressure and strain rate. Creation of CDM maps for rock with crystal scale anisotropy, such as ones with preferred crystallographic orientations, could be expected to have different rate laws than those with random crystallographic fabric. CDM maps for polymineralogic rocks (Tullis et al., 1991; Handy, 1994) would be more complex still, and require ‘mixing rules’ to allocate flow laws to each mineral component in the aggregate.

I suggest a comparable approach for understanding structural styles based on the attempt to recognize and separate the operative mechanisms during macroscopic deformation. Folds, fractures–faults and rock fabrics all can contribute to accommodating bulk strain of a rock body in the same way that different crystalline deformation mechanisms do on a smaller scale in a polymineralogic rock. Although we probably cannot write constituitive equations for the bulk strain rate of folding based on ‘unique’ material properties as we can for grain-scale processes, we can define the important parameters that control the occurrence of folding. Similarly, we can do the same for fracturing and faulting, and for the development of rock fabrics.

The formation of each structural style is a complex non-linear function of many microscale processes, leading therefore to difficulty in going from any single

Table 1
The common parameters usually considered in crystalline deformation mechanism maps are also included when considering macroscopic deformation processes. Additional parameters include distributional or geometric variables. At the crystal scale the mineralogy, mineral distribution and grain size–grain size distribution are the major external parameters. At the macroscopic scale the anisotropy–layering parameters are additional variables

External parameters:	Temperature Strain rate Mean stress Deviatoric stress Fluid pressure
Internal parameters:	Mineralogy/mineral distribution Grain size/grain size distribution Porosity Layering—Anisotropy —Viscosity contrast —Number of layers

geometric classification of structural features to a unique mechanistic understanding of their formation. Each macroscopic deformation process does not have a unique set of mechanisms responsible for accommodating shortening, elongation or shear. On the other hand in the same way that crystalline deformation mechanism studies on individual minerals contribute to understanding how strains occur on a larger scale, recognizing the balance among important macroscale processes contributes to understanding the origin and evolution of larger structures.

A first-order list of the significant parameters that affect the evolution of structures is presented in Table 1. Different variables affect the rate laws for each deformation mechanism in different ways, such that an increase in one mechanism may compensate for a decrease in another. For example, a decrease in temperature may lead to a decrease in the occurrence of a particular crystalline deformation mechanism in constant grain size material, but if the grain size decreases in parallel with the temperature decrease across an area, that single deformation mechanism may make a comparable contribution to deformation in rocks across the area. Similarly, changes in lithology from layer to layer can have an effect on rock fabric formation even if all other variables remain constant. The internal variables, or 'material properties' are all usually lumped into the single term competence, but it is useful to consider that a number of variables will control how 'competent' a rock may be.

2. Fracturing competitive with fabric development

Published deformation mechanism maps (Rutter, 1976; Knipe, 1989, and many others) commonly plot both intracrystalline deformation mechanisms and cataclasis on the same diagrams, mineral by mineral, in temperature–stress–grain-size space. Different minerals have different deformation mechanisms at the same temperature, pressure, grain size and strain rate. For a single mineral, at higher deviatoric stresses, higher strain rates, lower temperatures and larger grain sizes, brittle fracture will commonly be the most easily observed (macroscopically dominant) of the possible deformation mechanisms. Because grain sizes are never uniform within a rock mass, some diffusive mass transfer mechanisms and some dislocation creep mechanisms will also operate in particular grains at particular grain sizes or in high strain or strain rate regions of the deforming body. For rocks with several minerals, each mineral deforms by the mechanism which is the most efficient to accommodate the bulk strain at the deformation conditions.

The simplest extension of the competitive deformation mechanism map approach is to consider how variables affect the bulk material properties as in Table 2. Columns 1–5 summarize the effects of changes in one external or internal parameter (holding the others constant) on the tendency for a microscale mechanism to occur in a comparison between macroscopic fracturing and rock fabric forming processes. Lithology is of greatest importance in the development of diffusive mass transfer and crystal–plastic processes at relatively low temperature, pressure and strain rate (Ramsay, 1982; Engelder and Marshak, 1985; Marshak and Engelder, 1985). The diameter of brittle grains and the relative abundances of brittle grains compared to more ductile grains or matrix (i.e. very fine grains) determine failure stress in crystalline and many other rocks (Mitra, 1978). The presence of chemically active fluids may enhance crystal–plastic processes over brittle processes (Lloyd and Knipe, 1992), whereas increases in fluid pressure might enhance brittle processes (Gray, 1998, personal communication). Increasing porosity can be a significant variable in the transition from macroscopically brittle to ductile behavior (Rutter and Hadzideh, 1991; Hadzideh and Tullis, 1992; Zhang et al., 1993).

3. Folding competitive with fabric development

The folding process is dominated by anisotropic (layered) material properties, whether by slip between layers or by rapid changes in material response in one direction (across layers) vs relatively uniform material properties in two other orthogonal directions (within the layers) (Biot, 1965; Johnson, 1977; Johnson and Fletcher, 1994). Donath and Parker (1964) proposed a mixed geometric and mechanistic classification scheme for folding which tried to assign all folds into four

Table 2
Fabric development processes, fracturing processes, faulting and folding can all be considered in the context of the internal and external variables which effect their occurrence. I—(Increases) indicates that a deformation mechanism/process becomes more common or more penetrative as each variable increases. D—(Decreases) indicates that it becomes less common. Stable fracturing is generally synonymous with intra-granular fracturing (Mitra, 1978). However in polymineralic rocks, or rocks with polymodal grain sizes and abundant matrix, stable fracturing as used here indicates that cracks do not propagate more than several grain diameters. Unstable fracturing is generally synonymous with intergranular fracturing, or fractures that propagate across multiple grains and/or grains and matrix

Variable	1 Diffusive mass transfer	2 Crystal–plastic deformation	3 Grain boundary sliding	4 Stable fracture	5 Unstable fracture	6 Faulting	7 Folding
Temperature—I	I	I	I	I	D	D	I
Strain rate—I	I	D	I	I	I	I	D
Mean stress—I	I	I	D	I	D	I	I
Deviatoric stress—I	I	I	I	I	I	I	D
Fluid pressure—I	I	D	I	I	I	I	D
Chemically active fluids—I	I	I	D	D	D	D	D
Lithology							
Mineralogy							
% Quartz–feld—I	D	D	I	D	I	I	D
% Calcite—I	I	I	D	I	D	D	I
% Platy minerals—I	I	D	I	I	D	D	I
Grain size—I	I	D	I	I	I	I	D
Porosity—I	I	D	I	I	I	I	D
Layering							
# Layers—I	–	–	–	–	D	D	I
Anisotropy—I	D	D	–	–	–	D	I
Viscosity contrast—I	–	–	–	–	–	D	I

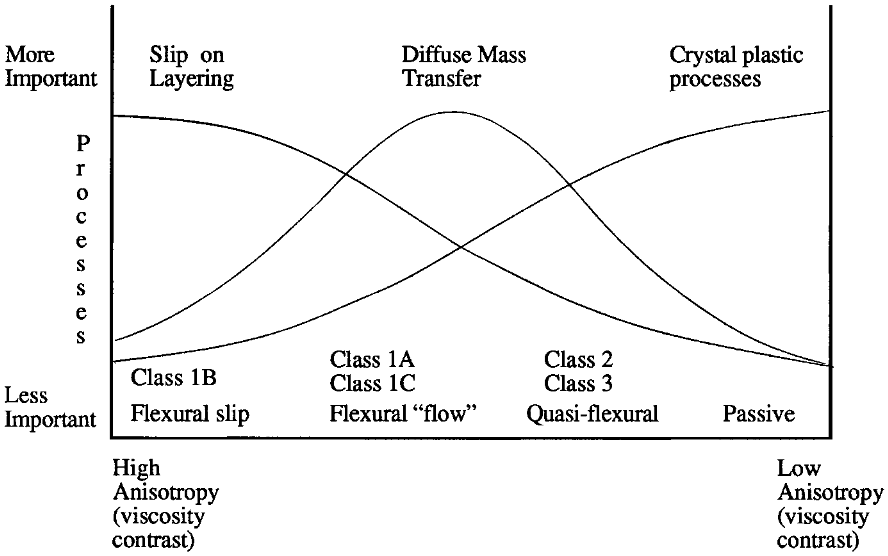

Fig. 2. Plot of importance of processes vs a qualitative assessment of the anisotropy of layered rock. This plot is one way to express the relative importance of layer slip, diffusive mass transfer and crystal–plastic mechanisms in rocks exhibiting folds with geometries matching those defined by Donath and Parker (1964) and Ramsay (1967). The contribution of the three different deformation mechanisms to formation of a single fold is estimated by evaluating the importance of each process for each fold from left to right. For example, a flexural 'flow' fold, or class 1A and 1B folds, may have roughly equal contributions of slip on layering and diffuse mass transfer mechanisms during 'fold' formation and a somewhat lesser contribution by crystal–plastic mechanisms. Viscosity is a bulk description of material properties, usually as a function of temperature, pressure and strain rate, that is not uniquely tied to individual crystalline deformation mechanisms. Viscosity contrast is another measure of layered anisotropic material properties.

classes, based on absolute viscosity of layers and viscosity contrast between layers. They defined four classes: flexural slip folds, flexural flow folds, quasi-flexural folds and passive folds. In their scheme, the mechanical significance of layering decreases from a maximum in flexural slip folds where deformation occurs primarily by slip on layering, to passive folds where layering serves only as a displacement marker. Slip on anisotropic layering is widely discussed in both geometric and theoretical studies of folding (Ramsay, 1974; Johnson, 1977; Ramsay and Huber, 1987). Other geometric and theoretical studies of folding (Biot, 1965; Ramsay, 1967; Hudleston, 1973; Hudleston and Lan, 1993, 1994; Lan and Hudleston, 1995; Hudleston et al., 1996) emphasize that both slip on layering and deformation within layers accommodates layer shape change, i.e. flexural 'flow' folding or folding with tangential longitudinal strain, and/or quasi-flexural folds. The operation of one mechanism locally, such as slip on layering, may influence the external parameters in other locations, such as the fold hinge, to enhance or retard other mechanisms such as fracturing or diffusive mass transfer (Laubscher, 1976).

Flexural flow and quasi-flexural geometries have progressively less significant layer anisotropy and interlayer slip, and require that significant changes in layer shapes be accommodated by rotation of grains, grain growth, crystalline deformation mechanisms and/or grain shape changes thereby producing the 'flow'. Hudleston et al. (1996) note that there are no theoretical or field studies documenting true parallel flexural 'flow' folds as the term is used by Ramsay (1967). The Donath and Parker (1964) field examples are generally not parallel folds, and all show roughly axial planar cleavage within the folds. Donath and Parker do not explicitly discuss the timing of the cleavage with respect to the folding. Thus, flexural flow folding as originally defined, occurs in rocks in which bulk deformation is not just a result of a 'folding mechanism'. Both layer-scale folding and grain-scale rock fabric formation contribute to the growth of the structure. The issue of the relative timing of folding and cleavage formation in individual folds has been a focus of much debate in the literature. The point being made here is that, in many cases, precise relative timing may not be the essential issue because interlayer sliding and internal deformation occur concurrently and competitively, with each taking up some of the bulk deformation at any time. Through time, an increase in one process may also compensate for a decrease in another process.

Cleavage nomenclature related to folding is highly complex, with ideal end-members varying from layer parallel shortening fabrics perpendicular to layering in which cleavage forms and then is folded, to transecting cleavage in which folds form first and are then cut by later cleavage (Ramsay, 1967). Cleavage, strain and folding relationships are commonly used to infer deformation sequences by independent processes (Powell, 1974; Gray, 1981a,b; Treagus, 1988; LaFrance and

Williams, 1992; Harris and van der Pluijm, 1998). There has also been discussion of whether fold symmetry and bulk strain symmetry necessarily coincide, leading to the question of whether axial planar cleavage should even normally be observed in many rocks (Powell, 1974; Treagus and Treagus, 1981, 1992; Treagus, 1993). Other authors, or the same authors in other localities, recognize stages of deformation within structures during which layer slip and/or fabric formation may be more or less important (Spang and Groshong, 1981; Reks and Gray, 1983; Groshong et al., 1984; Mitra and Yonkee, 1985; Gray and Mitra, 1993; Yang and Gray, 1994), or that formation of rock fabrics may be more important in some parts of structures than in others during the same interval of time (Mitra, 1987; Hedlund et al., 1994; Erickson, 1996; Markley and Wojtal, 1996).

Folding (layer slip dominated, with a buckling or kinking instability growth as the rate limiting step, for example) and rock fabric formation mechanisms (crystal–plastic deformation rate limited) can be compared as competitive processes within the Donath and Parker (1964) mechanistic or Ramsay (1967) geometric classification schemes (Fig. 2) to illustrate that all processes may occur within a single structure particularly in a sandstone–limestone–shale (quartz–calcite–clay) interval. As noted by Ramsay (1967) and Laubscher (1976), even predominant slip on multiple layers requires shape changes or dilatancy within the layers between slip surfaces to accommodate orientation changes during folding.

Table 2 also can be used to compare deformation variables in folding vs rock fabric formation (columns 1–3, 7). In general, as temperature and mean stress increase, folding dominated by layer slip processes become less common and rock fabric development becomes more common. Flexural folds, which necessarily have mechanically significant layering, as judged by its ability to reorient stress, become less common and passive folds in which layering records but does not control deformation, becomes more important. In sedimentary rocks carbonate and clay mineral grains tend to deform or reorient relatively easily compared to quartz and feldspar grains. Therefore, as quartz and feldspar content goes up, or deviatoric stress goes up, or as viscosity contrast between layers goes up, folding processes become more common and rock fabric less common. Cleavage can form at the same time as flexural slip folding in layers of different compositions or grain sizes. Ramsay's discussion (Ramsay, 1967) of how overall similar (class 2) folds in nature may be comprised of layers with alternating class 1 and class 3 geometries illustrates the results of this type of difference in 'competency' and deformation mechanisms in adjacent layers.

Ramsay (1974) and Hardy and Poblet (1994) demonstrated that rotation of fold limbs does not accommodate bulk shortening at a constant rate through the growth of a fold. Initial fold growth is slow, then accelerates, then slows again as room problems in the core causes the fold to lock. Therefore if the mineralogy, fluid content and strain rate are nearly right for cleavage formation under ambient temperature and pressure, whereas layering and anisotropy are nearly right for folding one might expect transitions from early layer parallel shortening by cleavage formation (during initial slow limb rotation), to folding with little cleavage formation (during rapid limb rotation) and finally to axial planar cleavage development (when limb rotation can no longer efficiently accommodate bulk shortening) (Reks and Gray, 1983; Groshong et al., 1984; Woodward et al., 1986; Gray and Mitra, 1993; Markley and Wojtal, 1996; Harris and van der Pluijm, 1998). Transitions from deformation dominated by rock fabric development to folding-dominated deformation (or vice versa) would be expected to occur as deviatoric stresses change from place to place in an area, from layer to layer, or as grain sizes or mineralogy change, even if the rock fabric forms by a consistent mechanism at all times.

4. Folding competitive with fracturing and faulting

Latham (1985a,b) argued that internally varying material properties in uniformly straining material could generate folds, kinks or faults depending on the distribution of material properties and resulting strains. Folding can occur above a weak detachment without faulting or rock fabric formation creating a detachment fold (Chapple, 1968; Dahlstrom, 1969; Jamison, 1987; Epard and Groshong, 1995; Homza and Wallace, 1995). Similarly, faults like cleavage, can transect earlier folds once the material property anisotropy in the rock is no longer significant. The common co-occurrence of folds and faults in many environments has led to the suggestions (Willis, 1893; Heim, 1919; DeSitter, 1956; Dahlstrom, 1970; Berger and Johnson, 1982; Chester and Chester, 1990; Chester et al., 1991; Dixon and Liu, 1991; Dixon and Tirrul, 1991; Rowan and Kligfield, 1992; Fisher and Anastasio, 1994; Johnson and Fletcher, 1994; Liu and Dixon, 1995; Spang and McConnell, 1997; Woodward, 1997) that strata first fold, then folds lock, and then faults form. This possibility is readily anticipated in the discussions of Ramsay (1974) and Hardy and Poblet (1994).

Stepped faults result in macroscopically folded strata because of fault bends not related to buckling or other folding processes (Rich, 1934; Suppe, 1983; 'bending folds' of Johnson, 1980). In some cases, geometric classifications have taken precedence over developing

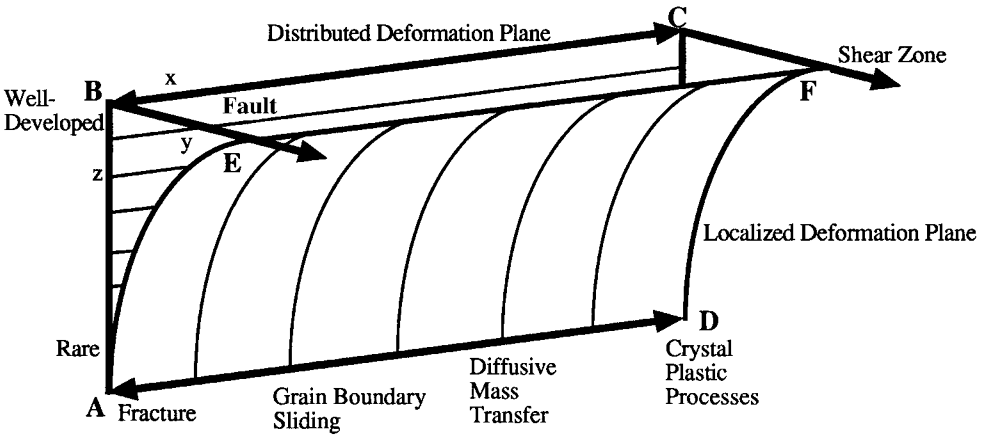

Fig. 3. Plot depicting the competitive deformation process approach graphically. Position along the z-axis denotes changes in the extent to which a deformation mechanism operates; position along the x-axis denotes changes in the dominant deformation mechanism; position along the y-axis denotes changes in the degree of deformation localization. The path AE illustrates a change from distributed but rare fractures to fracture coalescence and fault formation. The path DF traverses from widespread distributed strain to the formation of a shear zone. Any path from A to F indicates changes in deformation mechanisms from brittle to ductile, and changes from rare deformation features to highly localized ones. It can pass through any point within the volume ABEFDC. Distinctions can be drawn not only between processes at a given set of internal and external conditions (i.e. different positions along the x-axis) but also at different times during deformation (i.e. at different positions along the z-axis). Deformation features may also develop with non-uniform distributions; these paths would lie on the localized deformation plane (fractures localizing into a discrete fault zone, for example). In nature conditions will exist on both planes and within the volume which separates them.

sequential understanding of the deformation processes in fault-related folds. Rich (1934), Dahlstrom (1970), Suppe (1983) and many others have argued that slip on detachment zones dominates the structural development of fold and thrust belts. These arguments are based on layer anisotropy and weakness as the dominant variables controlling fracture–fault propagation and fault slip. Taking a competitive deformation process approach, areal changes in structural style within fold and thrust belts may result because of changes in the relative efficiency of folding by layer slip vs thrusting at accommodating bulk deformation in different areas, such as those now identified with fault-propagation folds (Suppe and Medwedeff, 1990), detachment folds (DeSitter, 1956; Dahlstrom, 1970) or break thrust folds (Fischer and Woodward, 1990; Fischer et al., 1992).

Roeder (1967) argued for a depth segregation of structures recognizing a ‘frontal zone’ type of deformation and a ‘transport zone’ type of deformation. Lamerson (1982), Boyer (1986), Mitra (1986, 1990) and Woodward (1992) also suggested that different fold types typified different structural positions on thrust sheets. These discussions suggest that temperature, pressure and possible areal strain localization may play an important role in structural style, not just initial anisotropy.

Folds are the result of relatively continuous deformation. Rocks that deform by brittle fracturing without loss of cohesion can also be treated as a continuum, although with some modifications (Angelier, 1984; Wojtal, 1986, 1989). Columns 4–7 in Table 2 compare the effect of the important internal and external variables upon folding vs stable fracturing, unstable fracturing and faulting. Transitions from fold-dominated deformation to fault-dominated deformation can be explained by variations of the material parameters, i.e. decreasing the number of layers or changing the composition of layers, which leads to the suppression of folding and enhancing the formation of faults (Johnson, 1980). All of the variables that enhance ductility including increasing temperature, mean stress, and calcite content and decreasing grain size, fluid pressure, strain rate, and deviatoric stress also enhance the occurrence of folding rather than fracturing and faulting. Within a single stratigraphic section the number of layers, the anisotropy of the layers and the viscosity contrast between layers will play a significant role because an increase in the number of layers and an increase in their ductility both tend to favor folding over faulting (Johnson, 1980).

5. Distributed deformation vs localization

Deformation localization in folding is most common in flexural slip folding where discrete anisotropic layers or layer boundaries accommodate most strain. Localization of fold hinges along an individual layer is usually wavelength dependent (Biot, 1965; Ramsay, 1967; Johnson, 1977, 1980; Latham, 1985a,b; Johnson and Fletcher, 1994), unless there are significant lateral changes in material properties (pinch-outs, facies or lithology changes). Faulting results from fracture localization so that large discrete discontinuities appear. The parallel situation in ductile deformation is the development of shear zones from a continuum of ductile deformation.

Fig. 3 depicts the competitive deformation process approach graphically. Changes in position along the vertical (z) axis represents changes in the extent to which a deformation mechanism operates. Changes in position along one horizontal (x) axis denotes changes in the dominant deformation mechanism (in this case the continuum between fracturing and crystal–plastic mechanisms). Changes in position along the other horizontal (y) axis denotes the degree of deformation localization. Thus, the x–z plane (ABCD) on this diagram is a distributed deformation plane. Along the curved front surface, AEFD, deformation is highly localized. The point I wish to make here is that there are numerous possible paths between any two locations within the volume depicted by diagram, for example from corner A to any point on the top face BECF. Which path a rock mass follows will depend on both external and internal variables. Why localization occurs is a separate question beyond the scope of this paper—however, initially variable material properties across an area, or development of strain-hardening or strain-softening behavior locally will enhance localization once it has begun (Wojtal and Mitra, 1988).

6. Discussion

Tabulation of material responses to deformation illustrates that structural styles are usually best characterized by a few macroscopic deformation processes, each of which is the sum of different combinations of microscale mechanisms. Few folded rocks have undergone no fracturing, pressure solution or grain-shape modification, few faulted rocks are completely unfolded and uncleaved, and few rocks with macroscopic fabric development are unfractured and unfolded. I have attempted to tabulate the major variables which affect the way rocks deform based on a survey of recent literature (certainly incomplete), and to illustrate that a particular feature may increase or decrease in intensity because of changes in any of several variables. It would be nice to pick three dominant variables such as are usually used in crystalline deformation mechanism maps, like stress, temperature and grain size to illustrate this point for folding, faulting and fabric development. However, many observed structural styles such as folding and faulting are strongly related to anisotropy in material properties such as bedding spacing and numbers of layers, of which there is an infinite variety.

In most deformed rocks, one deformation process accommodates the requisite bulk deformation most rapidly for a given set of external conditions. The rate limiting step is the slowest step required to reach the given end point. However, the material properties of the deforming rock mass change continuously during deformation. For example, as the orientation of layering changes over time the anisotropic properties may decrease or be lost, and the rate limiting process can change, not because of discrete overprinting, but because of the changed properties. The tabular presentation allows the variables to be discussed in the context of their effects on multiple deformation mechanisms. Two graphic figures suggest that macroscopic deformation process comparisons like those for crystalline mechanisms can be used to improve our understanding of how variables influence descriptions of macroscopic structures. Deformation history has not been discussed, because once a structure has formed, the patterns of the external parameters are altered (i.e. anisotropy, orientation of layering, etc). The next increment of macroscopic deformation will be dominated by new processes and mechanisms which most efficiently accommodate the strain.

7. Conclusion

Individual classifications for folding, faulting and fabric development in the past have commonly focused on a single deformation process only, and have not adequately recognized that multiple processes occur within deforming rocks. Relatively small changes in the material properties from place to place at one time, or in the external variables over time in a single location can cause a complex overprint of macroscopic deformation processes. This contribution suggests that the ‘deformation mechanism map’ approach which has been used to explain how crystalline deformation mechanisms relate to one another, can be expanded to include consideration of competitive macroscopic deformation processes as well. This approach also provides a context in which to teach the interrelationships among deformation processes to both beginning and advanced students, although that will require a more fully developed graphical presentation than was possible here.

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