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Analysis and interpretation of composite foliations in areas of progressive deformation

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Abstract—In areas of progressive deformation, where successive structures develop during a relatively continuous deformation within a geologically short time period, traditional chronological notations of structural elements (e.g. S_1, S_2, etc.) can give erroneous impressions of how large rock masses evolve in time and space. We demonstrate from field examples that successive structures can develop which: (a) are comparable in morphology and orientation but of different ages; (b) are different in morphology but of comparable age; and (c) show rapid morphological changes over short distances. Under such conditions, correct identification of the relative age of structures is often difficult to impossible.

We consider the concepts of a *composite foliation*, and of *Transposition Cycles* as vehicles to objectively evaluate the significance of different sets of structures in the evolution of larger rock masses. We suggest that: (1) structural elements be labeled using morphological notation, adding numerical subscripts only when independent evidence is available; (2) geologists more fully acknowledge and integrate the concept of deformation partitioning into their models; and (3) when analyzing areas of multiple deformation, more emphasis is placed on the *relationship* between domains of differing complexity. Integration of these three perspectives in the analysis will lead to a more realistic basis upon which to model the structural evolution of large rock masses.

INTRODUCTION

FOR over three decades, workers studying areas in which superimposed folding has occurred have used a nomenclature such as F_1, S_1, L_1, etc., and D_1, D_2, etc., to refer to certain structural elements and to ascribe a specific time sequence to the formation of these elements. This type of notation appeared to work reasonably well in depicting the structural history of many areas, since the assumption was that large rock masses deform more or less homogeneously and simultaneously over large areas. As more detailed work was done, however, it became apparent that the nature of deformation of large rock masses was most commonly heterogeneous and often diachronous (e.g. Chadwick 1968). In addition, the criteria used to differentiate between and regionally correlate structures of various ages was challenged (Park 1969). To alleviate some of the problems of regional correlation, some workers tried using geographic names to designate deformational phases (Cheeney & Matthews 1965, Tobisch *et al.* 1970, Higgins 1973), but most continued to apply the numerical designation of structures despite its shortcomings.

With the upsurge of interest in the evolution of zones where progressive deformation is readily documented (e.g. ductile shear zones), this traditional manner of designating and analyzing the structural history has proved inadequate, and if sufficient care is not taken, can lead to an erroneous impression of the manner in which structures relate to each other in time and space. Various workers, being confronted with this awkward legacy of terms, have tried to adjust to the problem by designating certain planar structures as a 'transposition' or 'composite' foliation (e.g. Turner & Weiss 1963, S_T of Williams & Compagnoni 1983, $S_{1\text{-}2}$ of Lagarde & Michard 1986) or have referred to successive deformations using alphabetical subscripts (e.g. D_s, D_t, etc.) while describing the details of the structures in non-chronological terms (e.g. Platt & Behrmann 1986). Recently, we have worked in areas in which this problem has become particularly acute, and in which it is not meaningful to discuss the structures in terms of a regionally occurring sequence such as S_1, S_2, etc. This is mainly because the deformation (and metamorphism) have been heterogeneous in both time and space.

The problems of correlation of structural elements between exposures has long been a concern of those working in metamorphic belts (Park 1969, Williams & Zwart 1977, Williams 1985). These problems can be particularly difficult in ductile shear zones where the rocks are undergoing a continuous progressive deformation, and where slightly shifting movement directions can produce multiple generations of essentially contemporaneous structures. These 'different generations' of structures (e.g. folds or cleavages) can display the following: (i) parallel orientations; (ii) the same morphology; (iii) changes in intensity over short distances resulting in rapid morphological changes (e.g. original continuous cleavage → crenulation cleavage → new continuous cleavage); and (iv) form under the same or similar metamorphic conditions and therefore be associated with comparable mineral assemblages. Under such circumstances, it is often difficult if not impossible to unequivocally identify the relative age of structures in the field (and even in thin-section!).

In this paper, we address the question of how to clearly and explicitly depict, analyze and interpret the structural history of a given area without recourse to the chronological designations traditionally used in structural analysis. To put the problems touched on above in more concrete terms, we will draw upon our recent mapping in two areas where specific temporal nomenclature of the above type does not work, discuss the mutual problems encountered and suggest a manner of treating the structural elements that will place the evolution of such areas in more meaningful context. We start by defining our use of the terms progressive deformation and deformation partitioning.

PROGRESSIVE DEFORMATION

The term *progressive deformation* was first used by Flinn (1962, pp. 387–388), who suggested that a rock undergoing progressive irrotational deformation will pass through a *continuous* series of shape changes "until the deformation ceases" (see also Means 1976, p. 224). It is also commonly defined in a more general sense, for example, without the constraints of 'continuous' or 'irrotational' (see, for example, Ramsay 1967, p. 55) or, in more specific cases, where the term has been applied in the context of different degrees of (non-) coaxiality (Means *et al.* 1980, p. 373). The common denominator is that the term implies a sequence of related structural events that give rise to a final fabric. In ductile shear zones, where movement or transport directions may change orientation over relatively short time intervals, the progressive deformation may be expressed by development of multiple sets of structures. Such is the case in the two areas where we have recently worked. In this paper, therefore, we use the term *progressive deformation* to imply: (1) a close relationship between the various sets of structures in terms of orientation, sense of movement, style and prevailing metamorphic conditions; (2) a relatively constant orientation of the regional stress field; and (3) the various sets of structures developing as a relatively continuous sequence of events within a geologically short period of time.

PARTITIONING OF DEFORMATION

The basic concept of deformation partitioning has been well-established in the geologic literature for some time, ushered in by the work of Sander (1911, 1930), and elaborated on by Turner & Weiss (1963) as well as others. The specific jargon used and the degree of sophistication in approaching the subject, however, have changed. In the most general case, deformation partitioning refers to the concentration of deformation in discrete domains in a rock mass. These domains can reflect variations in rock type, temperature–pressure conditions, presence of fluids, strain rate and so forth. Strain partitioning has also been used to represent different processes active in each domain, such as simple shear, pure shear and no strain (e.g. Bell 1985). In more rigorous, mathematical language, deformation partitioning has been analyzed in terms of the two components of vorticity active in a flowing rock mass expressed as *spin* and *internal* (*shear-induced*) *vorticity* (Means *et al.* 1980, Lister & Williams 1983). These two terms refer to the relation between the angular velocity of the instantaneous stretch directions and, respectively, the external co-ordinate system and material lines. The degree to which these two components are partitioned during deformation influences the manner and type of geologic structures which develop (Lister & Williams 1983).

In this paper we are mainly concerned with how deformation partitioning affects the *timing* of structures in various domains, and how our concept of the timing affects structural or tectonic models we construct. In most rock masses, structures of a given 'generation' will probably not develop simultaneously in all parts of the area, but will be strongly influenced by the larger-scale partitioning of the deformation. That is, structures will develop in that part of the rock mass in which stress or movement is concentrated at any given time. In this model, continuous cleavage (Powell 1979) in different parts of the rock mass may represent entirely different times of formation given a heterogeneous movement pattern. For example, in a thrust zone, different parts of the thrust sheet will move at different times (e.g. Coward & Potts 1983), as the deformation is sequentially partitioned to different parts of the sheet. It is entirely conceivable that in one domain (A), continuous cleavage may develop as that part of the sheet moves. With a shift in movement direction of the rock mass, however, crenulations of that foliation begin forming in domain (A), while in a contiguous domain (B), the new movement and/or relocalized high stress there has now initiated the development of a continuous cleavage. Under such conditions, continuous cleavage and crenulation cleavage are forming simultaneously in contiguous domains. For these reasons, traditional chronological notations such as S_1, S_2, etc., tend to create a regional picture which is misleading, greatly oversimplifies the timing and partitioning of deformation in a heterogeneously deforming body, and inhibits the construction of models which can realistically depict the manner by which rock masses deform.

The point to be made here is that in heterogeneous rock masses undergoing progressive deformation, the following are likely to hold true: (a) each part of the mass will have its own unique deformation path; (b) there is likely to be contemporaneous development of foliations showing different morphologies (e.g. continuous cleavage forming in domain B while crenulations are forming in domain A); and (c) because of the common occurrence of crenulation cleavages being transposed into continuous cleavages which are then subsequently crenulated, continuous cleavage in different parts of an area undergoing progressive deformation may be of different ages. The same concept applies to the age of crenulations. While placing structures in time categories (S_1, S_2, etc.) may be valid for any given point, conceptually there is often no justification to extend the correlation beyond the scale of the exposure or thin section.

In the following discussion, we designate the various planar structures using morphological subscripts as follows: (1) S_0, bedding; (2) S_b, bedding parallel fissility and/or compositional layering; (3) S_c, continuous cleavage; (4) S_{cr}, crenulations; (5) S_{cc}, crenulation cleavage with or without differentiated layers; and (6) S_T, transposed and/or composite foliation which includes at least some domains of new continuous cleavage (cf. Williams & Compagnoni 1983).

TWO STUDY AREAS

We have recently carried out field work in the central part of the Lachlan Fold Belt of southeast Australia and in the southern Foothills Terrane of the western Sierra Nevada, California. Rocks in the Lachlan Fold Belt are Lower Paleozoic while those in the southern Foothill Terrane are Mesozoic, but both areas are characterized by low- to medium-grade metamorphic rocks of volcanic and/or clastic origin and by deformed and undeformed granitoids. Rocks in both areas show a complex structural history characterized by multiple deformation and the presence of ductile shear zones, the latter of which appear in the study areas as integral parts of a progressive deformation. As is often the case in multiply deformed rocks, one or two exposures and/or thin sections from an area will demonstrate the structural and metamorphic complexities common throughout much of the area. In this spirit, we have picked one or two such domains from each area which exemplify and illustrate the problems outlined earlier.

Lachlan Fold Belt example

Various aspects of the Lachlan Fold Belt of southeast Australia have been examined over the last several decades (e.g. see references in Cas 1983). We have investigated an area lying along the eastern boundary of the Wyangala batholith which occurs in the central part of the belt (Fig. 1). Fine- to medium-grained siliceous Ordovician clastic rocks make up the bulk of the country rock, and have been intruded by batholithic-scale granitoids. To the north and west of the study area, the structural history of both country and granitoid rocks have been studied in some detail (Hobbs 1965, 1966, Zee *et al.* 1985, Morand 1987), with workers reporting two or three deformational events. The immediate study area has been mapped by Gibson (1973), who concentrated on examining the geochemistry of the granitoid rocks.

Our work has brought to light at least four sets of closely related structures in the country rock. The granitoid rocks are also tectonically deformed, but show a much less complicated history. We consider these structures to have formed in a ductile shear zone (thrust) for reasons outlined in detail elsewhere (Tobisch & Paterson in preparation), but we summarize the main points briefly: dips of the main structural surfaces are gentle to moderate westward, orientation of stretching, rodding and early fold axes is down dip of foliation, and the sense of symmetry (vergence) of structures in both

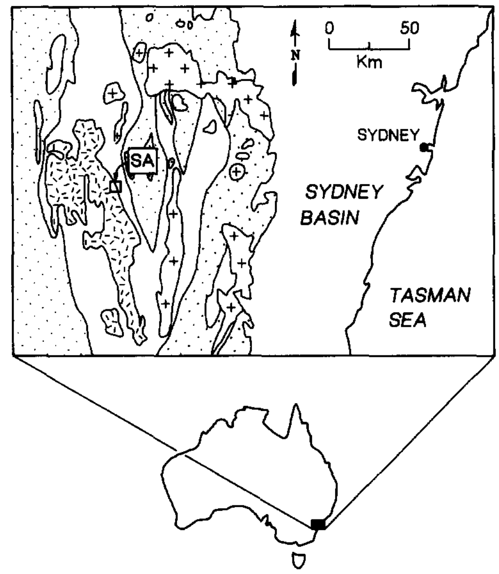

Fig. 1. Simplified map showing regional geological setting of study area (SA) within the Lachlan Fold Belt in SE Australia. Randomly oriented lines = Wyangala Batholith; crosses = other plutonic bodies; stippled = predominantly Silurian and Devonian sedimentary and volcanic rocks; no pattern = predominantly Ordovician sedimentary rocks; Sydney Basin = predominantly sedimentary rocks of Permo-Triassic age.

wall rock and granitoids (*S–C* fabrics) is consistently eastward.

The problem we are addressing in this paper is wonderfully elucidated in one or two thin sections of country rock, so we shall focus upon these to demonstrate our point. The sample shown in Fig. 2(a) comes from a zone of Ordovician quartzite and phyllite sandwiched between the edge of the Wyangala batholith and a satellite pluton to the east. Structures of a similar nature are not restricted to this area, but also occur in the Ordovician rocks east of the satellite pluton. The earliest recognizable tectonic structure is a moderate to intensely developed continuous cleavage (S_c) lying parallel or subparallel to compositional layering (S_b; Figs. 2a & b). Commonly, S_c is crenulated (S_{cr}) and eventually transposed into an intensely developed, often differentiated, crenulation cleavage (S_{cc}; Figs. 2a–c). Within certain lithologically controlled domains, S_{cc} develops into a transposed foliation (S_T) consisting of three components: the original continuous cleavage (S_c); a new continuous cleavage; and quartz-rich domains which constitute a new compositional banding (and contain relict crenulation morphology), all of which lie parallel or subparallel to each other (e.g. Fig. 2c; also, see arrow in lower left corner of Fig. 2a). In the field, it is often impossible to distinguish between these three planar structures, although in some thin sections they can be separately identified (Fig. 2).

Subsequently, a new set of crenulations which fold all earlier continuous and crenulation structures was developed with a comparable strike but a somewhat steeper dip (of axial planes) than the earlier structures. This set of crenulations is often only moderately developed and is relatively easy to differentiate from the earlier crenulations (Figs. 2b–c). However, domains exist in the field area where the intensity of this latest set of crenulations dramatically increases, and it assumes a comparable orientation and morphology of the earlier cleavages; in short, it becomes a new differentiated crenulation cleavage essentially with the same morphology as shown in Fig. 2(c). In some field exposures, this new crenulation cleavage is not only indistinguishable from the earlier crenulation set (S_{cc}) but also from the two earlier continuous cleavages. The rocks in these domains have gone through nearly two complete cycles of the sequence $S_c \rightarrow S_{cr} \rightarrow S_{cc} \rightarrow S_T$, and it becomes impossible to ascertain which foliation one is observing: is the foliation the original continuous cleavage (S_c), the first transposed continuous cleavage which formed from S_c, or an advanced stage of the newest crenulation cleavage? Making thin sections from such exposures sometimes resolves the problem, but it is impractical from a time/money perspective to sample every meter throughout the area, or even less, considering the scale over which structural changes occur in Fig. 2.

Foothills Terrane example

The general lithologic and structural framework of the Foothills Terrane in the west central Sierra Nevada of California (Fig. 4) has been outlined in earlier publications (Paterson *et al.* 1987, Tobisch *et al.* 1987, and in preparation). Slates overlying volcanic arc rocks have been subjected to a widespread late Mesozoic deformation which produced a slaty or phyllitic cleavage of variable intensity. Movement along a ductile shear zone (Bear Mountains fault zone) penecontemporaneous with the development of the slaty cleavage, has given rise to a zone of varying width (max <7 km) within which the metamorphic grade is higher and the structural history is more complex (dotted zone in Fig. 4). On the edge of this ductile shear zone, crenulations (S_{cr}) of the initial slaty cleavage (S_c) formed (Fig. 3a). Over short distances in this zone, the interlimb angle of the crenulations becomes smaller and a strong crenulation cleavage (S_{cc}) develops with orientations very close to the orientation of S_c (Fig. 3b). In some exposures, however, S_c has responded simply by rotating into the new direction without the intervening crenulation phase. In the most intensely deformed parts of the zone, the crenulation cleavage (S_{cc}) is completely transposed into a new continuous cleavage essentially indistinguishable from the initial slaty or phyllitic cleavage even in thin section (cf. Figs. 3a and 3c). This appears to be the case over a considerable area, although it is not possible to ascertain how widespread this transposition is for a number of reasons: (a) lack of continuous exposure; (b) the local presence of rapidly changing cleavage morphologies (i.e. crenulation cleavage $\rightarrow$ continuous cleavage within 1 m); and (c) the presence of another set of crenulations of variable intensity which post-dates the new continuous cleavage and has similar morphology and orientation to the earlier crenulation set just described.

Porphyroblasts of andalusite, cordierite and occasionally garnet bear well-developed internal fabrics (S_i) in certain samples and at least locally allow one to reconstruct the sequence of events in areas where complete transposition has occurred. In Fig. 3(c), for example, an early stage of crenulation of S_c has been preserved by the andalusite porphyroblast, while the external foliation continued to develop into a continuous cleavage (cf. Bell & Rubenach 1983). In areas (or exposures) within this ductile shear zone where these porphyroblasts are absent, however, we can only conjecture, as we have in the case of the Lachlan Fold Belt, as to the age of the dominant foliation in a given exposure: is the foliation the original continuous cleavage or is it a new continuous cleavage resulting from transposition of the earlier cleavage? And if crenulations are present, what cycle of transposition do they represent? In many exposures, there are not enough constraints to resolve this dilemma.

COMPOSITE FOLIATION

As we have shown for both the Lachlan Fold Belt and Foothills Terrane, domains of successive, morphologically similar, parallel foliations can develop in which it is not always possible to separate out the different components. In such domains, the concept of a composite foliation can be useful, and has been used by some workers (e.g. Turner & Weiss 1963, Williams & Compagnoni 1983, Lagarde & Michard 1986). The term, however, has not been sufficiently defined, and we suggest a definition of the term as follows: a *composite foliation* is a planar surface or group of surfaces whose components share similar morphological features and orientations. The process of generating a composite foliation can involve various mechanisms such as: (a) simple rotation of early foliation into a new direction without an intervening crenulation cleavage phase; (b) complex rotation of early foliation by passing through a crenulation cleavage phase, accompanied by transposition of layers or pre-existing cleavages with or without

Fig. 2. Photomicrographs (uncrossed-polars) of a large thin section (a) and two close-ups (b) and (c). Localities of close-ups are shown by white arrows in (a); (b) and (c) have been rotated *ca* 45° clockwise relative to their orientation in (a). See text for explanation of symbols. (a) Specimen shows most major structural elements found in area. S_b and S_c are oriented subhorizontal in photograph (except where folded). S_{cc} (expressed as a new continuous cleavage in some layers) dips gently to moderately to the left. In lower left corner (arrow), subhorizontal S_T consists of parallel components S_b, S_c, S_{cc} and a new continuous cleavage. Bar scale = 1 cm. (b) Details showing geometrical relation between $S_b + S_c$ (gently dipping to right), S_{cc} (horizontal) and S_{cr} (moderate dip to left). Bar scale = 0.5 mm. (c) Detail of strongly differentiated S_{cc} (horizontal) showing a new continuous cleavage in mica-rich layers; poorly preserved S_c in quartz-rich layers defines a relict S_{cr} formed earlier in the transposition cycle. Weak crenulations (e.g. lower right) of a new transposition cycle dip moderately to left. Bar scale = 0.3 mm.

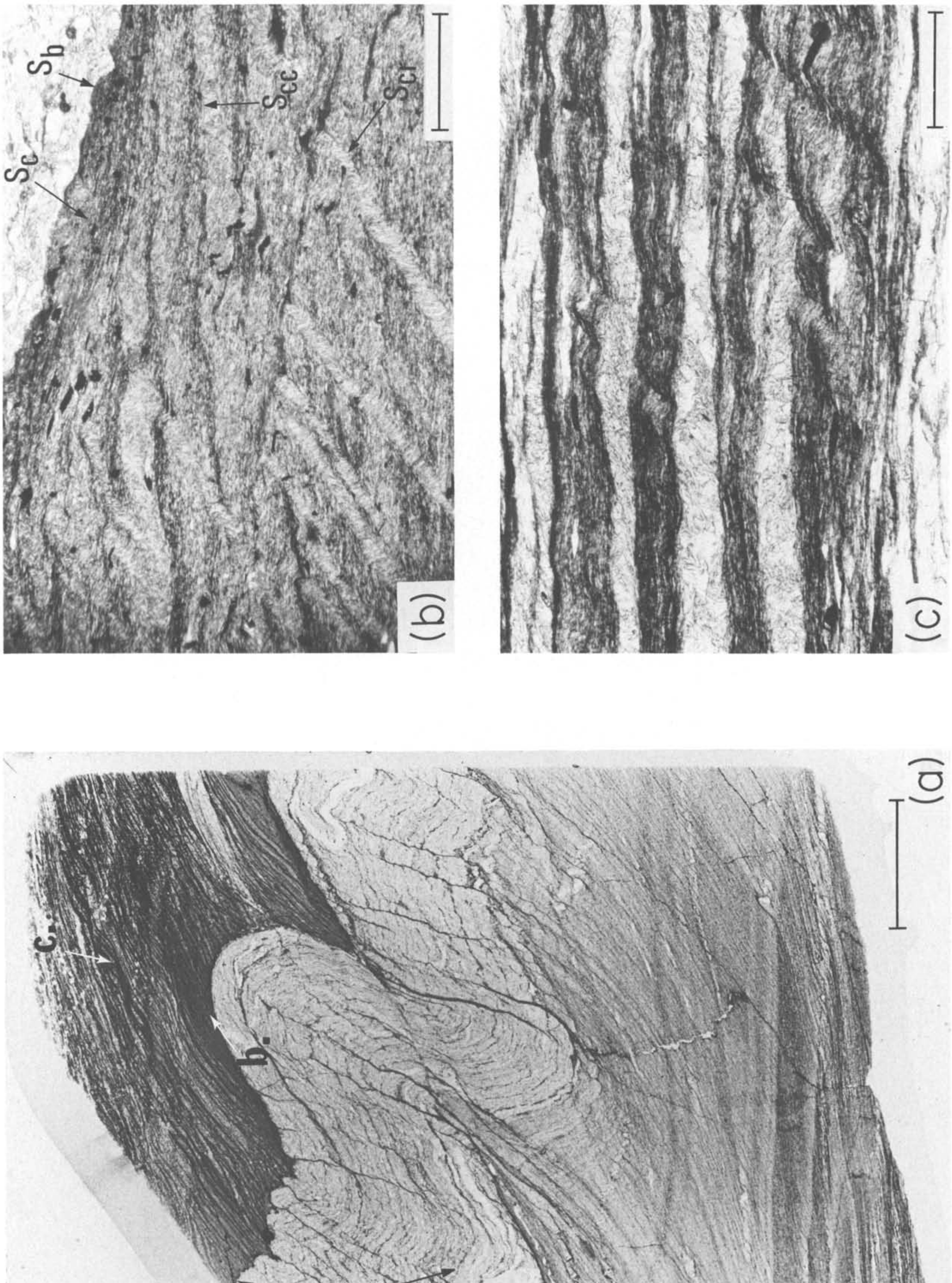

Fig. 2.

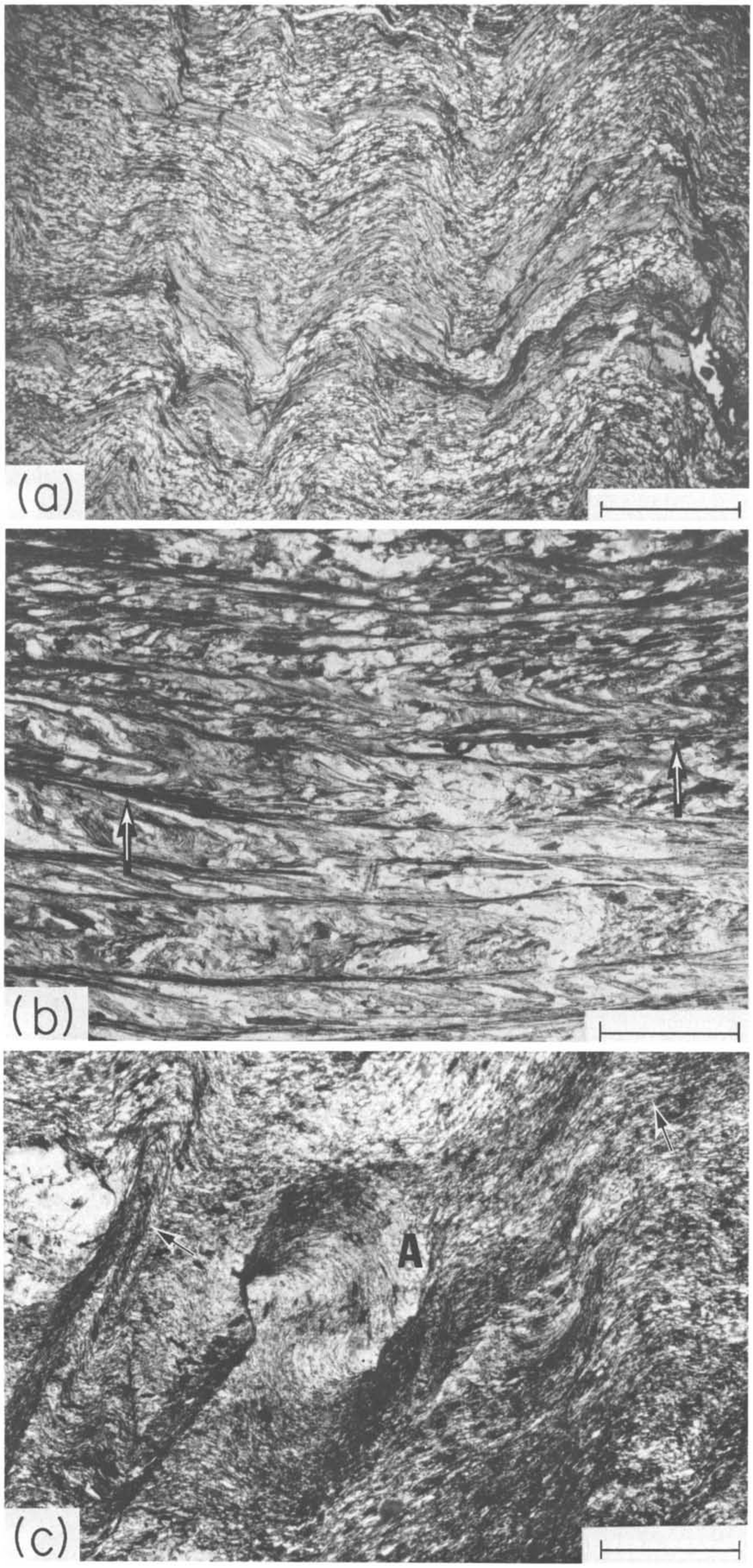

Fig. 3.

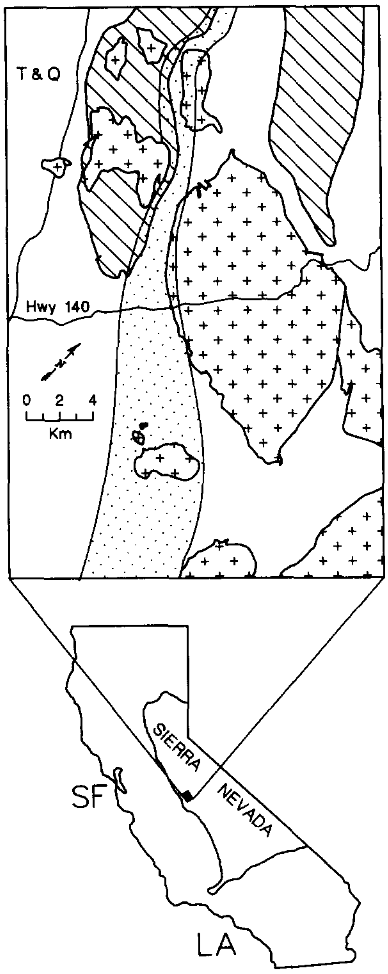

Fig. 4. Lower: location of field area in west central Sierra Nevada, California. San Francisco (SF) and Los Angeles (LA) are about 600 km apart. Upper: simplified geologic map of area. Crosses = late Jurassic to early Cretaceous granitoids; slanted lines = early to mid-Jurassic volcanic rocks; no pattern (except for T & Q) = mostly Jurassic sedimentary rocks; T & Q = mostly Tertiary and Quaternary deposits. Stippled zone represents region in which structures of Transposition Cycle II or higher are widespread (see text). Zone corresponds in part to the Bear Mountains fault zone.

differentiation; and (c) recrystallization and formation of neoblasts in the new direction. In addition, the composite foliation can include remnants of early isoclinal folds or other early and/or later structural elements which lie parallel or nearly parallel to each other, and where in most cases, it is difficult to distinguish when the various components were formed. Following Williams & Compagnoni (1983), we have notated this *composite foliation* as S_T.

The generation of a composite foliation in the areas outlined is a function of the partitioning of progressive deformation. In both the Lachlan Fold Belt and Foothills Terrane, domains where S_T is developed are different either in containing a more readily ductile rock type (e.g. mica-rich phyllite) and/or higher temperature metamorphic conditions from adjacent domains, and these factors have been important in partitioning a more involved deformation into these domains. Figure 2 summarizes this concept on a microscale, showing how differing rock types have partitioned the deformation into domains where (1) S_c, S_{cc}, new continuous cleavage and crenulations are clearly distinguishable (relatively high content of quartzite and/or the presence of such layers near mica-rich layers), from domains where (2) most structures are parallel and only S_T is distinguishable (mica-rich domains lying away from quartz-rich layers). The effect of rock type in controlling the intensity and type of strain in the Foothills Terrane has been documented on a regional scale as well (Paterson *et al.* in press). In addition, the ductile shear in the Foothills Terrane (Bear Mountains fault zone) is contained within a zone of higher grade metamorphism. It is likely that higher temperature and/or fluid activity in that zone may have contributed to the partitioning of a more complicated deformation history relative to adjacent domains (Tobisch *et al.* in review).

TRANSPOSITION CYCLES

The above considerations bring to light a very useful way to look at the timing of foliations showing different morphologies in multiply deformed regions, and most especially in ductile shear zones and their contiguous domains. We have pointed out how the original foliation (S_c) is likely to go through distinct stages in developing a new continuous cleavage ($S_c \rightarrow S_{cr} \rightarrow S_{cc} \rightarrow S_T$). Recently, Bell & Rubenach (1983) have discussed how different crenulation morphologies represent stages of progressive cleavage development. They demonstrated that a new continuous cleavage develops from a pre-existing one by passing through six stages. In areas of low-grade metamorphism and/or where the rocks lack abundant syn-tectonic porphyroblast growth, however, early and intermediary stages of new foliation development are not commonly preserved. Enlarging on their concept, we suggest from the examples given above and from observations we have made elsewhere, that three well-defined, easily identifiable stages of new foliation

Fig. 3. Photomicrographs (uncrossed-polars) of samples which show the progression $S_{cr} \rightarrow S_{cc} \rightarrow S_T$ (a–c, respectively), taken from within stippled area of Fig. 4. (a) S_c (horizontal) crenulated by steeply oriented S_{cr}. Large phyllosilicate is chlorite. Bar scale = 0.9 mm. (b) S_{cc} (horizontal) showing weakly differentiated layering. Note hinges of very tight to isoclinal crenulations occurring at left and right (arrows). Bar scale = 0.5 mm. (c) S_c completely transposed into a new continuous cleavage in the matrix, dips moderately to left (see arrow in upper right of photo). Andalusite porphyroblast (A in photo center) preserves a crenulation with axial planes also dipping to left, which represents an early stage in the transposition cycle. Note that the shared limb of the sigmoid (just to lower left of A) within the andalusite shows intensified S_c, which is characteristic of crenulation geometry but not a rotated crystal geometry. The new continuous cleavage (arrow, upper right) is deformed by a 'new' crenulation or localized crenulation cleavage (arrow, middle left) which dips steeply to left and represents a new transposition cycle. Bar scale = 0.5 mm.

development stand out and are commonly preserved whether syn-tectonic porphyroblast growth is present or not. These three stages can form sequentially and comprise what we call a *Transposition Cycle.*

Let us consider that the first Cycle (I) will be imposed on rocks that have not been previously deformed ductilely, and will result in a continuous cleavage developing in rock which may or may not have involved transposition of a sedimentary fissility (Weber 1981) and/or compositional layering:

Cycle I

S_b: bedding fissility and compositional layering

↓

S_c: continuous cleavage.

Cleavage morphologies which arise in this cycle have been treated by various workers (e.g. Gray 1977, Alvarez *et al.* 1978, Powell 1979). Subsequent cycles will all go through three general stages shown by:

Cycles II, III, etc.

Stage 1: S_{cr}—crenulation of S_c: crenulation cleavage and/or compositional differentiation is absent or minimally developed (Fig. 3a);

↓

Stage 2: S_{cc}—secondary cleavage and compositional differentiation is well developed, with a new continuous cleavage forming locally in very thin domains (Figs. 2 and 3b);

↓

Stage 3: S_T—new foliation is a composite of S_b, S_c, S_{cr}, S_{cc} and a new continuous cleavage; components may not always be easily identifiable (cf. Figs. 2 and 3).

In the ideal cycle, S_T eventually develops entirely into a new continuous cleavage which may show no vestige of the earlier foliations. The start of a new cycle of transposition, then, is shown by the formation of crenulations which fold the new continuous cleavage. In the examples illustrated from the two areas above, foliation development has progressed to Stage 2 of Transposition Cycle III (Figs. 2 and 3), although field observations in the Lachlan study area suggest that some specimens may have reached Stage 3 in some microdomains.

It is also clear from Figs. 2 and 3 that it is not always crucial for the cleavage to pass through every stage in the cycle or for the entire rock to completely transform through Stage 3, before a new cycle can start forming. In Fig. 2(c), for example, weakly formed crenulations (S_{cr}) folding the new continuous cleavage in the mica-rich layers represents the start of Transposition Cycle III in that layer, even though the rock on a larger scale is still in Cycle II (Stage 3, S_T). In addition, certain deformation mechanisms may exclude a given stage of new cleavage development. For example, if pressure solution is the dominant mechanism active in the early stages of a new Cycle, Stage 2 could be very weak (e.g. Gray 1977, fig. 1a) or even bypassed.

In any event, applying the concept of Transposition Cycles to areas of multiple deformation can provide a reasonably objective qualitative tool by which to indicate the relative complexity of the structural history of various domains, which in itself is a reflection of the degree of deformation partitioning between the domains. Within the stippled zone of Fig. 4, for example, widespread deformation has proceeded to Transposition Cycle II, Stage 3, or locally to Transposition Cycle III, Stage 2. Outside the stippled zone, the rocks show a continuous cleavage transposing bedding (Cycle I) or are undeformed (Cycle 0). Such notation can immediately communicate that rocks in some zones have undergone a more involved history than others. Plotting domains of like Transposition Cycles and/or stages on a map can provide a qualitative idea of the degree, location and extent of deformation partitioning on a regional scale. It also avoids the use of chronological notations (i.e. S_1, S_2, etc.), which can give a misleading impression of the spatial and temporal distribution of the structural elements. Integrating the concept of Transposition Cycles with other structural data such as orientation of structural elements, metamorphic mineral assemblages, etc., provides a powerful base from which to construct more realistic regional deformation models, and can assist in bettering our understanding of orogenic processes.

CONCLUSIONS

All the above leads up to the questions of: (1) how do we treat field situations where it is not possible to unequivocally ascertain which generation of foliation one is observing?; and (2) how do we interpret the regional timing of successive structures in areas of progressive deformation? We suggest that the answers come in several parts.

(1) Despite the difficulties touched upon above, we clearly need to know as precisely as possible what kind and how many 'generations' of structures are present at each point in a rock mass, what their characteristics are, how they are distributed, etc.

(2) However, the use of chronological subscripts for structural elements in complexly deformed regions was originally conceived on the assumption that all structures of like morphology and orientation have formed contemporaneously. We now know that this assumption is highly questionable, especially in ductile shear zones, but we continue to use chronological notation even though it can set the stage for unrealistic interpretations of how the rock body deforms. We therefore need to refine our language when discussing heterogeneously deforming rock masses. For example, it is common for workers to describe a region as having undergone three or four deformations, even though later structures (e.g. S_{cr}, etc.) occur only in isolated domains, leaving substantial parts of the region recording only one deformation (e.g. S_c). In such cases it would be very desirable not to make generalized statements which may mislead readers

into thinking that the entire area has undergone three or four regional deformations.

(3) To enhance the possibility of constructing realistic deformation models, we suggest that the nomenclature of structural elements be initially based on their *morphology*, rather than on their supposed time of formation. *Temporal notations should be used only if there is independent data available by which to rigorously relate the different structural elements to time,* either on an absolute scale by radiometric dating, or on a relative scale based on tightly constrained geological data. The latter relies on being able to identify bedding (S_0) or bedding fissility (S_b) in order to establish the first cycle (e.g. $S_b \rightarrow S_c$) of transposition in the rocks to which all subsequent cycles can be related. When such independent data are available, it is entirely appropriate to combine morphological and chronological notations, which can then provide an accurate statement of both the type and timing of structures. As an example of such a combination, one could notate the Transposition Cycles in the following manner:

$$\text{Cycle I}\begin{cases} S_b \\ \\ S_{c1} \end{cases};\ \text{Cycle II}\begin{cases} S_{cr2} \\ S_{cc2} \\ S_{T2} \end{cases};\ \text{Cycle III}\begin{cases} S_{cr3} \\ S_{cc3} \\ S_{T3} \end{cases};\ \text{etc.}$$

Since the notation S_T does not clearly specify the nature of the foliation formed during later cycles, it could be delineated precisely in descriptive terms (e.g. S_T consists predominantly of alternating domains of new continuous cleavage and S_{cc}, etc.).

(4) If one can document the progressive relationship of structures on a regional scale, the deformation should be considered as *one composite deformation*, consisting of various components (e.g. morphologies) which represent different deformational stages in the evolution of that rock body. Since the different morphologies (e.g. S_c, S_{cr}, etc.) may form at various times in different parts of a progressively deforming mass, they may be more realistically viewed as being largely penecontemporaneous rather than representing discrete pulses of deformation separated by geologically meaningful periods of time.

(5) We need to integrate the concept of deformation partitioning more fully into our interpretations of deforming rock masses, and accept the likelihood that every part or domain of a deforming rock mass will have its unique deformation path. To gain a realistic picture of how the rock mass *in toto* is responding to regional stress, *it is important to establish the areal extent of domains showing a similar history, as well as the relationship between domains showing differing histories.* Parameters used to define a similar history might include the complexity of deformation, basic rock types, prevailing physical conditions (metamorphic history) and so forth. In this way we are focusing our analysis on the relationship between various domains, rather than on the zones of complexity which tend to attract our attention more readily.

(6) In summary, we suggest the use of a morphological classification of structural elements with the addition of numerical subscripts only when independent evidence allows. Application of the concepts of a composite foliation (S_T) and the Transposition Cycle can assist in a more objective and rigorous analysis of the timing of foliations and other structural elements in a given area, as well as contribute to the delineation of domains of differing structural history and their interdependency during deformation. This approach is likely to provide an objective and healthy basis from which we can create more realistic models and thereby gain greater insight into the manner by which the larger rock mass has evolved.

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