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Shear zone origin of quartzite mylonite and mylonitic pegmatite in the Coyote Mountains metamorphic core complex, Arizona

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Abstract—Mylonites derived largely from granite, pegmatite and sedimentary quartzite occupy a 500 m thick, gently N-dipping zone along the northern flank of the Coyote Mountains, west of Tucson, in southeastern Arizona. The quartzite mylonites are exceptionally well developed and occur as discrete layers and lenses, 2–5 m thick, within yet thicker, boudinaged, sill-like lenses of mylonitic pegmatite. Mylonitization took place in the Tertiary within a normal-slip ductile shear zone. The shear zones formed in response to regional extension of continental crust. Extension is along a north–south line, and N-directed sense of shear is revealed by mica fish, oblique foliations in dynamically recrystallized quartz aggregates, and asymmetric quartz *c*-axis fabrics. The microstructures and *c*-axis fabrics, taken together, disclose that ductile and brittle deformation was achieved by intense, penetrative, non-coaxial laminar flow dominated by progressive simple shear.

INTRODUCTION

DETAILED structural studies of metamorphic core complexes in southeastern Arizona have disclosed that thick mylonitic tectonites were fashioned in normal slip shear zones which accommodated regional crustal stretching during the Tertiary (Davis 1980, 1981, 1983, Davis *et al.* 1981, Davis & Hardy 1981). The Coyote Mountains, west of Tucson, figured in an important role in elucidating both the shear zone origin and the Tertiary age of the metamorphic core complexes. Evidence for ductile normal shearing is well expressed in the structural geology and structural petrology of exceptionally well exposed quartzite mylonite and mylonitic pegmatite (Davis 1977, 1980, Gardulski 1980, Davis *et al.* 1981). In this paper we call attention to the kinematic significance of the mylonitic rocks by discussing structural and microstructural expressions of the Tertiary deformation.

GEOLOGIC SETTING

The Coyote Mountains are located about 45 km southwest of Tucson, Arizona, within the Desert subprovince of the Basin and Range tectonic/physiographic province (Fig. 1). They lie at the northern end of the Baboquivari Mountain complex, made up of the Pozo Verde, Baboquivari, Quinlan, and Coyote Mountains. The rocks of

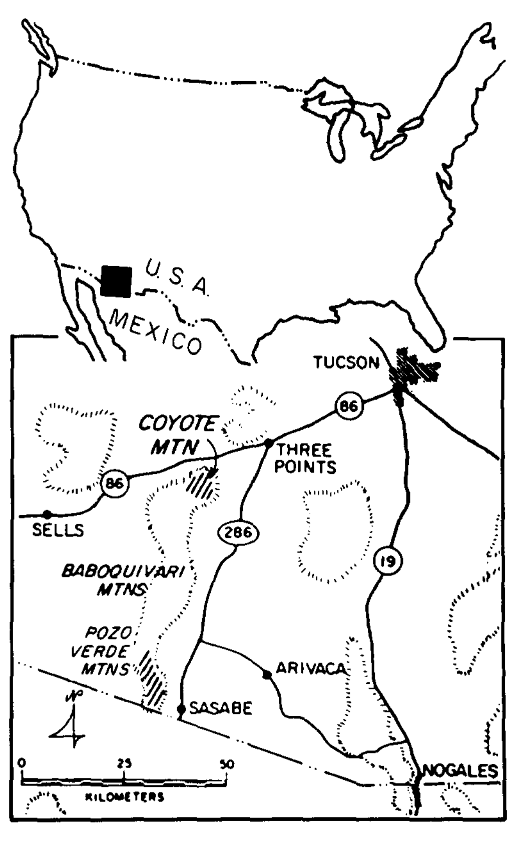

Fig. 1. Location of Coyote Mountains in southern Arizona, U.S.A.

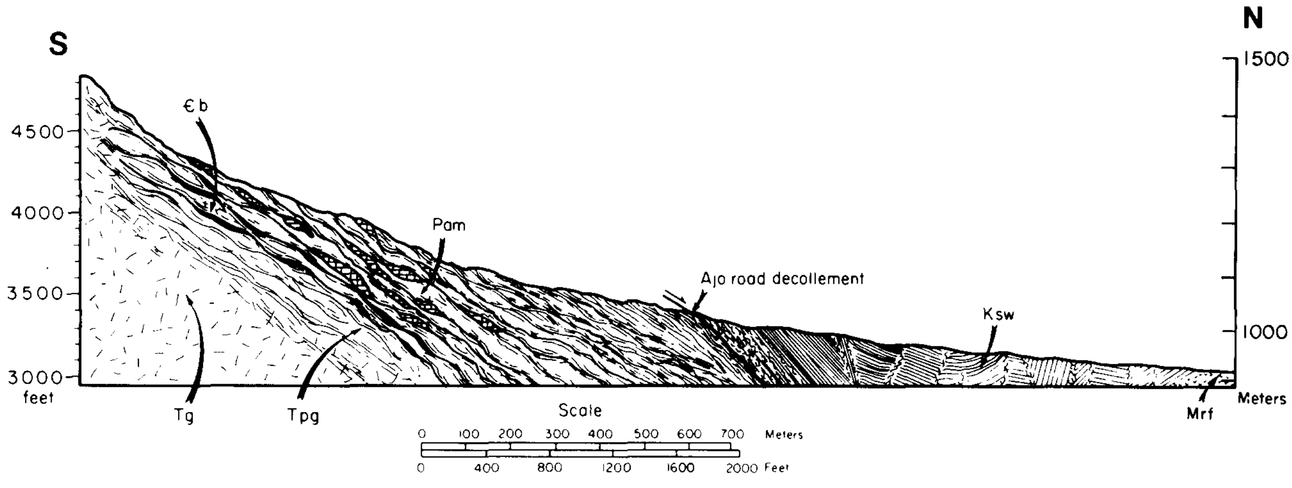

Fig. 2. Cross-section showing geologic relationships within Coyote Mountains study site. Tg = Pan Tak granite, Tpg = pegmatites of Pan Tak granite, Єb = Bolsa Quartzite (Cambrian), Pam = Abrigo and Martin Formations (Cambrian and Devonian), Mrf = Roadside Formation (probably Cretaceous), Ksw = Sand Wells Formation (Cretaceous).

interest are mylonites derived from granite, pegmatite and sedimentary quartzite. These mylonites occur at the extreme northern end of the Coyote Mountains and lie immediately beneath a system of mid-Tertiary detachment faults. Exposures of these mylonites were identified as core complex tectonites by Davis (1977, 1980), who mapped them at a scale of 1:62,500 and described and measured the physical and geometric characteristics of the mesoscopic fabric elements.

The country rock framework of the Baboquivari Mountain complex is dominantly composed of Mesozoic rocks (Heindl & Fair 1965, Haxel *et al.* 1980, Haxel *et al.* 1984), except within the Pozo Verde and Coyote Mountains where there are significant Tertiary granites and pegmatites. Haxel *et al.* (1980) have named these rocks "granites of the Presumido type", where Presumido refers to Presumido Peak in the northern part of the Pozo Verde Mountains. These granites are muscovite–garnet–biotite per-aluminous granites which generally are fine- to medium-grained hypidiomorphic in texture. Haxel *et al.* (1980) distinguished an older leucocratic phase which contains little garnet, and a younger, white-weathering leucocratic phase which usually has garnet. The Pan Tak granite in the Coyote Mountains, one of the Presumido granites, was dated at 58 ± 3 Ma based on U–Pb isotopic analysis of zircons (Wright & Haxel 1980, 1982).

The Baboquivari Mountains have been interpreted by Haxel *et al.* (1984) as a fenster within a Late Cretaceous to Early Tertiary thrust-fault system. Haxel *et al.* (1984) convincingly argue that the Pan Tak granite and other granitic bodies of the Presumido type are anatectic melts representing the culmination of a (Laramide) crustal-shortening orogenic episode that commenced in late Cretaceous time. Tertiary mylonitization, chloritic brecciation and detachment faulting were superimposed on the 58 Ma granitic rocks. The time of formation of the mylonites, as noted by Haxel *et al.* (1984), can be bracketed between 58 Ma and approximately 28 Ma.

LITHOLOGIES OF THE COYOTE MOUNTAINS STUDY SITE

The general geology of the study site is shown in structure profile view in Fig. 2. The profile, based on detailed mapping by Gardulski (1980), shows a number of lithologic units, ranging in age from Lower Paleozoic to Tertiary. The rocks which constitute the main focus of this paper are the Pan Tak granite (Tg, Tpg) and the Cambrian Bolsa Quartzite(Єb). Both the granite and the quartzite were transformed into mylonitic rocks in the Tertiary. Additionally, rocks of the Cambrian Abrigo and Devonian Martin Formations (Pam) locally occur within the zone of mylonitic tectonite and crop out as deformed calc–silicate and marble assemblages.

A décollement zone, the Ajo Road décollement (Fig. 2), separates mylonitic tectonite from overlying non-tectonite, unmetamorphosed sedimentary and volcanic rocks. Closest to the décollement are andesitic to latitic volcanic flows, breccias and derivative sedimentary rocks of the Roadside Formation (Mrf). Heindl (1965) assigned a Cretaceous age to this lithologic assemblage. Overlying the rocks of the Roadside Formation, but still within the upper-plate detachment, are red clastic sedimentary rocks of the Cretaceous (?) Sand Wells formation (Ksw) (G. Haxel, personal communication, 1980).

The Bolsa Quartzite is the basal formation of the Paleozoic section in southeastern Arizona. Although originally a sedimentary unit, the Bolsa Quartzite crops out in the Coyote Mountains as a highly foliated, strongly lineated tectonite. At the Coyote Mountains study site it is a mineralogically homogeneous, quartzite mylonite containing only very minor feldspar, biotite, muscovite, and heavy minerals. It is white, gray, black, or more rarely, maroon in outcrop. The total exposed thickness of the quartzite is estimated at 30 m. Assigning this quartzite mylonite to the Bolsa Quartzite is an interpretation which we think is compatible with the

Fig. 3. West-directed view of part of Tohawa Canyon showing pegmatite (white) and interlayered quartzite (dark gray layered rocks). Saguaro cacti are 3–5 m tall.

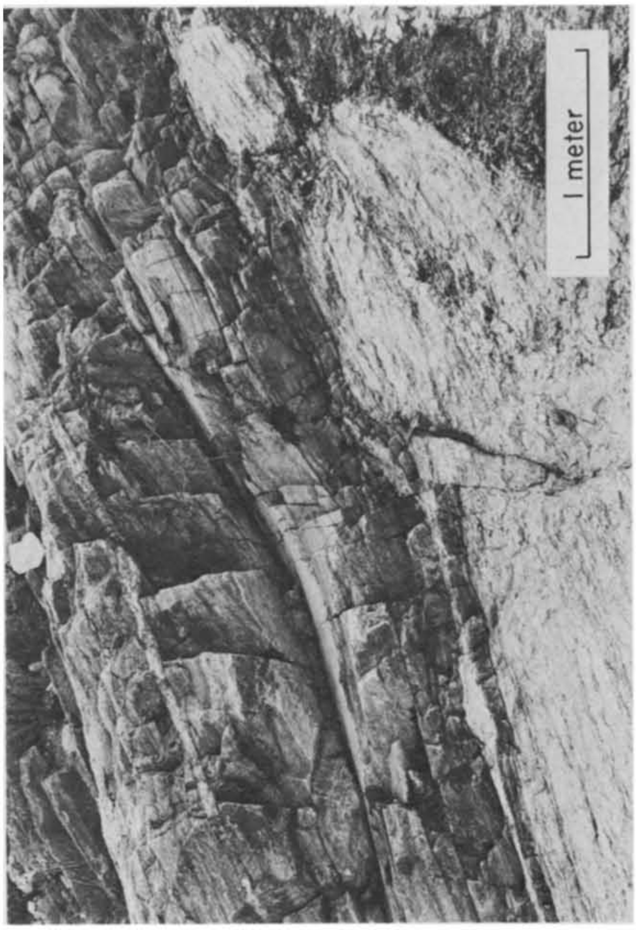

Fig. 4. Contact between quartzite mylonite (gray) and mylonitic pegmatite (white). Note normal faults and overlying drape.

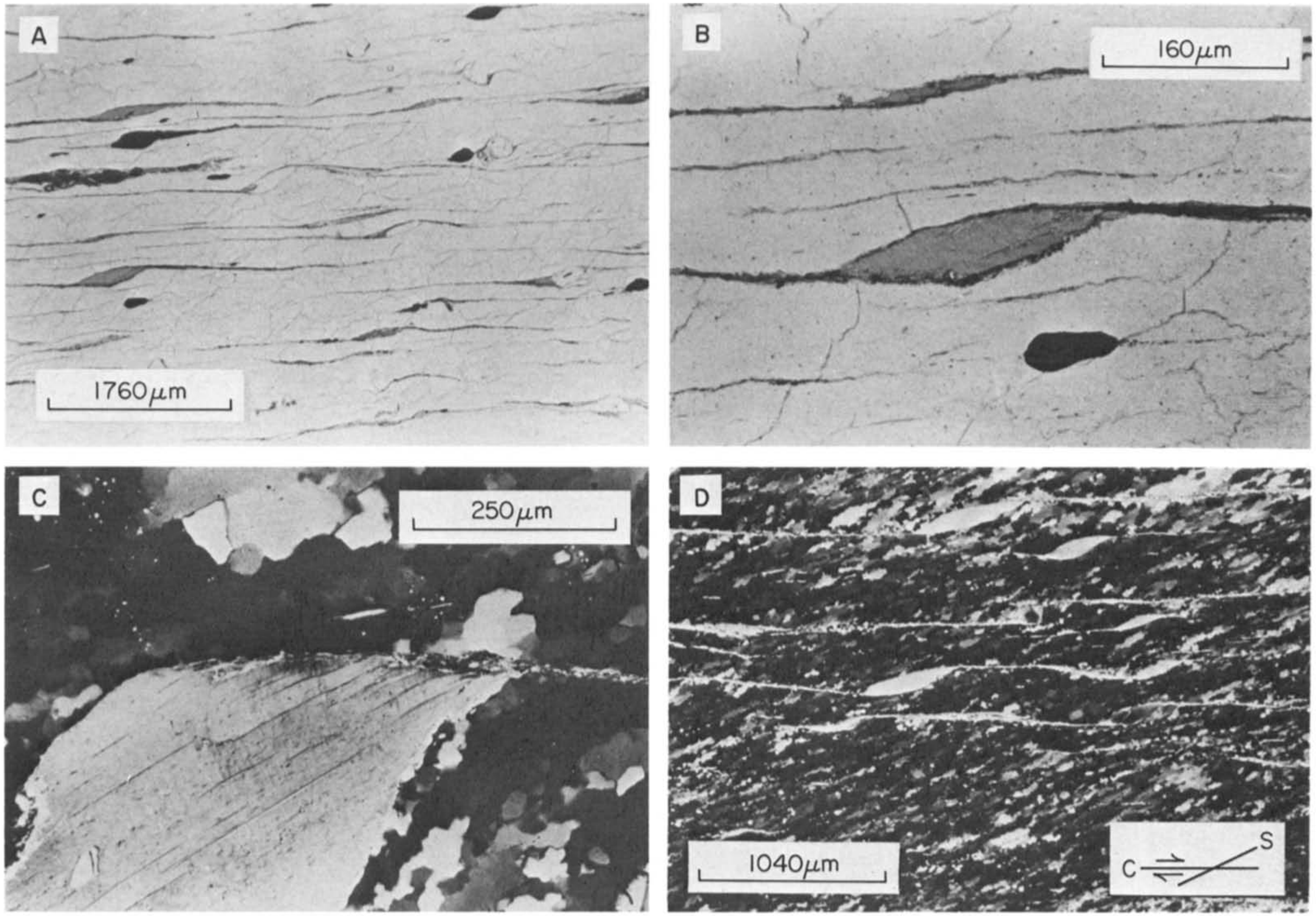

Fig. 6. (A) Mica 'fish' (gray) in quartzite mylonite. Dextral sense-of-shear is disclosed by the geometric nature of the stair–step relation of each 'fish' to microscopic shear bands (dark horizontal lines). (B) Close-up view of mica 'fish' and interconnecting microscopic shear bands. (C) Yet closer view with mica 'fish' trail smeared out from top of the mica. (D) Quartzite mylonite showing mica fish (white), microscopic shear bands (white lines, horizontal), and dynamically recrystallized quartz aligned obliquely to the shear bands.

mineralogy and its structural position underneath recognizable Abrigo and Martin Formations.

The Abrigo and Martin Formations are composed of limestone, dolomite and calcareous sandstone. Metamorphism has produced mineral assemblages containing garnet, epidote, and diopside. Locally the rocks have been metamorphosed to massive skarns, but in general the bedding is still recognizable.

As defined by Haxel *et al.* (1980), the Pan Tak granite has four phases—an older equigranular granite and three younger phases. These younger phases include equigranular coarse-grained granite, xenomorphic medium-grained granite, and swarms of pegmatites. The pegmatites comprise a large part of the northern Coyote Mountains. The phase of the Pan Tak granite which yielded the 58 Ma age (Wright & Haxel 1982) is the younger equigranular coarse-grained granite. The pegmatites are even younger.

The older granitic phase of the Pan Tak granite does not occur in the study area. The younger phases do crop out, but because they are nearly identical compositionally and so intimately mixed, they are generally impossible to map as discrete units. The pegmatite and granite are commonly gradational, and there are few examples of clear-cut intrusive relationships between the phases. Mineralogically, the pegmatite and granite consist of quartz, microcline, albitic plagioclase, biotite, and locally abundant muscovite and garnet. In some sills, a delicate zoning is developed as compositional banding.

STRUCTURAL GEOLOGY OF THE TECTONITES

General relationships

The shear zone of mylonitic tectonite is exceptionally well exposed in a canyon that Gardulski (1980) informally named Tohawaw Canyon (Fig. 3). The Tohawaw Canyon study site is mainly a broad expanse of tectonite pegmatite, some of which is mylonitic. Quartzite mylonite layers are exposed in the walls, but the undulating floor seems to be a structural surface on the top of a series of pegmatite layers and lenses from which the once overlying quartzite has been eroded. Quartzite mylonite derived from the Bolsa Quartzite is interlayered with sill-like bodies of pegmatite, the outer margins of which are converted to mylonitic tectonite. There are usually good exposures of the quartzite in shear-zone contact on the tops of underlying pegmatite which displays pinch-and-swell morphology.

Bolsa Quartzite

The Bolsa Quartzite is lineated mylonite wherever it crops out in the northern Coyote Mountains. A *very strong* mineral lineation and foliation penetrate the rock, and these elements are defined by the orientation of streaked plates of muscovite and biotite as well as by elongate quartz grains. Foliation strikes W–NW and dips gently N–NE; lineation plunges gently N.

In thin section, the quartz grains are seen to be undulose and variably recrystallized. Elongation of quartz parallel to the lineation is quite pronounced, in spite of recrystallization. Original grain shape is not preserved.

Small pinch-and-swell features with wavelengths of 1–10 cm occur locally in the quartzite mylonite, and the foliation and lineation have been warped by these small structures. These linear structures trend perpendicular to the lineation. Where quartzite layers are thin (0.5 cm) and alternating with concordant veins of pegmatite, this pinch-and-swell feature more closely resembles mullion structures whose presence is due to the competency contrast of the two media. They occur where underlying pegmatite has been stepped-down by normal faulting, thus requiring the quartzite mylonite to undergo an extra high degree of local stretching.

Small normal–slip faults occur locally in the quartzite, and slip ranges from 1 mm to 20 cm in the direction of plunge of the lineation. Normal–slip faults with larger amounts of slip are rare, but they affect both quartzite and pegmatite (Fig. 4).

Pan Tak granite

The coarse-grained young phase of the Pan Tak granite has developed a strong foliation and lineation which may be considered penetrative within the constraints of its grain size and mineralogic heterogeneity. Quartz grains show features typical of plastic deformation: undulatory extinction, grain elongation and recrystallization. A great deal of the strain in the granite appears to have been accommodated in the quartz component of the lithology, while the feldspar fraction has been merely fractured and microfaulted.

This style of deformation is also characteristic of the pegmatite phase but it is not as penetrative. Discrete slip surfaces exist in the pegmatite, and these are well-developed only at the margins of the pegmatite bodies. They become very closely spaced as contacts with the quartzite are approached.

Where sedimentary rock packages are insignificant within large volumes of pegmatite, as in the southeastern part of the map area, fairly widely spaced slip surfaces are developed through zones as thick as 100 m. The zones of slip surfaces are separated by undeformed rock, and such alternating bands of deformed and apparently undeformed rock may be traced east and west along strike for hundreds of meters.

Striated surfaces, spaced centimeters apart, pervade many parts of the mylonitic pegmatite exposed in the study site. The surfaces display a range of orientations, but mostly they strike E–W and dip at gentle to moderate angles, either N or S. These surfaces are interpreted to be a result of extensional stretching and normal–slip. Striae on these surfaces trend N. Some surfaces are spoon-shaped, with dip–slip striae in the depression and strike–slip striae on the walls. The stretching accommodated by the formation of these striated normal fault surfaces is revealed in a structural profile constructed by

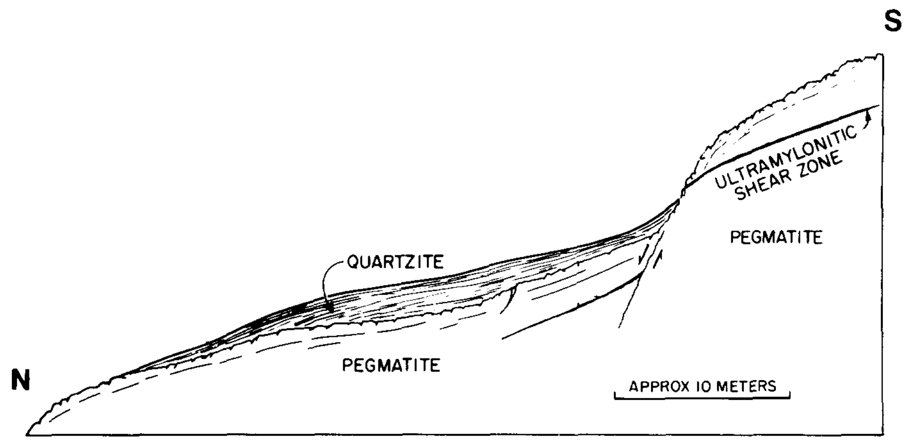

Fig. 5. Structural profile showing striated surfaces and small-scale normal–slip faults along contact between pegmatite and quartzite.

S. L. Beard (Fig. 5). Data were collected along a line parallel to lineation. The profile shows the stretched nature of a discrete pegmatite/quartzite contact.

MICROSTRUCTURES IN QUARTZITE MYLONITE

S–C fabrics

The Coyote Mountains is a spectacular type locality for a class of fabrics and microstructures described by Lister & Snoke (1984) as type II S–C mylonites. The quartzite mylonites have a dominant mylonitic schistosity that is defined by C-surfaces (in the sense of Berthé *et al.* 1979), and these C-surfaces contain elegant mica 'fish', stair-stepping mica 'fish' trails, and various other kinematic indicators (Fig. 6). The C-surfaces have in many cases been interpreted to involve actual displacement discontinuities formed during ductile deformation that produced the mylonite. Furthermore there are oblique foliations (oblique with respect to C-surfaces) apparently formed during dynamic recrystallization. This obliquity is interpreted to indicate periodic resetting of the finite strain 'odometer' by recrystallization during progressive simple shear (Lister & Snoke 1984).

The C-surfaces most commonly are delineated by trails of tiny white mica fragments, but other minerals like biotite and pyrite help define the C-surfaces as well (Fig. 6d). The S-surfaces are expressed by individual elongate quartz grains, alignment of segments of grain boundaries, and aligned domainal aggregates of recrystallized quartz having similar *c*-axis orientations. Such domains may occupy the locations of pre-existing, now recrystallized, larger grains.

The most common kinematic indicators observed in thin-section are asymmetric mica 'fish', stair-stepping mica 'fish' trails, and oblique foliations. These microstructures consistently reveal that the Coyote Mountains shear zone accommodated a N-directed, normal–slip sense of shear.

Quartz c-axis fabrics

The microstructures present in the quartzites suggest that flow was achieved by either progressive simple shear, or by non-coaxial laminar flow with a strong component of progressive simple shear.

Distinguishing the relative roles of coaxial versus non-coaxial deformation was explored by examining the nature of the *c*-axis fabric. The working hypothesis is: if the deformation is coaxial, the *c*-axis fabric should form symmetrically with respect to the grain shape foliation (Lister & Hobbs 1980). But if the deformation approximates progressive simple shear, and the mica 'fish' trails do indeed mark C-surfaces aligned closely with the orientation of a 'bulk' shear direction, the quartz fabric should have a skeleton with elements nearly perpendicular to mylonitic lineation and to C-surfaces. Furthermore the quartz *c*-axis fabric skeleton should be inclined at approximately 30° to the grain shape foliation.

Thin sections from several localities within the Coyote Mountains were checked photometrically, and the fabrics in general were found to be inclined approximately 30° to the grain shape foliation, and slightly forward inclined (with respect to the inferred sense of shear) relative to the orientation of the C-surfaces. This suggests to us that the bulk deformation was not coaxial, and that dominantly progressive simple shear created the mylonite.

To explore the kinematic significance of the mylonites even further, four *c*-axis fabrics were measured using a digital U-stage (Fig. 7). The *c*-axis pole figures show incomplete fabrics. The presence of partially clad fabric skeletons generally can be attributed to one or more of several factors: (a) during a complex deformation history the symmetry of the deformation path deviates from a monoclinic pattern; (b) a pre-existing fabric is not completely overprinted by the dominant, superposed fabric; (c) a few large grains in the original protolith deform and recrystallize during deformation to produce the measured population of grains, but the effect of dynamic recrystallization is not sufficient to simulate the effects of a wholly random initial orientation distribution (see Lister & Williams 1979).

Interpreting the incomplete *c*-axis pole figures was aided by constructing a synoptic plot of maximum orientations, skeletal outlines, and pole-free areas (Fig. 8). Such synoptic diagrams have been utilized successfully

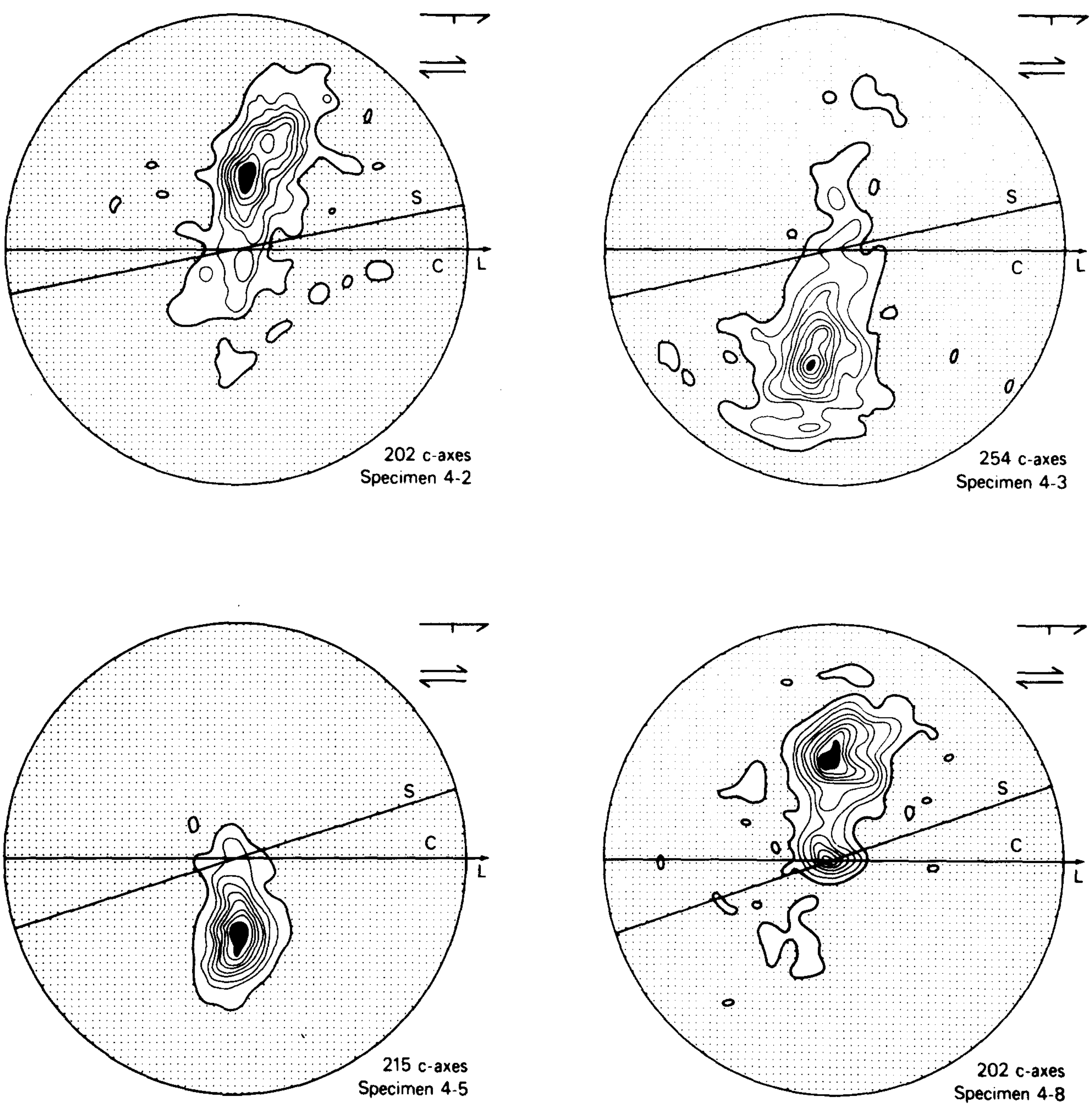

Fig. 7. Lower-hemisphere equal area projections of *c*-axes of quartz in four specimens of quartzite mylonite. Asymmetry of single girdle discloses dextral sense-of-shear. S is defined by grain shape orientations in dynamically recrystallized quartz aggregates. C is defined by the best developed discrete surfaces and mica trails. L is the orientation of penetrative mineral lineation as measured in outcrop.

by Van Roermund *et al.* (1979), Lister & Williams (1979), and Behrmann & Platt (1982). The synoptic plot for the Coyote Mountains data shows a typical 'dog-leg' single girdle fabric, a pattern which has been commonly reported in major ductile shear zones (Bouchez & Pêcher 1981, Lister & Williams 1979). The S-surface marked in Fig. 8 is the orientation of the grain shape foliation. Skeletal elements in the fabric are inclined at approximately 30° with respect to this foliation, consistent with the obliquity of fabric to grain shape foliation expected in normal–slip ductile shear zones. The C-surface noted is the orientation of the longest, most planar mica 'fish' trails in the individual thin sections. We consider it to be the closest approximation to the bulk shear plane as viewed on the scale of an individual thin section. The fact that the central part of the fabric skeleton is nearly perpendicular to the C-planes (and to the mylonitic lineation) is consistent with theoretical predictions for fabric development during progressive simple shear (Bouchez *et al.* 1983, Lister & Williams 1979), and hence supportive of the argument that bulk simple shear is the deformation causing development of the observed microstructure.

INTERPRETATION OF OVERALL GEOMETRY

The mylonitic pegmatites appear to be intrusions which have been modified to sill-like forms (see Fig. 3) by shortening and stretching accompanying normal–slip

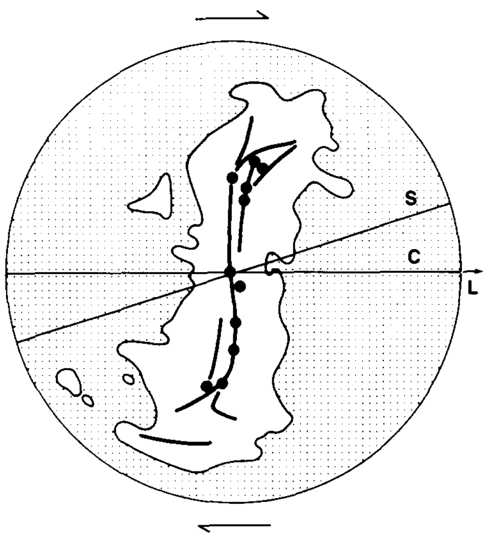

Fig. 8. Synoptic plot of maximum orientations of *c*-axes, showing 'dog-leg' single girdle fabric and interpreted sense of shear. Black dots are maxima for individual fabric diagrams.

simple shear. We do not regard the pinch-and-swell forms of the pegmatites to be primary, nor do we believe that pegmatite intrusion alone could have produced the penetrative deformation exhibited by the quartzite mylonite lenses. Both the pegmatite and the quartzite were deformed concurrently, by the same movements. Rheological responses were such that the quartzite experienced ductile behavior between more competent pegmatite layers and lenses, which experienced both brittle and ductile behavior.

The contact relationships and internal structures resulted from dominantly simple shear movements. The ductile shear zone contacts differ markedly from ordinary fault contacts because they typically do not display any physical break like a fracture surface. Instead, such contacts appear as if one rock were welded or smeared onto the other as a result of plastic deformation (Ramsay 1980). A foliation is imparted to the rocks but no cohesion is lost at the boundary. Normal–slip ductile shearing, along with the conspicuous penetrative normal–slip faulting, accomplished profound stretching and attenuation. The quartzite mylonites accommodated very large shear strains, the exact range of magnitude of which has not been determined. Locally shear strain may have been in excess of 20, based on the geometry of mica 'fish' trails. Unfortunately, no estimate of stratigraphic attenuation was possible.

TECTONIC SIGNIFICANCE

The zone of quartzite mylonite and mylonitic pegmatite in the northern part of Coyote Mountains represents a ductile shear zone of subregional to regional proportions, only a small part of which has been exposed to view. The ductile shear zone expresses the results of regional tectonic movements which stretched and thinned upper-crustal rocks in the southern Basin and Range in the Tertiary (Davis 1983). The location of the shear zone may have been pre-determined by the site of intrusion of the Pan Tak granite and related pegmatites. The thermal input of these bodies may have softened the country rocks, and the rheology of the cooling igneous bodies and the locally heated country rock would have made the northern Coyote Mountains a site vulnerable to ductile flow once continental extension commenced.

Development of the tectonite was completed before displacement on the Ajo Road décollement, a detachment fault which separates tectonites from non-tectonite sedimentary and volcanic cover. Middle Miocene brittle deformation along the décollement contact was achieved by normal-slip faulting along the same azimuth as that of lineation in quartzite mylonite. This kinematic coordination, which exists for all core complexes in the southern Basin and Range (Davis 1981), suggests that there may have been a prolonged continuum of Tertiary extensional deformation, episodes of which contributed in different ways to the overall goal of stretching and thinning the continental crust.

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