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Structural evolution of the Whipple and South mountains shear zones, southwestern United States

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ABSTRACT

The Whipple and South mountains of the southwestern United States have undergone a strikingly similar sequence of deformations. In both ranges, gently dipping mylonitic fabrics have been overprinted by successively more brittle structures associated with a low-angle detachment fault. Kinematic indicators reveal that the mylonitic rocks, brittle structures, and detachment faults are kinematically coordinated and were all formed by top-to-the-northeast shear. The structural evolution of both areas can be explained in terms of major, shallow-dipping shear zones that accommodated Tertiary crustal extension. We suggest that detachment faults and associated zones of brecciation, cataclasis, and seismic slip were originally continuous downdip along the low-angle shear zones into mylonitic gneisses formed below or near the ductile-brittle transition. As the mylonites were drawn out from beneath the brittlely extending upper plate, they were progressively uplifted above the ductile-brittle transition and were overprinted by successively more brittle structures.

INTRODUCTION

In recent years, geologists working in the North American Cordillera have recognized a number of areas where major, gently dipping detachment faults separate a brittlely distended upper plate from a lower plate consisting of plutonic and metamorphic rocks that are commonly overprinted by a shallow-dipping mylonitic fabric. These areas, which have been termed metamorphic core complexes (Coney, 1973, 1980), have been the subject of controversy, mostly revolving around the kinematic and tectonic significance of mylonitic fabrics in the lower-plate rocks (Crittenden et al., 1980). One controversy concerns whether the mylonitic fabrics are the result of coaxial or noncoaxial deformation (i.e., pure shear or simple shear) and whether such deformation was caused by crustal shortening or extension. There has also been considerable debate about what genetic relationships exist between mylonitization and detachment faulting. Some models for core-complex evolution link mylonitization and extensional faulting together as synchronous ductile and brittle manifestations, respectively, of Tertiary crustal extension. Variations on this general theme include crustal-scale boudinage (G. H. Davis and Coney, 1979; G. H. Davis, 1980a), ductile stretching at depth with in situ brittle extension at higher crustal levels (Rehrig and Reynolds, 1980; Miller et al., 1983), and extensional shear zones of regional extent (G. H. Davis, 1980b, 1983; Wernicke, 1981; Reynolds, 1982, 1985; G. A. Davis et al., 1983; Lister and Davis, 1983). Another group of models suggest that the mylonitic fabrics are genetically unrelated to younger detachment faulting (Thorman, 1977; Howard, 1980; G. A. Davis et al., 1980; Frost, 1981).

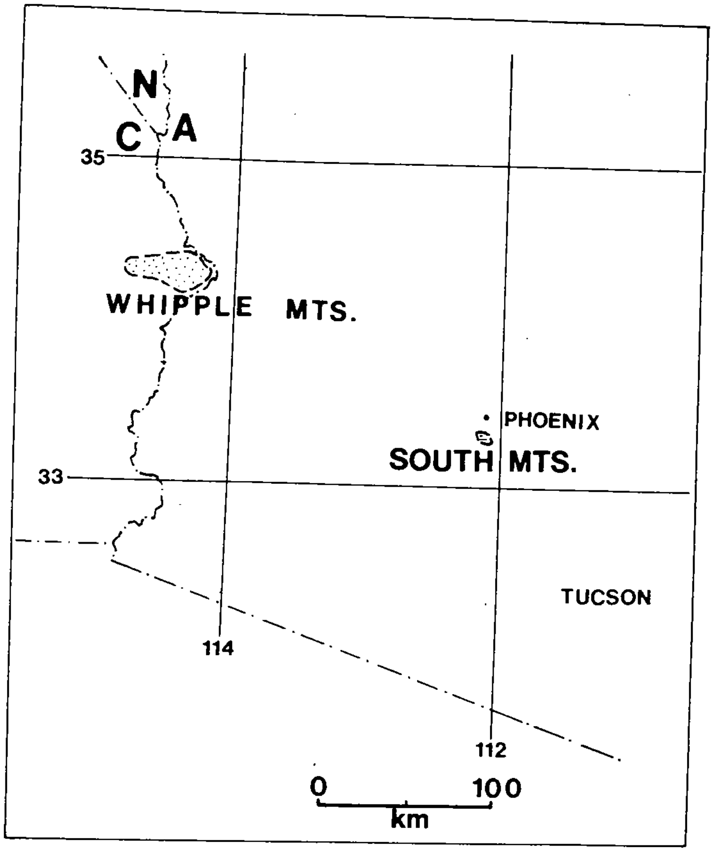

Figure 1. Location map for Whipple Mountains, California (C), and South Mountains, Arizona (A). N = Nevada.

A comparative analysis of the Whipple Mountains (southeastern California) and South Mountains (central Arizona) demonstrates striking similarities in structural evolution, even though the two areas are located 225 km apart (Fig. 1). In this paper, we briefly summarize the structural evolution of the two areas, discuss the kinematics of mylonitization and detachment faulting, and present evidence that at least some Cordilleran metamorphic core complexes represent evolving crustal shear zones developed during Cenozoic extensional tectonics.

STRUCTURAL EVOLUTION OF THE COMPLEXES

In both the Whipple Mountains (WM) (G. A. Davis et al., 1980, 1982) and the South Mountains (SM) (Reynolds, 1985; Reynolds and

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Rehrig, 1980), we have evidence for the following sequence of deformational events:

1. Formation of a subhorizontal zone of mylonitic fabrics (more than 3.5 km thick in WM; less than 200 m thick in SM) within Precambrian metamorphic rocks and younger intrusions, some of which were emplaced synkinematically. During mylonitization, quartz deformed plastically and/or recrystallized, whereas plagioclase behaved brittlely. Preexisting steep foliation in the Precambrian rocks was variably rotated into parallelism with mylonitic foliation, or transported and folded during mylonitization, or cut discordantly by mylonitic fabric.

2. Development of mylonitic fabrics in narrow zones (0.1–10 cm thick) of intense shear strain. Previously formed mylonitic fabrics were cut and/or rotated by these localized shear zones.

3. Formation of a zone up to 300 m thick (WM) of chloritic breccias by shearing, brecciation, and retrograde alteration of kinematically inactive mylonitic gneisses and locally adjacent nonmylonitic lower-plate rocks. Injection veins of pseudotachylite(?) that branch out from subhorizontal generation surfaces within the breccias (Fig. 2a) suggest the transient existence of seismically generated fault melts.

4. Formation of discrete, throughgoing, low-angle detachment faults, underlain by thin zones (less than 1 m) of microbreccia, a rock that may be an ultracataclasite that deformed superplastically (Phillips, 1982).

5. Late-stage, relatively shallow-level detachment faulting with formation of fault gouge in the upper-plate rocks directly above the detachment fault.

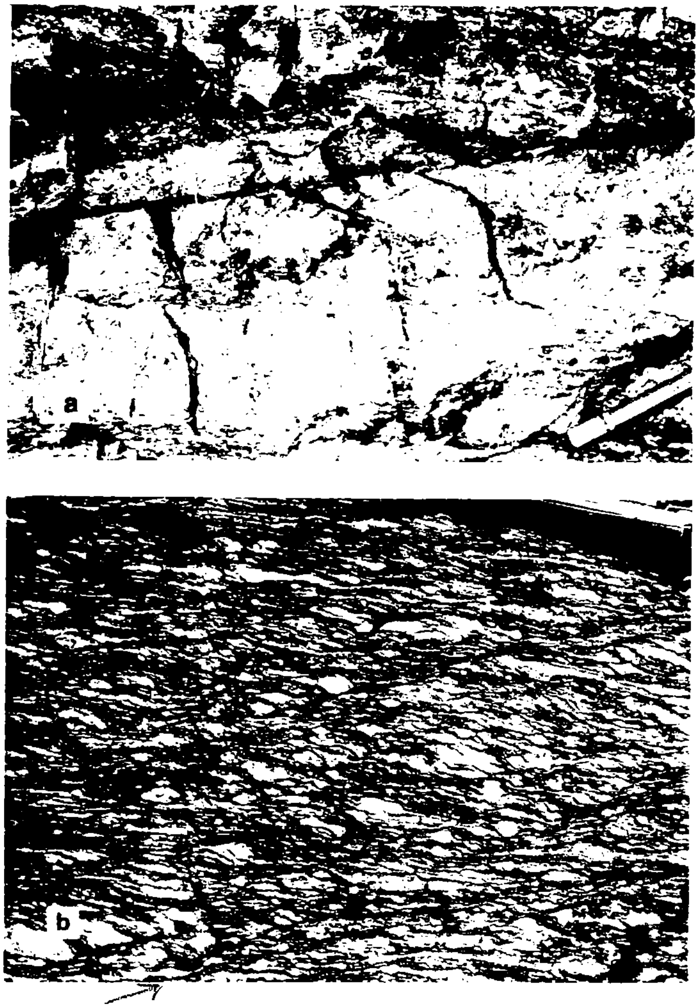

Figure 2. A: Pseudotachylite layer with small, downward-projecting dikes cutting sheared, retrograded mylonitic gneisses (chloritic breccia), lower plate of Whipple detachment fault, upper Whipple Wash, Whipple Mountains; see pencil in lower right corner for scale. B: Type I, S-C tectonite from upper Whipple Wash, Whipple Mountains. Narrow shear bands (C-surfaces) transect and distort mylonitic foliation (S-surfaces) superimposed upon Precambrian augen gneiss. Upper rocks have been displaced northeast (to left) with respect to lower levels. Width of photograph represents about 80 cm of outcrop.

KINEMATIC INDICATORS IN THE MYLONITIC ROCKS

Mylonitic rocks from both ranges are characterized by a gently dipping foliation and northeast- to east-northeast–trending lineation. In thin section, these rocks exhibit evidence for several deformational mechanisms. Quartz grains and aggregates have accommodated large strains by means of crystal-plastic behavior. Individual quartz grains are commonly undulose, and most quartz aggregates display strongly preferred crystallographic orientations. Microstructures suggest dynamic recrystallization of quartz under a regime of steadily decreasing temperature. Feldspars have typically accommodated deformation by fracture and variable degrees of cataclasis. Diffusional mass transfer is suggested by the presence of quartz in synkinematic tension gashes and dilation sites between feldspar fragments.

The kinematic indicators used in this study include the following: (1) S-C relationships on both mesoscopic and microscopic scales (Fig.

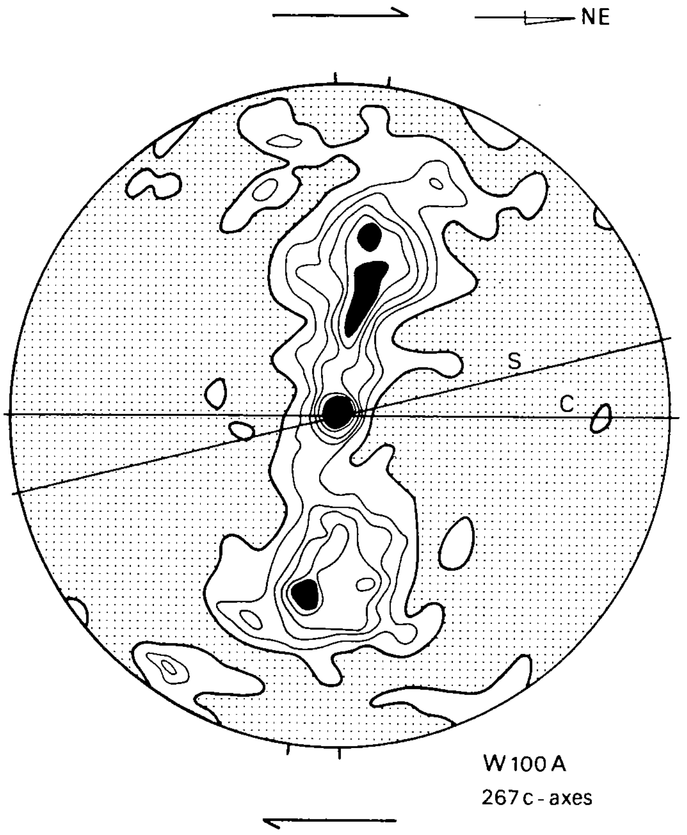

Figure 3. Quartz c-axis fabric determined by photometric techniques from a strongly deformed quartz aggregate, Whipple Mountains. Fabric has asymmetry consistent with northeastward sense of shear inferred from other microstructural indicators.

2b), involving penetratively developed shear bands (C-surfaces) transecting mylonitic foliation (S-surfaces; see Berthe et al., 1979; Lister and Snoke, 1984); (2) asymmetric mica "fish" and stair-stepped distribution of trails originating from and/or linking individual mica "fish" across microscopic faults and zones of intense shear; (3) asymmetric pressure shadows; (4) oblique foliations in dynamically recrystallized quartz aggregates; and (5) asymmetric quartz c-axis fabrics (Fig. 3).

The use and the application of these kinematic indicators are discussed elsewhere (Bouchez and Pecher, 1981; Behrmann and Platt, 1982; Simpson and Schmid, 1983; Lister and Snoke, 1984). In the main mylonitic zone of the Whipple Mountains, 70 localities had a northeast-directed sense of shear, 15 had a southwest-directed sense of shear, and 15 were indeterminate. In the South Mountains, all 20 samples taken from deformed igneous rocks in the main mylonitic zone displayed a northeast-directed sense of shear. In both ranges, mylonitic fabrics with an antithetic (southwest-directed) sense of shear locally occur in southwest-dipping dikes and in folded Precambrian gneiss, presumably reflecting localized shear between adjacent rotating blocks, as might be expected for domino-type rotations.

Quartz fabrics measured in the Whipple and South mountains (Fig. 3) indicate that the mylonitic lineation is parallel to a kinematic stretching lineation, that the overall deformation does not deviate significantly from plane strain, and that noncoaxial laminar flow (i.e., flow that is dominantly progressive simple shear) has been involved in the production of the fabrics and microstructures that we observed. However, it is important to emphasize that the quartz fabrics and other kinematic indicators, by themselves, give no indication as to whether the shear zones formed in compressional or extensional tectonic regimes. Structures indicative of subhorizontal extension in mylonitic terranes (i.e., tension gashes or ductile, normal faults) can develop in any shallow-dipping shear zone and are not diagnostic of either crustal shortening or crustal extension.

KINEMATICS OF DETACHMENT FAULTING

The kinematics of detachment faulting have been determined using the following data: (1) the average trend of striations on the detachment fault and in the associated chloritic breccia zone (N60°E in SM; N45°–50°E in WM); (2) observed offsets on small-scale normal faults within the chloritic breccia zone; (3) direction and sense of rotation of preexisting mylonitic fabrics within the chloritic breccia zone, and the geometry of drag folds in upper-plate strata where they are intersected by the main detachment fault (WM); (4) the average strike of extension joints in the chloritic breccia zone (N30°W in SM; N40°–45°W in WM); (5) kinematics of upper-plate normal faults, including observed offsets on marker units between adjacent fault blocks (WM); and (6) matching lithologies across low-angle faults below, but subsidiary to, the main detachment fault.

These kinematic indicators reveal that tectonic transport during detachment faulting was northeast in the Whipple Mountains and east-northeast in the South Mountains. In both mountain ranges this transport direction is approximately parallel to and in the same sense as the shear direction deduced for the underlying mylonitic rocks.

EVOLVING CRUSTAL SHEAR ZONES IN AN EXTENDING OROGEN

The observations summarized above are consistent with a general model in which low-angle normal shear zones, originally dipping at 10° to 25°, changed with increasing depth in the following manner (cf. Wernicke, 1981; Reynolds, 1982, 1985; G. H. Davis, 1983; our Fig. 4): (1) shallow segments of each detachment fault led to a deeper zone of brecciation, shearing, and pervasive hydrothermal alteration; (2) this zone of cataclasis passed downward toward the brittle-ductile transition into narrow, mylonitic shear zones; (3) these mylonitic shear zones widened and became more penetrative with increasing depth.

Operation of such a shear zone will lead to overall crustal extension (Fig. 4). During evolution of the shear zone, lower-plate mylonitic rocks are drawn toward higher regions where they cease to undergo penetrative ductile deformation and are cut by narrow shear zones. Ductile normal faults and some S-C relationships probably form at this time. Further motion on the shear zone results in mylonitic rocks being transported above the ductile-brittle transition where they become kinematically inactive and begin their long history of retrogression, cataclastic shearing, and brecciation. Note that at depth other rocks have now been drawn into the zone of penetrative shear and will follow the same progressive struc-

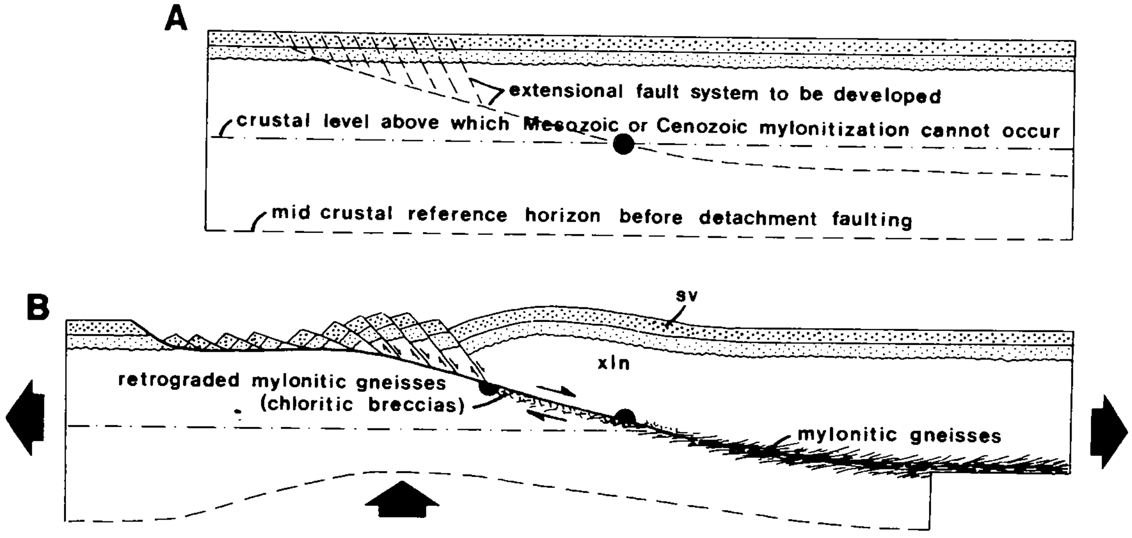

Figure 4. Diagram illustrating development of evolving shear zone during lithospheric extension. A: Configuration of crust prior to onset of extension of crystalline basement and overlying sedimentary and volcanic cover. Depth of section is about 20 km with no vertical exaggeration. B: Configuration of distended crust after about 20% extension (from A) and isostatic uplift. Section is balanced. Lower-plate rocks are drawn upward and out from beneath upper-plate rocks. Mylonitic gneisses formed below crustal levels indicated by dash-dot line are transported to higher structural levels where they are retrograded and cataclastically deformed.

tural evolution as described before. Thus, the once deep-seated (5–15 km) mylonitic complex is drawn upward and outward from beneath overlying crustal levels. Eventual exposure of the complex results from variable combinations of regional and subregional warping, tectonic denudation as described above, rotation due to structurally lower detachment faults, and erosion.

The evolving shear-zone model explains the observed geologic relationships in the South Mountains, where a shear zone of the type described above appears to have operated in the period 25 to 17 Ma with no change in the direction or sense of shear from penetrative mylonitization to late-stage detachment faulting (Reynolds, 1985). The situation is more complex in the Whipple Mountains, however, where field mapping indicates at least two episodes of detachment faulting, multiple episodes of rotation of upper-plate fault blocks, and at least two episodes of lateral warping along northeast-southwest axes. Geochronologic data and structural relations in the Whipple Mountains indicate that detachment faulting was in progress from at least late Oligocene–early Miocene time to 16 Ma. The structural evidence demonstrates kinematic continuity between the period of deformation in which the now-exposed mylonitic gneisses formed and the period in which detachment faulting occurred. Field data, therefore, suggest that some mylonitization (perhaps all) occurred during Tertiary evolution of the shear zone. Geochronologic studies in progress may help resolve the apparent conflict between structural data and previously published geochronologic data interpreted as indicating a pre-Tertiary age for some mylonitic fabrics in the WM lower plate and in boulders in upper-plate clastic rocks (G. A. Davis et al., 1980, 1982).

CONCLUSIONS

Geologic relationships in the South Mountains, Arizona, and the Whipple Mountains, California, can be explained in terms of the concept of evolving Tertiary shear zones in an extending orogen. This conclusion is supported by geometric relationships, by evidence for kinematic continuity of deformation from middle crustal to surficial levels, and by the temporal and spatial variation of deformation mechanisms, microstructures, metamorphism, and igneous activity. This model of an evolving crustal shear zone is similar to models proposed by Wernicke (1981), Reynolds (1982, 1985), and G. H. Davis (1983), and has widespread applicability to other extensional terranes of the North American Cordillera.

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