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Progressive deformation and superposed fabrics related to Cretaceous crustal underthrusting in western Arizona, U.S.A.

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Abstract—In the Maria fold and thrust belt, a newly recognized E-trending Cretaceous orogenic belt in the southwestern United States, ductile thrusts, large folds and superposed cleavages record discordant emplacement of crystalline thrust sheets across previously tilted sections of crust. Style of deformation and direction of thrusting are in sharp contrast to those of the foreland fold-thrust belt in adjacent segments of the Cordillera. The net effect of polyphase deformation in the Maria belt was underthrusting of Paleozoic and Mesozoic metasedimentary rocks under the Proterozoic crystalline basement of North America. The structure of the Maria belt is illustrated by the Granite Wash Mountains in west-central Arizona, where at least four non-coaxial deformation events (D_1–D_4) occurred during the Cretaceous. SSE-facing D_1 folds are associated with S-directed thrusts and a low-grade slaty cleavage. D_1 structures are truncated by the gently-dipping Hercules thrust zone (D_2), a regional SW-vergent shear zone that placed Proterozoic and Jurassic crystalline rocks over upturned Paleozoic and Mesozoic supracrustal rocks. Exposures across the footwall margin of the Hercules thrust zone show the progressive development of folds, cleavage and metamorphism related to thrusting. D_3 and D_4 structures include open folds and spaced cleavages that refold or transect D_1 and D_2 folds. The D_2 Hercules thrust zone and a D_3 shear zone are discordantly crosscut by late Cretaceous plutons.

INTRODUCTION

AN ENIGMATIC and poorly known segment of the North American Cordillera stretches from southern Nevada to northeastern Sonora across southwestern Arizona and southeastern California (Fig. 1). The central part of this segment is dominated by the Maria fold and thrust belt (Reynolds *et al.* 1986), an E-trending zone of folds and faults transverse to the general northerly structural grain of the Cordillera. Unlike faults in most of the Cordilleran fold and thrust belt, major thrust faults in the Maria belt verge southward and southwestward *away* from the craton and carry basement crystalline rocks in their upper plates. Because of these contrasts, the structure of the Maria belt is not adequately accounted for by existing models of Cordilleran foreland fold-thrust tectonics. Knowledge of the structure of the Maria belt is important for understanding the tectonic evolution of the southern Cordillera. Deciphering Mesozoic structure of the region is difficult, partly because a sequence of superposed Mesozoic deformations has produced a complex array of crosscutting and interfering structures and partly because of structural dismemberment by mid-Tertiary extensional tectonism. In addition, the age(s) of deformation in the Maria belt is not yet well constrained.

The Granite Wash Mountains of western Arizona (Figs. 1–3) provide a key to unlocking the structure of the Maria fold and thrust belt. Metasedimentary rocks in the range record at least four non-coaxial deformation phases and two metamorphic events. Overprinting relations and small-scale kinematic indicators document the directions of fault movement associated with each deformation phase. Furthermore, crosscutting relations between faults and Cretaceous plutons permit unequivocal discrimination between Mesozoic thrusts and Tertiary detachment faults and demonstrate that Mesozoic fabrics in the Granite Wash Mountains do not have a Tertiary overprint.

In this paper we describe the spatial and temporal pattern of deformation and metamorphism in the Granite Wash Mountains. The resulting structural sequence is used to constrain tectonic models of the southwestern North American Cordillera. Our study also outlines the progressive deformation and cleavage patterns associated with regional-scale ductile thrusts that formed during crustal underthrusting.

GEOLOGIC FRAMEWORK OF THE GRANITE WASH MOUNTAINS

The Granite Wash Mountains are located in the Basin and Range province of western Arizona, about 70 km east of the Colorado River (Fig. 1). The most prominent structure in the range is the Hercules thrust zone, a

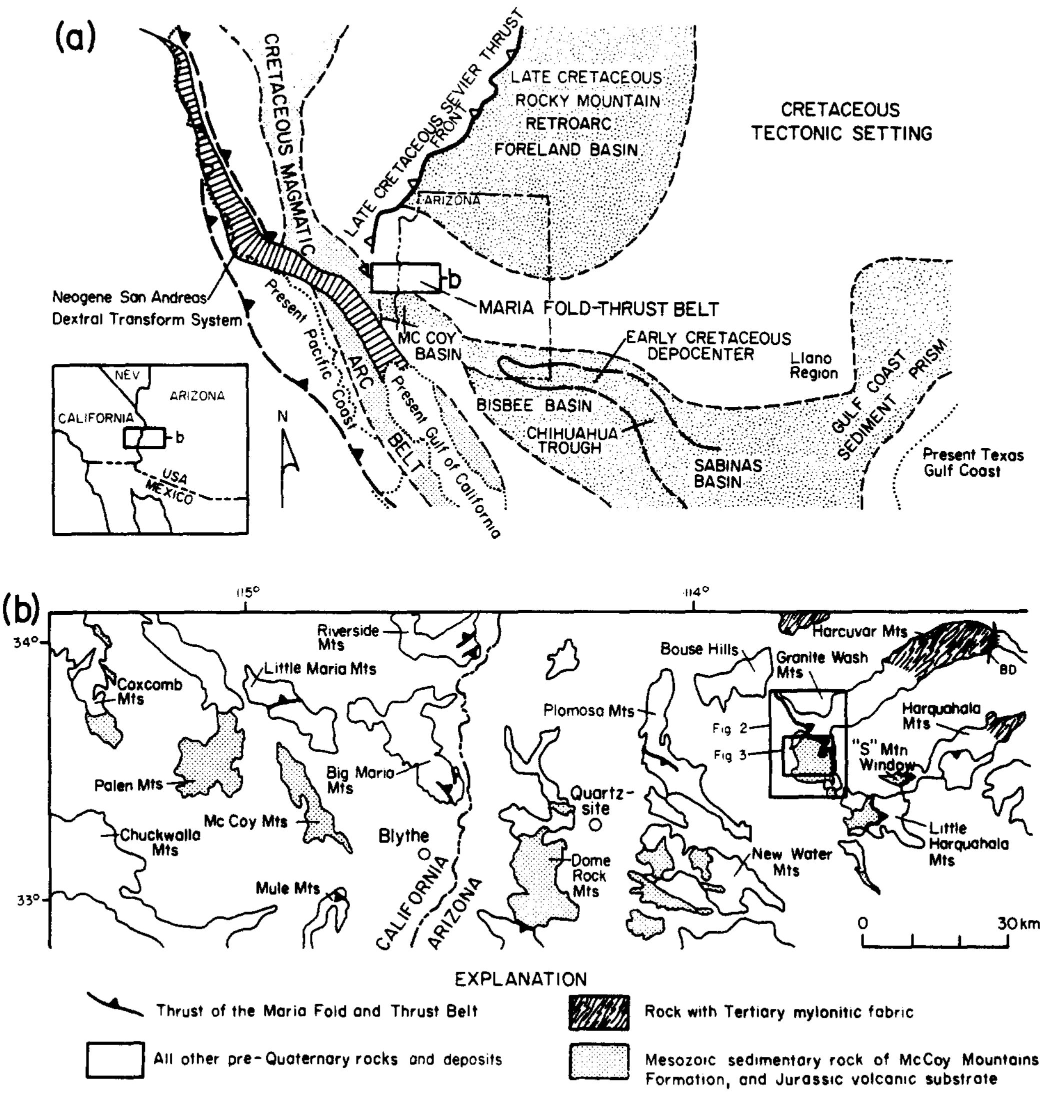

Fig. 1. (a) Location and Cretaceous tectonic setting of the Jurassic to Cretaceous McCoy basin and the Cretaceous Maria fold and thrust belt in the southwestern North Americal Cordillera. Tectonic elements that flank the Maria belt are modified from Dickinson (1981). (b) Location of the Granite Wash Mountains in the Maria belt. Also shown are Mesozoic sedimentary rocks of the McCoy Mountains Formation (stippled), its substrate of Jurassic volcanic rocks and some major faults of the Maria belt. BD is the Tertiary Bullard detachment fault.

SW-vergent subhorizontal shear zone of regional extent that places Proterozoic and Jurassic crystalline rocks over polydeformed Paleozoic and Mesozoic supracrustal rocks (Figs. 2 and 3). The shear zone is characterized by intense deformation and prograde metamorphism of lower-plate rocks and mylonitization and retrograde metamorphism of upper-plate rocks. Several individual ductile faults can be recognized within the shear zone.

Beneath the Hercules thrust zone is an upturned sequence of S-facing Paleozoic and Mesozoic rocks that represents one limb of a regional recumbent syncline (Laubach *et al.* 1987). The stratigraphic sequence exposed beneath the thrust zone comprises, from north to south and from oldest to youngest, the following units: (1) Middle and Upper Paleozoic rocks in both depositional and fault contact with stratigraphically overlying Lower Mesozoic siliciclastic rocks; (2) Jurassic(?) silicic volcanic rocks that grade upward into volcaniclastic rocks of similar composition; and (3) clastic rocks, with local interlayered mafic igneous rocks, correlated with the Jurassic(?) and Cretaceous McCoy Mountains Formation.

The overlying Hercules thrust zone is several hundred meters thick and consists of thrust-bounded lenses of strongly deformed rocks. The lowest ductile thrust fault within the Hercules zone is the Yuma Mine thrust, which places a sheet of Proterozoic granite and Cambrian quartzite discordantly across the upturned Paleozoic and Mesozoic section. The granite and quartzite are unconformably overlain by Mesozoic rocks that are stratigraphically distinct from any rocks beneath the thrust. They have been correlated with the Upper Triassic or Jurassic Vampire Formation (Laubach *et al.* 1987, Reynolds *et al.* 1987).

These rocks are overlain by laterally discontinuous tectonic slivers of Paleozoic metasedimentary rock, Jurassic metavolcanic rocks and Mesozoic clastic rocks possibly correlative with the McCoy Mountains Formation. These tectonic lenses are structurally overlain by Proterozoic crystalline rocks above the main Hercules

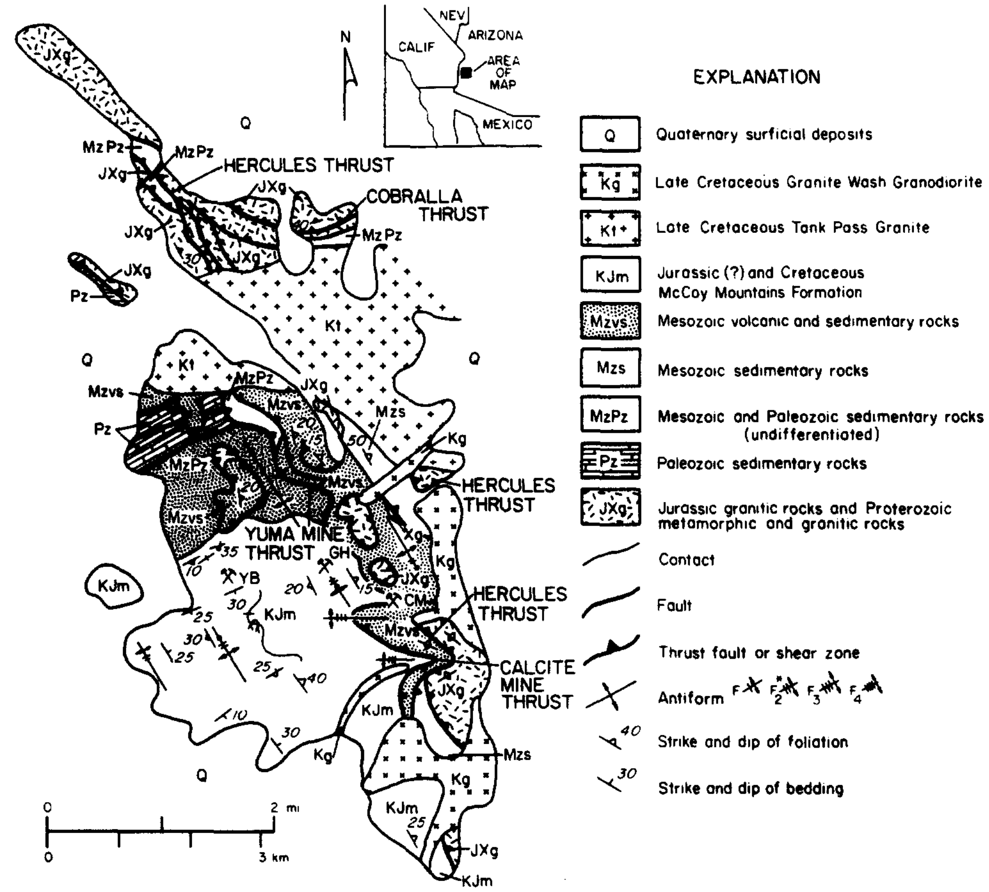

Fig. 2. Simplified geologic map of the Granite Wash Mountains. Note the belts of Paleozoic rocks and the undeformed Cretaceous plutons crosscutting the faults.

thrust. The lower-plate Mesozoic rocks and upper-plate Proterozoic rocks are most intensely deformed adjacent to the thrust.

The undeformed character of late Cretaceous plutons in the Granite Wash Mountains and lack of significant Tertiary normal faults indicate that rocks of the Granite Wash Mountains were not affected by Tertiary structural overprint and comprise part of an unextended footwall block below the Bullard detachment fault (Reynolds & Spencer 1985). The Hercules thrust and associated structures are discordantly crosscut by two undeformed late Cretaceous plutons, the Tank Pass granite and the Granite Wash granodiorite (Reynolds *et al.* 1986, 1988b) (Figs. 2 and 3). The range lies southwest of and structurally below the regionally NE-dipping mid-Tertiary Bullard detachment fault. The Harcuvar Mountains, a metamorphic core complex that is continuous to the northeast with the Granite Wash Mountains, contains Cretaceous plutons and older rocks that have been mylonitically deformed during Middle Tertiary down-to-the-northeast ductile shear on deep levels of the Bullard detachment fault (Reynolds & Spencer 1985).

FABRIC ELEMENTS AND STRUCTURAL DOMAINS

Outcrop and petrographic evidence indicates that the rocks in the Granite Wash Mountains contain four generations of superposed cleavages and associated range- and outcrop-scale folds and shear zones. Cross-cutting and refolding relations between these different generations of structures are the basis for distinguishing four discrete deformation events (D_1–D_4, Table 1). The four cleavages change in character across the range and are not equally well expressed everywhere. For purposes of discussion, the Granite Wash Mountains can be divided into three structural domains (A, B and C, Figs. 4 and 5) based on the degree to which the earliest cleavage (S_1) and associated minor structures are overprinted by a younger S_2 fabric and associated minor structures and on the character of the S_2 fabric. Because S_3 and S_4 cleavages and associated minor structures occur only locally, they were not used to define domains. Contacts between the three fabric domains are gradational. Domains are approximately tabular and dip gently ENE, concordant to the overlying Hercules thrust zone. Rocks in Domain A in the western part of the range are successively overlain to the east by rocks of Domains B and C (Figs. 4 and 5).

In Domain A, the dominant cleavage is S_1, with only a slight D_2 overprint marked by non-penetrative, steeply-dipping S_2 cleavage, open F_2 folds with steep axial surfaces, and small shear zones (Figs. 6a–c). In the structurally overlying Domain B, S_2 fabric in pelitic rocks is a schistosity that completely obscures S_1 cleavage. In coarser grained sedimentary rocks of

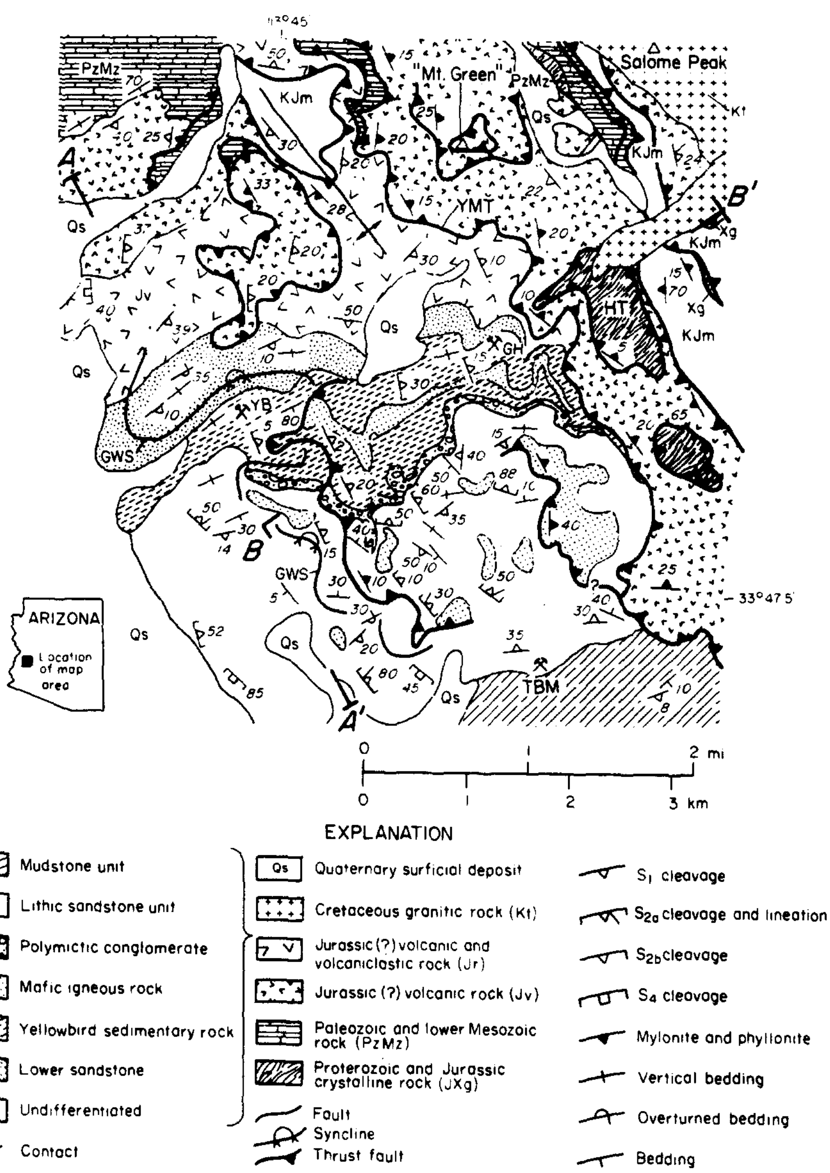

Fig. 3. Geologic map of the central Granite Wash Mountains illustrating the truncation of strike belts of Mesozoic metasedimentary rocks (D_1) by the Hercules thrust zone (D_2). Many small faults and folds have been omitted. GWS, Granite Wash syncline axial trace; HT, Hercules thrust; YMT, Yuma Mine thrust.

Domain B, however, S_2 fabric is a spaced cleavage, and S_1 cleavage is generally still visible. In Domain C, S_1 cleavage is no longer recognizable, and S_2 fabric has evolved into a gently-dipping penetrative mylonitic foliation (Figs. 6d–f and 7).

In the following sections, we describe the D_1 and D_2 fabrics and structures with reference to the structural domains, and we demonstrate that D_1 is associated with the development of a major fold, the Granite Wash syncline, and that D_2 is associated with movement on the Hercules thrust zone. D_3 and D_4 produced more localized post-thrust structures.

D_1 STRUCTURES

D_1 *fabric elements and mesoscopic structures*

Suites of D_1 fabrics and minor structures recognized in Domain A (Figs. 6a & b and 8) include slaty to phyllitic cleavage (S_1), a weak lineation (L_1) defined by the preferred orientation of white mica and quartz, and mesoscopic folds (F_1). The L_1 mineral lineation consists of mineral overgrowths on rigid grains and is parallel to F_1 axes. In pelitic rocks, S_1 slaty cleavage is defined by dimensional alignment of white mica, chlorite and flattened quartz grains. In sandstone, S_1 is composed of closely spaced domains defined by clay mineral concentrations that probably accumulated as a consequence of pressure solution. S_1 slaty cleavage is subhorizontal and is axial-planar to F_1 mesoscopic folds. Scatter of S_1 cleavage attitudes reflects both refolding by the D_2 event and cleavage refraction (Fig. 6a). Convergent fanning of S_1 in gently-dipping competent sandstone locally produces steep cleavage dip. Mesoscopic F_1 folds are commonly recumbent and tight to isoclinal, and range in amplitude and wavelength from meters to tens of meters. F_1 folds are subsimilar, with Ramsay (1967) class 1c to 1b shapes in sandstone and class 3 shapes in phyllite.

Conglomerate clast aspect ratios indicate that the

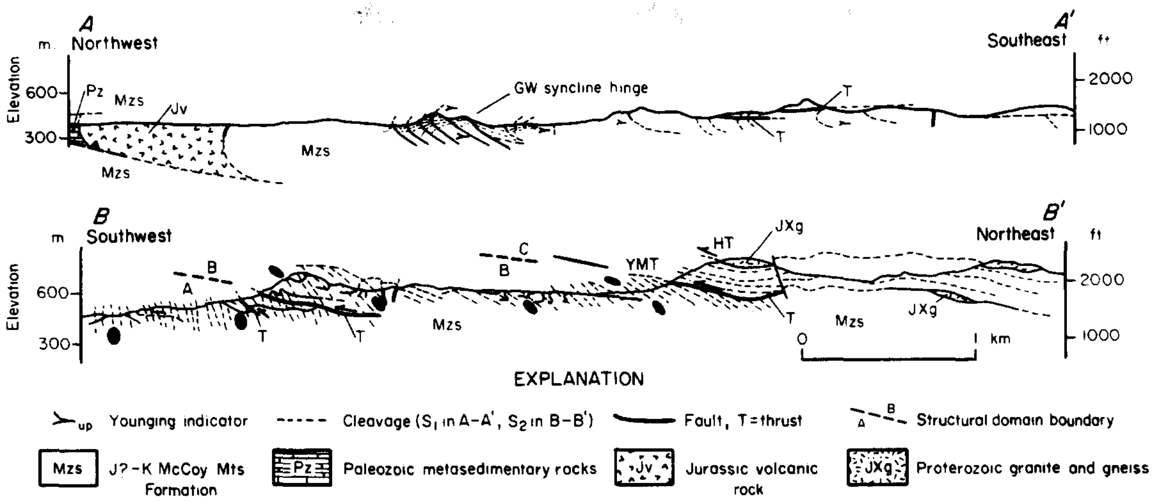

Fig. 4. Cross-sections illustrating (a) the D_1 Granite Wash syncline (section A–A') and (b) the D_2 Hercules thrust zone (B–B'). Locations of the cross-sections are shown in Fig. 3. S_1 cleavage attitude is shown schematically on A–A', and S_2a cleavage is shown schematically on B–B'. HT is the Hercules thrust and YMT is the Yuma Mine thrust. Also shown on B–B' are the locations of structural domain boundaries and the attitude and dimensions of X–Z sections through D_2 deformation ellipsoids derived from clast ellipticities (Laubach 1986).

lowest finite strains in the Granite Wash Mountains are associated with the S_1 cleavage of Domain A (Laubach 1986, fig. 4). Many rigid quartzite and silicic volcanic clasts in this domain retain their primary shapes (Fig. 7a).

The Granite Wash syncline

Paleozoic and Mesozoic metasedimentary rocks in the western Granite Wash Mountains strike E to ENE and dip mainly to the south (Figs. 2 and 3). Stratigraphic succession and sedimentary structures show that the younging direction is also to the south. The Paleozoic rocks dip steeply and form three ENE-trending strike belts separated by steep, section-repeating faults. Within each strike belt, the Paleozoic strata young to the south. Basal Mesozoic units are present at the top of the two southern Paleozoic strike belts. The remainder of the Mesozoic sequence, however, lacks bed-parallel, section-repeating faults such as those observed in the Paleozoic rocks. Flat-lying thrusts of the D_2 Hercules thrust zone discordantly crosscut the strike belt (Fig. 2).

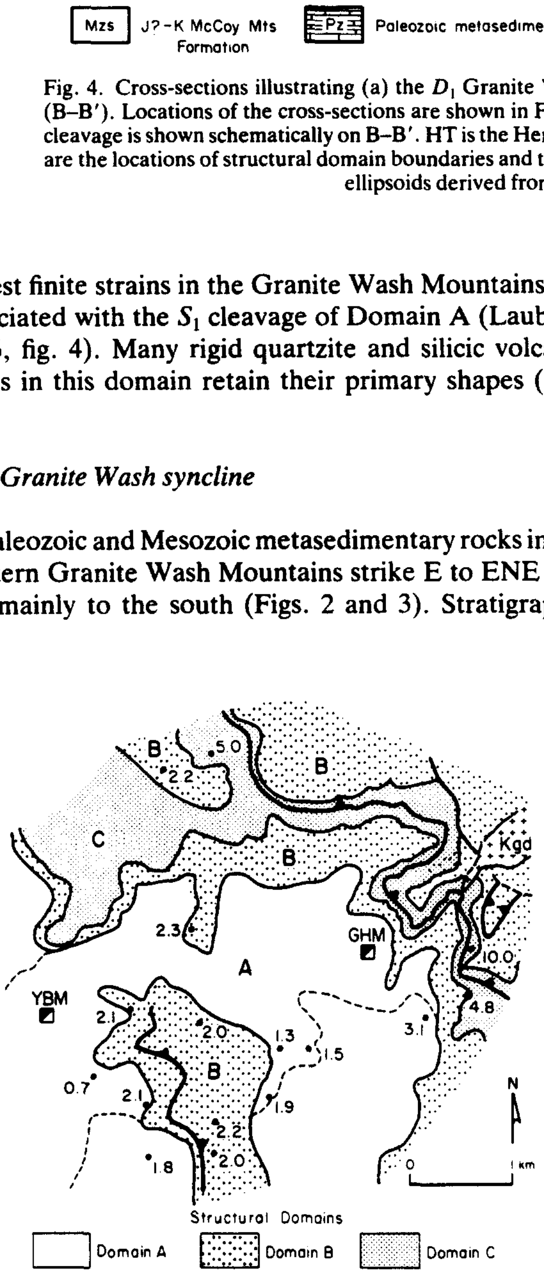

Fig. 5. Map of structural Domains A, B and C. Values on map are d-values of Ramsay & Huber (1983, p. 202) where $d = [(R_{xy} - 1) + (R_{yz} - 1)^2]^{1/2}$, a measure of the amount of deformation that in this case is derived from quartzite and rhyolitic volcanic clast axial ratios (R_{xy} and R_{yz}). Since these clasts are generally less distorted than other clast types, the d-value represented here is only an indication of relative amount of deformation between different parts of the range and not the shape of the strain ellipsoid.

Mesoscopic structures show that the upturned, NE-striking attitude of Paleozoic and Mesozoic rocks in the western Granite Wash Mountains reflects a range-scale, SSE-facing recumbent fold, named the Granite Wash syncline (Fig. 4). The existence of this fold is not obvious, as its two limbs are unequally exposed. Evidence of the syncline is: (1) at several locations it is possible to trace beds continuously from SE-dipping, right-side-up beds, through a fold hinge, to NW-dipping, inverted beds (Figs. 4 and 8c); (2) mesoscopic F_1 folds, where they have not been refolded, are typically recumbent with a moderately to steeply NW-dipping overturned limb and a gently SE-dipping, right-side-up limb; (3) a subhorizontal vergence boundary can be mapped based on vergence reversal of mesoscopic F_1 folds. Such a vergence boundary is interpreted as separating opposite-verging parasitic folds on either side of the trace of the axial surface of a large fold; (4) cleavage that is axial planar to mesoscopic F_1 folds generally dips gently, consistent with gentle dip of the axial surface of the major fold. Steeper dips of the S_1 cleavage are due to refolding or cleavage refraction; (5) cleavage refraction patterns are also compatible with the existence of the Granite Wash syncline (Fig. 8). The association of the Granite Wash syncline with D_1 fabric elements and mesoscopic structures suggests that the major syncline is itself a D_1 structure.

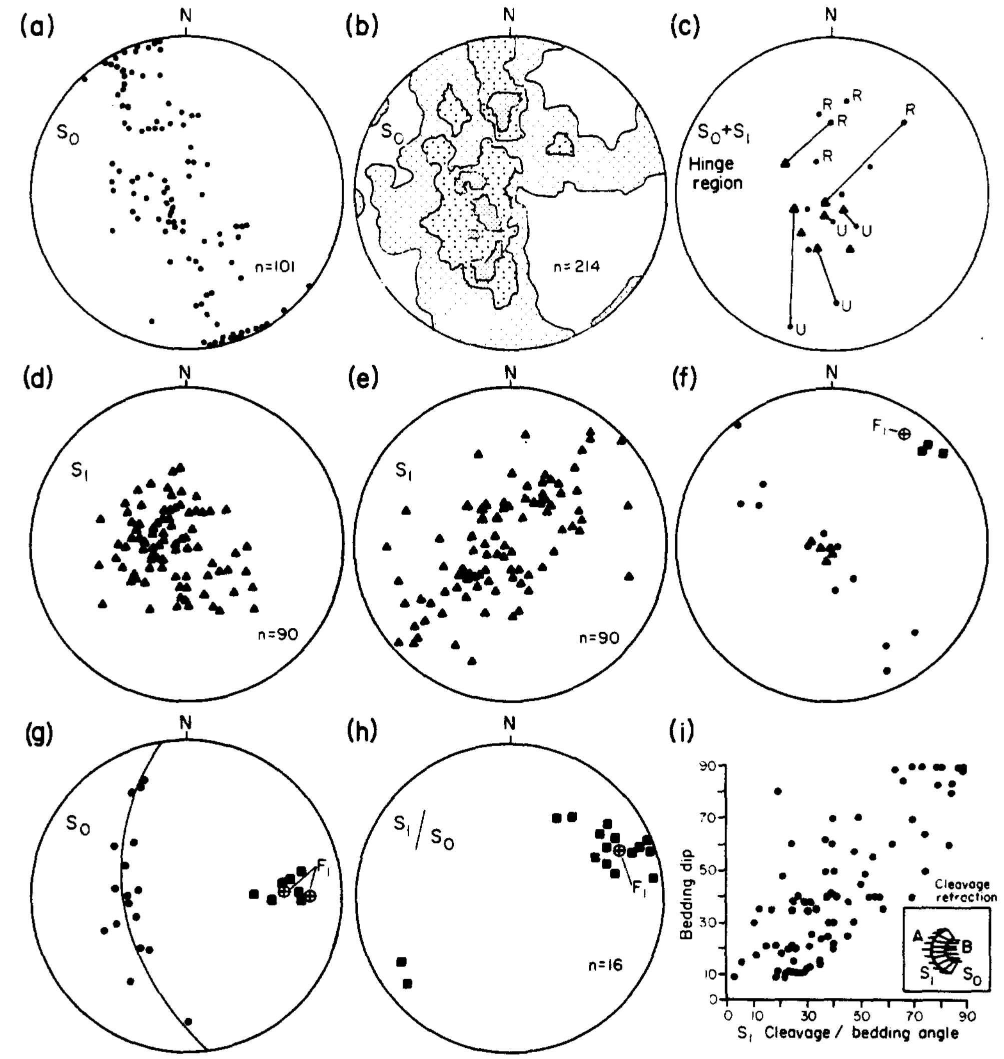

Fig. 8. Lower-hemisphere, equal-area plots of poles to bedding (filled circles), S_1 cleavage (triangles), F_1 fold axes (open circles) and S_1 cleavage–bedding intersection lineation (filled squares) in Domain A. (a)–(c) show bedding attitudes in northwestern, central and southern parts of Domain A, respectively, and illustrate E- to ENE-trending F_1 folds. Scatter of bedding and cleavage attitudes in (b) reflects superposed, small-scale F_2 folding. Contours 1, 3 and 7% per 1% area. (c) Bedding attitude and associated S_1 cleavage across the major F_1 hinge. R = right-side up. U = upside down. (d) and (e) S_1 cleavage attitudes from northwest and central part of Domain A, from the same areas as (a) and (b). (f)–(h) Reorientation of S_1 cleavage, bedding and/or S_1–S_0 intersection lineation trends in the central part of Domain A by F_2 and F_2^* folds. (i) Cleavage refraction patterns reflect the Granite Wash syncline in Domain A. Large angles between S_1 cleavage and bedding in steeply-dipping beds and low angles in gently-dipping beds suggest that the F_1 fold is recumbent.

D_2 STRUCTURES

D_2 *fabric elements and mesoscopic structures*

D_2 fabric elements, dominant in most exposures of McCoy Mountains Formation (Figs. 6, 7 and 9), include cleavage (S_2) and well-developed 055°–065°-trending mineral and clast-elongation lineations (L_2). These fabrics are associated with mesoscopic folds (F_2) and shear zones developed at scales ranging from microscopic to map scale.

Two morphologically distinct cleavages formed during the D_2 event. Thus, S_2 is subdivided into two categories, S_2a and S_2b. S_2a is best developed (or preserved) away from and structurally below the Hercules thrust, whereas S_2b is best developed within the thrust zone (Figs. 5 and 10). S_2a is a spaced cleavage with variable morphology. In fine-grained rocks in Domain A that possessed a strong S_1 slaty cleavage, S_2a is a crenulation or closely spaced disjunctive cleavage. In coarser grained rocks, S_2a is disjunctive and appears to have formed by pressure solution. S_2a cleavage contains new metamorphic minerals in Domain B. Microlithons are generally more closely spaced and more gently dipping close to the Hercules thrust zone.

S_2b fabric is defined by subhorizontal, anastomosing ductile shear zones with a uniform southwest sense of movement. S_2b is rare in Domain A, but is well developed close to the Hercules thrust. S_2b cleavage domains are generally 0.5–3 cm thick and spaced 1–5 cm apart. Close to zones of strong S_2b fabric, S_2a cleavage changes attitude and merges asymptotically with S_2b cleavage. In Domain B, sigmoidal S_2a cleavage occurs in less deformed lenses of rock that are bounded by S_2b

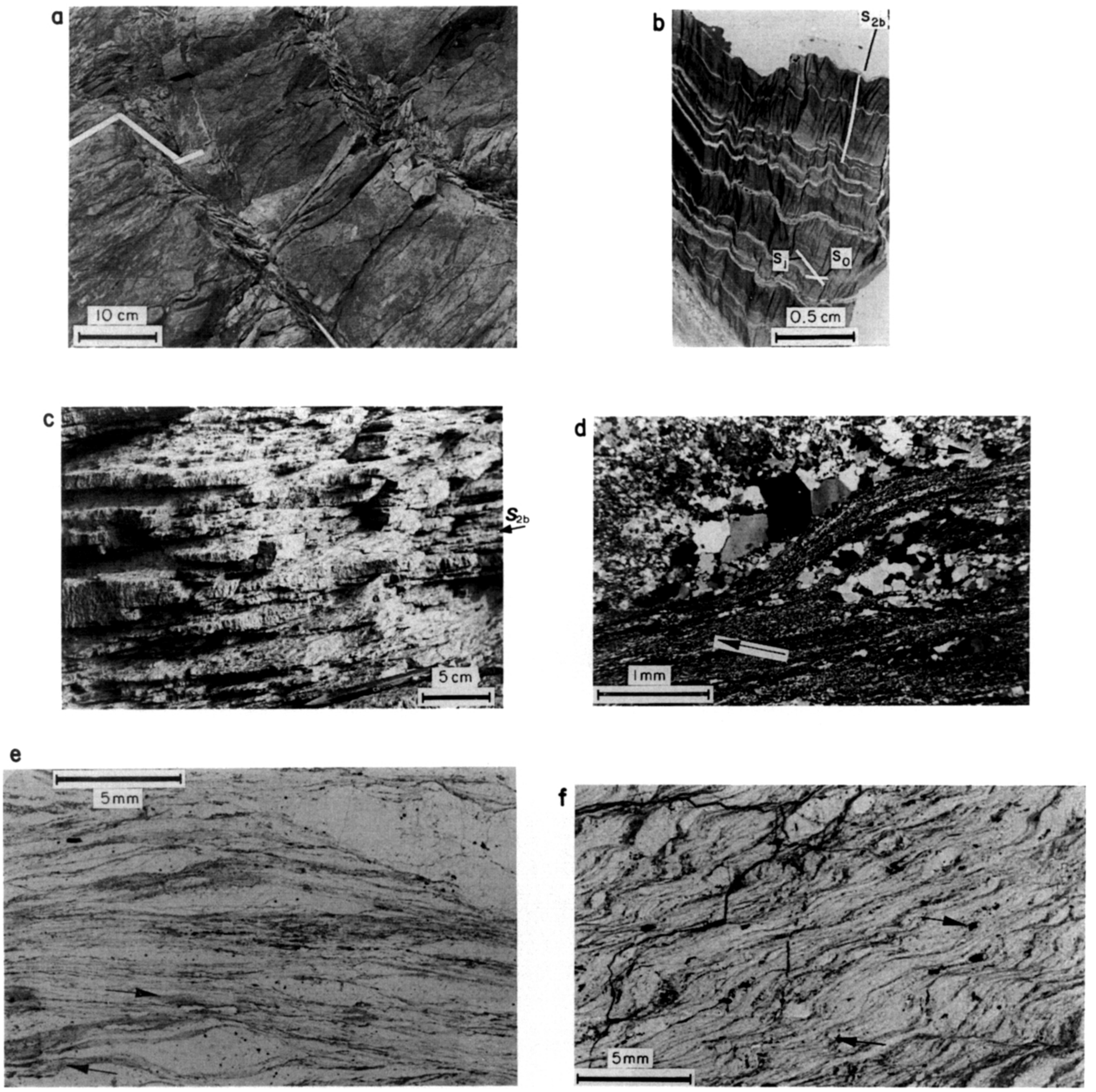

Fig. 6. Fabrics and structures. Photographs (a)–(c) are from below the Hercules thrust. (a) S_1 cleavage refraction in conglomerate, shale and sandstone. View is N70°E. (b) Photomicrograph of phyllite showing S_1 crenulated by S_2a, Domain A. (c) Gently-dipping S_2b (shear bands) in Domain B. View is to the SE. Fabrics and structures in the Hercules thrust zone (Domain C). (d) Photomicrograph of mylonite derived from coarse-grained Proterozoic granite. (e) Mylonite derived from metasedimentary rock. *S–C* fabric indicates southwest-directed shear sense. (f) *S–C* fabric in mylonitic Proterozoic granite with top-to-the-southwest shear sense.

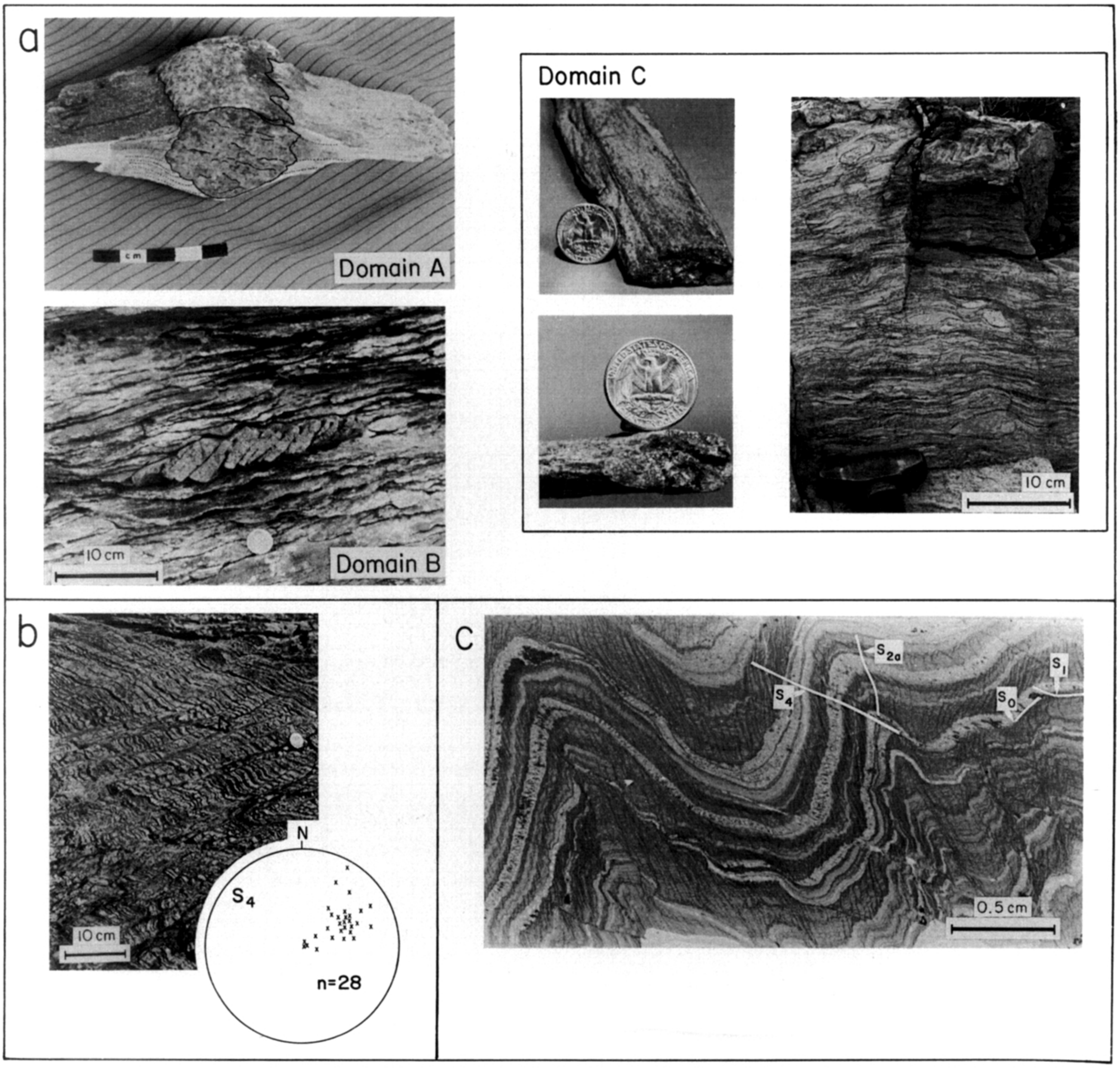

Fig. 7. (a) Deformed cobbles from Domain A, B and C. (b) Spaced S_4 cleavage in outcrop. View is NW. Inset shows lower-hemisphere, equal-area plot of poles to cleavage. (c) Photomicrograph of widely spaced S_4 cleavage crosscutting bedding (S_0), S_1 and S_2a (the prominent closely spaced cleavage). S_1 intersects S_0 at a low angle.

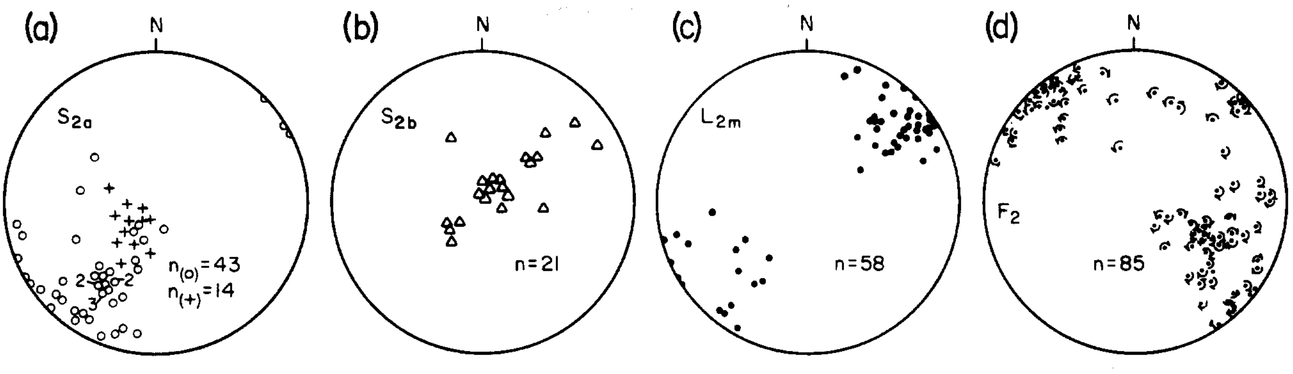

Fig. 9. Lower-hemisphere, equal-area projection of D_2 structural elements. (a) Poles to S_2a cleavage planes. Circles indicate cleavage in Domains A and B, crosses indicate folds in Domain C. (b) Poles to S_2b cleavage. (c) Attitude of stretching lineation (L_{2m}) in Hercules thrust zone. (d) Attitude of F_2 folds. Vergence is indicated by arrows.

cleavage. These lenses range from centimeters to tens of meters in length.

F_2 folds trend NW and are generally SW-vergent (Figs. 2 and 9). L_1 lineations and F_1 folds are folded by F_2 folds, and S_2a cleavage is axial planar to F_2 folds. In profile, F_2 folds in Domains A and B are Ramsay (1967) class 1b–1c. F_2 folds are gentle to tight and non-cylindrical with non-planar axial surfaces, and fold amplitudes range from centimeters to tens of meters.

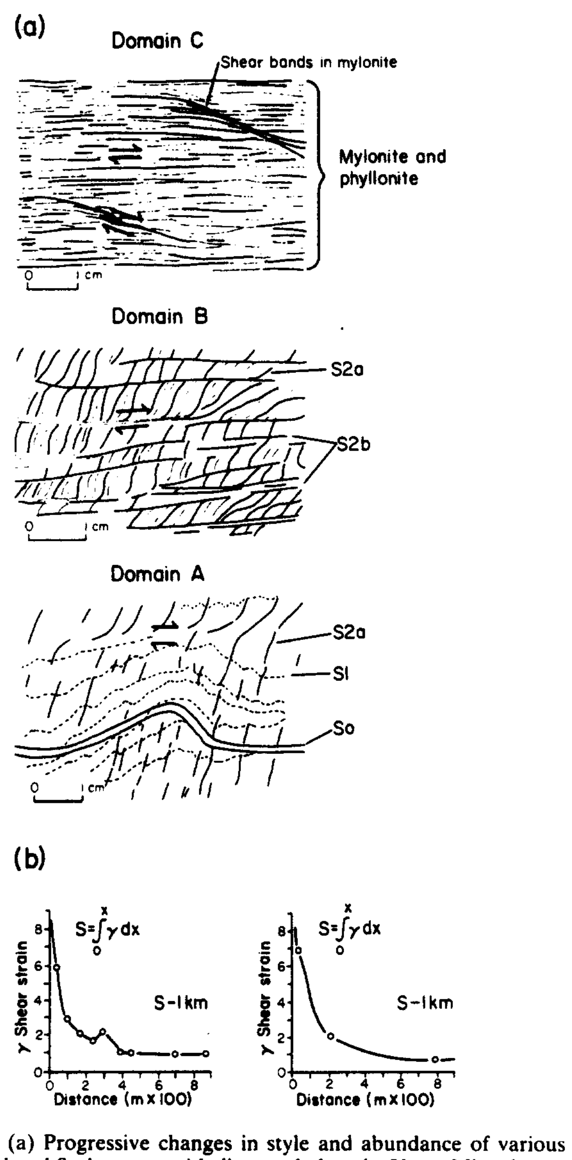

Fig. 10. (a) Progressive changes in style and abundance of various thrust-related S_2 cleavages with distance below the Yuma Mine thrust. (b) Displacement estimates based on strain integration from S_2a cleavage attitude with distance below the Yuma Mine thrust (YMT).

The attitude of F_2 folds varies across the range: axial surfaces are upright to NE-dipping in Domain A, but dip more gently NE in Domains B and C (Fig. 9a). Locally, non-planar F_2 axial surfaces are concave to the southwest. F_2 fold axes are straight structurally below the main thrust zone, but are shorter with more discontinuous, curved hinges close to the thrust. In Domain A, the plunge of F_2 folds also varies depending on the position of the small F_2 folds on the larger F_1 syncline. Steep southeast plunges occur where F_2 folds formed on steep, NE-striking bedding (Fig. 8d). In Domain C, hinges curve toward the NE-trending mylonite zone lineation, and sheath folds are present, together with isolated, intrafolial folds.

Ellipticity of rigid quartzite and silicic volcanic clasts in conglomerate increases systematically from southwest to northeast across the range (Figs. 4 and 7), toward higher structural levels and closer to the Hercules thrust. The most elongate clasts, those having axial ratios >40:10:1, occur in association with mylonitic fabric in the Hercules thrust zone, suggesting that the strain pattern reflects D_2 thrusting. Clasts in Domain A preserve primary sedimentary shapes and are little affected by either D_1 or D_2 deformation. In all Domains, quartzite and silicic volcanic clasts are less distorted than associated shale and micaceous sandstone clasts. Rigid clasts have fractures as well as ductile fabric, which indicate that clasts deformed by a combination of ductile flow and brittle fracture.

The Hercules thrust zone

The Hercules thrust zone consists of several discrete ductile shear zones within an approximately 200 m wide zone of mylonitic rocks (Figs. 3–5). The individual shear zones juxtapose various Proterozoic, Paleozoic and Mesozoic lithologic units. Crystalline units above or within the thrusts contain well-developed *S–C* fabrics

(Fig. 6f). Lower-plate rocks within the thrust zone contain mylonitic fabric developed by the coalescence of S_2b cleavage. Structural Domain C is defined by the pervasive overprint of mylonitic and phyllonitic fabric on earlier structures.

Movement on the Hercules thrust is considered a D_2 event because F_2 folds show systematic tightening and more gently inclined axial surfaces closer to the thrust zone and S_2 cleavage and F_2 folds merge with thrust-zone fabrics and structures rather than crosscutting or folding them. In addition, the movement direction inferred from the kinematic indicators in the mylonites is parallel to that inferred from the vergence of F_2 folds (Fig. 9).

Rocks in the mylonite zone are finer grained and more strongly foliated and lineated than their protoliths outside the shear zone (Figs. 6e & f). Groundmass quartz grain sizes are typically 10–20 μm. Foliation is defined by preferred orientation of mica, by platy quartz-rich domains that may be partially recrystallized ribbon quartz, and by millimeter-scale bands defined by variations in the proportions of quartz, feldspar and white mica. Foliation surfaces have a prominent NE-trending lineation defined by alignment of lenticular quartz aggregates, fractured feldspar porphyroclasts, pressure shadows and recrystallized tails on rigid inclusions, and streaks of fine-grained mica. Boudinaged crystals and elongate clasts indicate that this is a stretching lineation (Fig. 7).

S–C fabrics, porphyroclast–foliation relations (Berthé *et al.* 1979, Simpson & Schmid 1983, Lister & Snoke 1984, Passchier & Simpson 1986), and vergence of open asymmetric intrafolial folds indicate that transport of the hangingwall of the Hercules thrust zone was toward 240°, parallel to the stretching lineation. This transport direction is compatible with that inferred from the map pattern of reoriented contacts in the McCoy Mountains Formation (Fig. 3) and with vergence of F_2 folds in rocks below the mylonite zone (Fig. 9).

Minimum offset on the Hercules thrust zone is greater than 10 km based on the occurrence of a window in the thrust zone at 'S' Mountain in the western Harquahala Mountains (Fig. 1). Displacement across the Hercules thrust zone was accommodated by movement on individual discontinuities or ductile faults and by ductile strain within the broad shear zone. Widths of klippen of individual thrusts within the Hercules thrust zone in the Granite Wash Mountains indicate displacement of at least 2–3 km. The reorientation of initially vertical marker horizons by penetrative shearing below the Yuma Mine thrust suggests minimum displacement of 1–2 km. Similar minimum displacements are given by estimates of shear strain based on the systematically varying angle between S_2a and the thrust plane, and the attitude and ellipticity of distorted clasts (Fig. 10). The juxtaposition of crystalline basement over the thick McCoy Mountains Formation and the contrast of Mesozoic stratigraphic terranes across the thrust zone implies offset substantially greater than these minimum estimates.

Post-Hercules-thrust folds

NW-trending, SW-vergent kink bands that post-date D_2 mylonitic foliation and cleavage within the Hercules thrust zone are common in micaceous rocks where the foliation is phyllonitic. Kink domains, the bands of rock between paired kink-band hinges, are centimeters to meters wide and are vertical where phyllonitic foliation is horizontal. In plan view, kink-band hinges anastomose and terminate by gradual decrease in width or by intersection with other kink bands. Spacing between kink bands ranges from tens of centimeters to meters.

The entire Hercules thrust zone is folded by open, NW-trending, symmetric to SW-vergent folds (F_2^*) with amplitudes of tens to hundreds of meters (Fig. 11). F_2 and F_2^* folds have the same vergence and could be only slightly different in age. F_2^* are coaxial with F_2 folds, but reorient and therefore post-date F_2 folds and S_2 fabrics. For example, the orientation of the axial surfaces of small F_2 folds changes across the axial trace of the F_2^* fold of the thrust zone but F_2 fold vergence does not reverse as would be expected if the F_2 folds were parasitic on the larger F_2^* structure (Fig. 4); the F_2 enveloping surfaces are folded by the F_2^* fold. F_2^* folds typically have straight limbs and angular hinges. Kink bands and F_2^* folds have the same flexural-slip style, trend, vergence and crosscutting relations to D_2 structures, and F_2^* folds could therefore be contemporaneous with the kink bands.

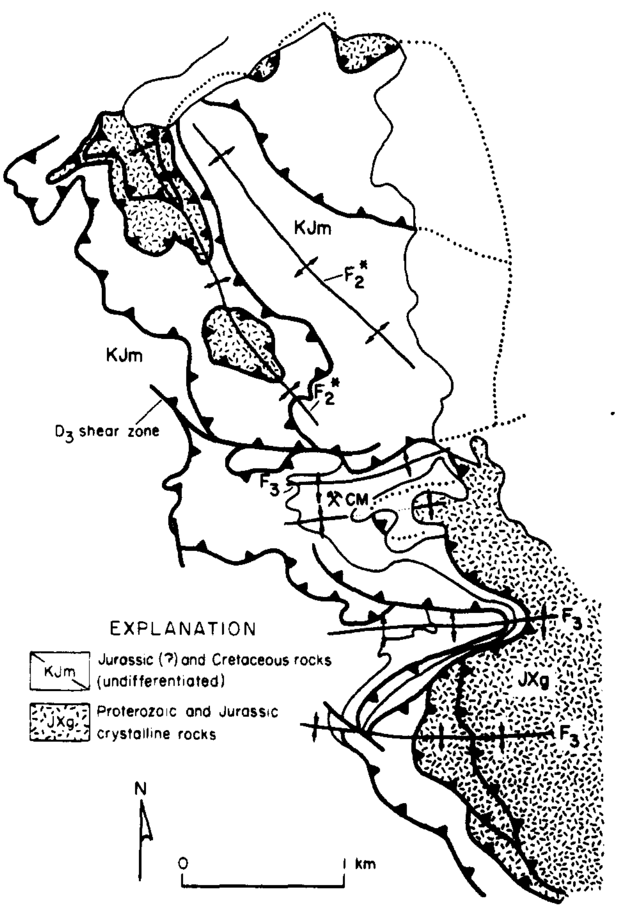

Fig. 11. Map of major F_2^* and F_3 folds in the eastern Granite Wash Mountains. CM = Calcite Mine.

D_3 STRUCTURES

D_1 and D_2 structures are locally overprinted by E-striking crenulation cleavage (S_3), E-trending folds and brittle–ductile shear zones. S_3 crenulation cleavage is localized in F_3 fold hinges. F_3 folds are large, upright to slightly asymmetric, S-vergent folds with widely spaced (>1 km) hinges. The most prominent F_3 fold is responsible for the large bend in the trace of the Hercules thrust in the southern part of the range (Fig. 11). This fold and smaller folds of the same generation are spatially associated with and subparallel to an E-trending, S-vergent brittle–ductile shear zone north of Calcite Mine (Fig. 11). Within this shear zone, D_2 fabrics are cut by N-dipping D_3 crenulation cleavage and refolded by S-vergent D_3 folds. This shear zone also cuts across the trace of several large F_2^* folds. A steeply plunging fold of the Hercules thrust represents interference between F_2^* and F_3 folds.

D_4 STRUCTURES

A fourth phase of deformation is indicated by the local presence, primarily in the western part of the range, of a SW-dipping cleavage (S_4) that crosscuts both S_1 and S_2 (Fig. 7) and discordantly transects the axial surfaces of F_2 folds. S_4 fabric is fairly uniform in orientation and does not have a systematic geometric relationship to D_1 or D_2 fabrics or structures.

S_4 cleavage is well developed only in fine-grained rocks, where it is disjunctive and widely spaced, with a stylolitic morphology suggestive of pressure solution. Veins filled with quartz and calcite commonly occur in association with S_4 cleavage. Mutual crosscutting relations between these veins and S_4 cleavage suggest that they are coeval. The veins typically occur in NE-dipping en échelon sets, and in the poorly exposed western part of the range they are associated with gently dipping brittle shear zones and faults with unknown movement sense.

D_4 structures post-date D_2 and could also conceivably post-date intrusion of the late Cretaceous plutons because S_4 cleavage is well expressed only in fine-grained rocks. D_4 fabrics have not been identified in the crosscutting late Cretaceous plutons, but, in view of the dependence of S_4 cleavage development on rock type, the lack of these structures in plutonic rocks cannot be taken as evidence that the plutons post-date D_4. The relation of S_4 cleavage to F_2^* folds is also ambiguous; although most F_2^* folds pre-date the D_3 shear zones, some of the large NW-trending folds mapped as F_2^* could instead be D_4 structures.

METAMORPHISM ASSOCIATED WITH DEFORMATION

Metamorphism accompanied development of the S_1 and S_2 fabrics (Table 1). Metamorphism (M_1) associated

Table 1. Relative chronology of deformation and metamorphism in the Granite Wash Mountains

Event	Structure	Metamorphism
D_1	S-directed thrusts and S-facing folds, slaty cleavage	Greenschist
D_2	SW-directed thrusts, spaced cleavages grading into mylonite	Greenschist
D_3	E-trending open folds, locally developed spaced cleavage	None
D_4	NE-directed thrusts and NW-trending folds, locally developed spaced cleavage	Local pressure solution and recrystallization

with D_1 deformation is preserved only in the western part of the range, where phyllites contain the assemblage quartz + albite + chlorite + muscovite.

Metamorphic grade indicated by mineralogy in S_2 domains of pelites increases upward from Domain A to Domain C, from no new M_2 mineral growth to chlorite-grade and locally biotite-grade assemblages. Similarly, in metabasites chlorite is gradually replaced by brown biotite, and in Domain C metamorphic amphibole occurs locally. Within the mylonite zone, metamorphic amphiboles zoned from hornblende rims to actinolitic cores occupy pull-apart necks between crystals boudinaged in the L_2 stretching lineation, indicating that mineral growth was synkinematic. Also in Domain C, aluminous rocks were converted to quartz-kyanite schists (Laubach *et al.* 1986, Reynolds *et al.* 1988a). The highest grade rocks occur near the Hercules thrust zone. The distribution of mineral assemblages suggests that M_2 metamorphic grade increases upward toward the thrust zone in an inverted zonation (Laubach 1986).

Metasedimentary rocks within tectonic slivers in the thrust zone are generally fine-grained slates and phyllites that locally contain brown biotite, andalusite and garnet. This suggests that metasedimentary rocks in the shear zone are higher metamorphic grade than are those below the thrust zone. In general, metamorphism in Domains A and B produced only fine-grained minerals, but metamorphic mica is coarser grained near the thrust zone in Domain C. Such mineralogic coarsening near the thrust parallels increasing intensity of fabric development in feldspathic and micaceous rocks and increasing metamorphic grade upward.

STRUCTURAL SYNTHESIS

Geometry and progressive development of shear zone fabrics

Below the mylonitic Hercules thrust zone, upward intensification of thrust-related cleavages is visible in a zone at least 700 m thick (Domains A and B). Two different styles of S_2 cleavages, S_2a and S_2b, formed during thrusting in this transitional zone (Fig. 10). We interpret S_2a as a flattening fabric subparallel to the X–Y plane of the strain ellipsoid, and S_2b as discrete ductile shear zones subparallel to the Hercules thrust zone. Thrust-related S_2a and S_2b cleavages are thus analogous to *S*- and *C*-surfaces, respectively, in mylonites (Berthé *et al.* 1979, Lister & Snoke 1984). In addition to small-scale faulting and folding, thrust-related deformation in the lower plate of the thrust zone was partitioned between (1) the accumulation of finite strain, shown by intensification of S_2a cleavage and increases in the distortion of clasts and (2) slip on S_2b surfaces.

The decrease in angle between S_2a cleavage and shear-zone boundary provided a measure of shear strain that can be used to infer minimum displacements across the zone (Ramsay & Graham 1970) (Fig. 10). This method underestimates total shear strain in the lower plate of the Hercules thrust zone because discontinuous displacement on S_2b is not taken into account. In the transition zone below the main thrust zone, mylonitic fabric develops chiefly by an increase in abundance and width of S_2b domains rather than by intensification of S_2a. The main tectonic foliation in the most highly strained rocks is S_2b, but that fabric must also contain S_2a rotated into near parallelism with S_2b by high shear strains.

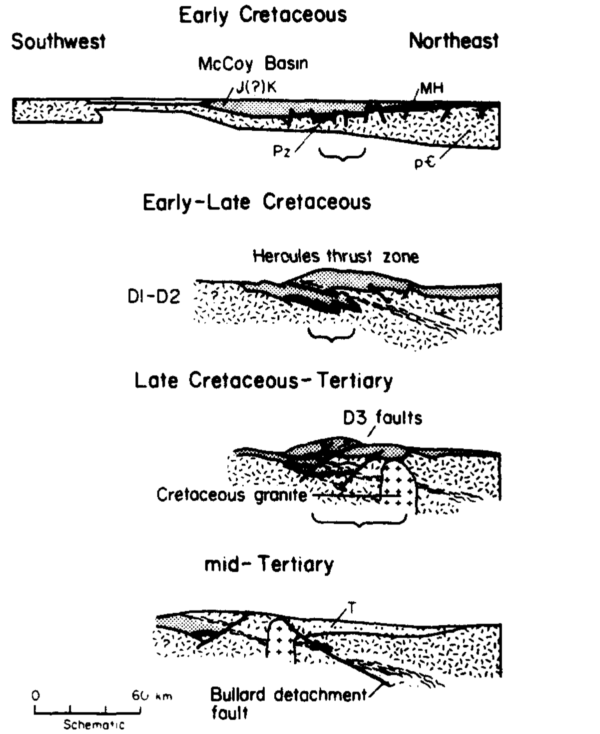

Fig. 13. Schematic SW–NE cross-sections showing the evolution of the Maria fold thrust belt by crustal underthrusting. The prethrust configuration of the McCoy basin is not known and is shown only schematically. Horizontal bracket indicates relations exposed in the Granite Wash Mountains.

Structural evolution

The S- and SW-directed thrusts of the Maria belt root underneath the North American craton, so the net result of D_1 and D_2 deformation was NNE-ward underthrusting of Mesozoic volcanic and sedimentary rocks, Paleozoic platform rocks and Proterozoic crystalline rocks beneath the North American craton. The structural sequence in the Granite Wash Mountains is: (1) an early phase of D_1 resulted in repetition of Paleozoic and lower Mesozoic units with decoupling within pelitic and evaporitic Paleozoic and lower Mesozoic units (Figs. 4 and 12); (2) early D_1 faults were folded together with the McCoy Mountains Formation into D_1 folds of regional extent that face SSE. A slaty to phyllitic cleavage that is axial planar to these folds also developed at this time; (3) D_1 folds were truncated by the Hercules thrust zone (D_2) with its upper plate of Proterozoic and Jurassic crystalline rocks. During thrusting, S_1 fabrics near the thrust were overprinted by S_2 cleavages that formed under sub-greenschist and greenschist conditions; (4) the attitude of thrusts was subsequently modified by NW- and E-trending F_2^* and F_3 folds (Fig. 13); (5) thrusts and folds were intruded by late Cretaceous postkinematic granite.

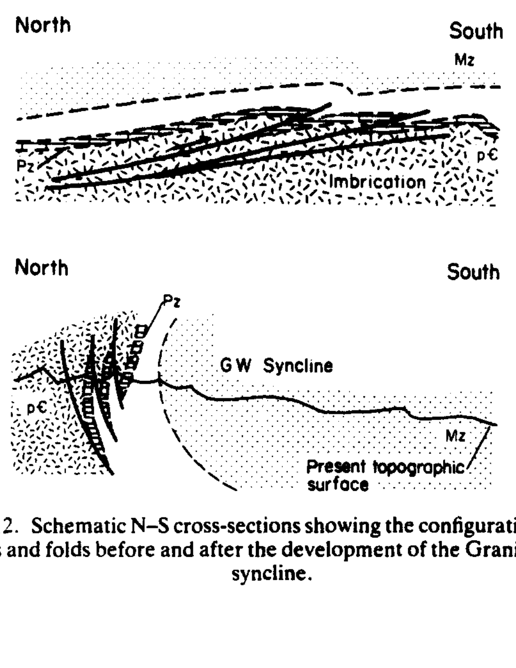

Fig. 12. Schematic N–S cross-sections showing the configuration of D_1 faults and folds before and after the development of the Granite Wash syncline.

Regional structural correlations

Evidence from the Granite Wash Mountains suggests that the Maria fold and thrust belt comprises at least two crosscutting belts of Cretaceous deformation. Structures and fabrics resemble and probably correlate with those of nearby ranges in southwestern Arizona and southeastern California. In spite of such similarities, however, correlations of fabrics and fold sets between adjacent ranges must be considered tentative until more detailed structural and geochronological data are available.

The McCoy Mountains Formation is variably deformed and metamorphosed throughout its outcrop area in western Arizona and southeastern California (Reynolds *et al.* 1986, Stone & Howard 1987) (Fig. 1), reflecting regional Mesozoic events. The strike of the McCoy Mountains Formation in southwestern Arizona and southeastern California is east to northeast, defining a large S-facing homocline at the present level of exposure (Harding & Coney 1985, fig. 1). Most of the McCoy Mountains Formation and older rocks have E- to NE-striking spaced to slaty cleavage. Large-scale, ENE- to E-trending, S- to SE-facing folds occur throughout much of the Maria fold and thrust belt (Hamilton 1982, Reynolds *et al.* 1986). SE-vergent minor folds that could be parasitic to larger structures occur locally in right-side-up beds in the central Dome Rock Mountains and northern McCoy Mountains. Such structures could be equivalent to D_1 in the Granite Wash Mountains. If so, the D_1 event affected the entire region and produced the regional homoclinal dip and the common low-grade cleavage. The homocline could be the lower limb of a regional S-facing syncline. Alternatively, the south dip of the units could reflect either post-cleavage rotation (Stone *et al.* 1987) or a younger deformation equivalent to D_2 or D_3 in the Granite Wash Mountains.

D_1 and D_2 structures and fabrics can be traced from the Granite Wash Mountains into the adjacent Little Harquahala and Harquahala Mountains. These adjacent ranges also contain S-vergent thrusts (Richard 1982, Reynolds *et al.* 1986). The S-vergent thrusts and older fabrics are overprinted in the Harquahala and Little Harquahala Mountains by a consistently oriented SW-dipping cleavage (S. M. Richard personal communication 1986) analogous to S_4 in the Granite Wash Mountains. There is similarity in style and vergence direction between two generations of structures of the southern Dome Rock Mountains (D_3 and D_4 of Tosdal 1986) and the D_2 Hercules thrust zone and D_4 structures of the Granite Wash Mountains. These fabrics could be correlative.

Timing and tectonic significance

Deformation in the Granite Wash Mountains must be younger than the McCoy Mountain Formation, which is Jurassic(?) and Cretaceous in age (Haxel & Tosdal 1986, Stone *et al.* 1987). The major structures that affect the McCoy Mountains Formation are discordantly intruded by undeformed late Cretaceous plutons, interpreted to be 70–85 Ma on the basis of K–Ar biotite ages and an Rb–Sr isochron (Rehrig & Reynolds 1980, Reynolds *et al.* 1986). In addition, K–Ar ages on M_2 micas are 60–70 Ma (Shafiqullah *et al.* 1980). Deformation, therefore, is probably Middle to late Cretaceous, in accord with geochronologic evidence of late Cretaceous deformation events from southeastern California (Hoish *et al.* 1988).

Western Arizona and southeastern California were part of the North American craton during Paleozoic time. A thin Paleozoic sequence like that of the western Grand Canyon was deposited on a basement of Proterozoic gneiss and granite. Cratonic conditions continued through Middle Triassic time, but were interrupted in the late Triassic or early Jurassic by an episode of uplift (Reynolds *et al.* in press). In Middle to late Jurassic time, a magmatic arc was constructed in the region of the future Maria fold and thrust belt (Dickinson 1981, Tosdal *et al.* 1988). The setting in which the thick (>7 km) predominantly fluvial McCoy Mountains Formation was deposited is uncertain; it may represent latest Jurassic(?) and early Cretaceous rifting in a back-arc setting within the continental margin volcanic arc (Laubach *et al.* 1987) (Fig. 13). Harding & Coney (1985) suggested that the formation was deposited in a pull-apart basin along the trace of the Middle Jurassic Mojave-Sonora megashear, a major left-slip fault system that may have extended through western Arizona (Anderson & Silver 1979, Anderson & Schmidt 1984), but the Upper McCoy Mountains Formation is too young to be directly related to the Jurassic megashear and the distribution of Paleozoic strata in west-central Arizona and adjacent California apparently precludes location of the megashear in this area (Stone *et al.* 1987).

Cretaceous plate convergence along the western margin of North America could have generated the stresses that deformed the McCoy basin through interaction between the down-going slab and North America (Burchfiel & Davis 1981) or an impact of microplates against the North American margin (Vedder *et al.* 1982). The change in the direction of tectonic shortening between D_1 and D_2 could result from changes in convergence direction or from changes in the geometry of microplate collision. Current data suggest that there were both abrupt and gradual changes in convergence direction and rate along the western margin of North America during the late Cretaceous (Page & Engebretson 1984, Engebretson *et al.* 1985). Deformation of the McCoy basin has also been interpreted as a result of transpressional strike-slip movement of the Mojave-Sonora megashear (Harding & Coney 1985), but the Cretaceous age of the Upper McCoy Mountains Formation is not consistent with Middle Jurassic movement of the megashear.

Present data do not allow a confident choice between a single protracted orogenic event with changing kinematics and strain rates, and several discrete, temporally separated, kinematically distinct events for the evolution of the Maria belt. The lack of structures with trends intermediate between the three principal deformation phases and the contrast in metamorphic conditions and structural style between structures of different deformation phases, as well as the pronounced differences in kinematics, suggest that D_2 and D_3 structures are not simply continuations of D_1 deformation. Ultimately, isotopic dating of minerals defining distinct cleavages may allow direct age determination of the events that produced the cleavages and permit closer correlation with Cordilleran orogenic events in adjacent segments of the orogen.

As noted by Burchfiel and Davis (1975, 1981) and others, the style of deformation in the back-arc region on continental crust reflects not only the stress field but also the nature of the crustal section being deformed. Within the Cordilleran miogeocline of Nevada and Utah, Middle Jurassic through late Cretaceous deformation led to the development of the N- to NE-trending E- to SE-verging Sevier fold-thrust belt. In the Maria belt, the thick miogeoclinal wedge is absent and deformation impinged on the Paleozoic craton of North America. In this setting, pre-existing structures could play an important role in localizing the position of the major thrusts. In this context, compression of young, presumably thinned crust beneath the young, deep McCoy depositional basin could have led to the underthrusting of the basin beneath the North American craton, rather than overthrusting of the basin over the craton (e.g. Le Pichon *et al.* 1982). Perhaps, as suggested by Howard (1986), the NE-dipping thrust faults of the Hercules thrust zone, and crustal underthrusting, were also promoted by thermal softening of continental lithosphere southwest of the thrust zone due to arc-related heating and plutonism.

CONCLUSIONS

The eastern Maria fold and thrust belt in western Arizona was affected by at least four phases of folding, faulting and cleavage development. D_2 involved SW-directed ductile thrusting that moved a thick Jurassic to Cretaceous sedimentary basin and its substrate of North American continental crust underneath the southwestern edge of the intact North American craton. This continental underthrusting is in sharp contrast to the contemporary nonmetamorphic, craton-directed thrusting in adjacent segments of the Cordillera.

The footwall block of the D_2 Hercules thrust zone is a wide shear zone containing two thrust-related spaced cleavages, S_2a and S_2b. The two thrust-related cleavages are *S*- and *C*-surfaces, respectively. Deformation is partitioned between flattening, shown by intensification upward toward the thrust of S_2a cleavage and by increased distortion of clasts, and shearing on S_2b surfaces. Thrust-zone mylonitic fabric developed below the thrust, primarily by an increase in the abundance of S_2b shear planes.

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