Shear-zone model for the origin of metamorphic core complexes

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ABSTRACT

Core-complex tectonite results from simple-shear rotational strain within regional ductile shear zones that have accommodated a Tertiary crustal stretching. The emplacement of younger and/or upper-level nontectonite rocks on older and/or deeper level tectonites is the ordinary and predictable result of normal-slip translation along shear zones that cut upward through the local geologic column. Progressive deformation produces a structural stratigraphy marked, from bottom to top, by normal country-rock protolith, mylonitic gneiss, tectonite carapace, microbrecciated tectonite, microbreccia, decollement, and upper-plate detachment rocks (as young as mid-Miocene). The reconstructions suggest that local regional crustal stretching locally exceeded 100%.

STRUCTURAL RELATIONSHIPS IN METAMORPHIC CORE COMPLEXES

~~The fundamental relationship that imparts to core complexes their distinctiveness is the presence of unmetamorphosed, generally brittlely deformed upper-level rocks in sharp, low-angle decollement-like contact on severely strained deep-level tectonites (Davis and Coney, 1979; Crittenden [illegible] 1980).~~ Four different structural tiers can be distinguished in core complex terranes (Davis, 1980; Davis et al., 1981). The lowest level, barely shown in Figure 1, just as it barely shows in most core complexes, is normal country rock, the protolith for the tectonites. The country-rock protolith can be any rock from Precambrian to at least early Tertiary in age. Structurally upward, the country-rock protolith is transformed into mylonitic tectonite marked by low-dipping foliation and penetrative unidirectional mineral lineation.

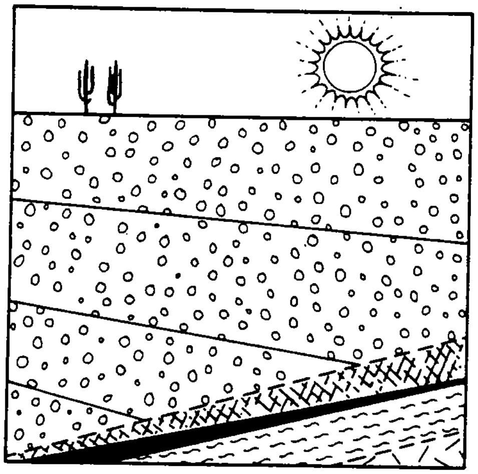


Figure 1. Schematic cross section showing structural components of metamorphic core complexes. Oligocene-Miocene sandstone and conglomerate in decollement contact (dashed line) on microbrecciated tectonite (cross-hatched), tectonite carapace (black), mylonitic gneiss (wavy lines), and nontectonite protolith (extreme bottom-right corner).

In core-complex terranes in southern Arizona, the most common rocks that have been transformed to mylonitic tectonite are Precambrian quartz monzonite, Paleozoic sedimentary rocks, and Tertiary granitic rocks. Tectonites derived from granitic protolith are augen mylonites. Tectonites derived from sedimentary strata typically form a sheet-like carapace, represented in Figure 1 as a thin black strip on top of mylonitic gneiss. Although not always present, the carapace typically consists of dramatically thinned and distended tectonite equivalents of recognizable units.

Upward from carapace and/or mylonitic tectonite is a relatively thin "decollement zone" distinguished by intensive microbrecciation and hematite-chlorite-epidote alteration of tectonite. This zone is indicated in Figure 1 by cross-hatching. Within the decollement zone the rocks are shattered both at the outcrop and microscopic scale. Detailed mapping of the internal structure of zones of altered and shattered microbrecciated tectonites have revealed that original foliation and lineation are commonly rotated out of their normal orientations, often to steep attitudes (Davis, 1980; Davis et al., 1981; Reynolds, 1982). The top of the zone of microbrecciated tectonite generally has topographic expression in the form of a thin resistant ledge of very fine grained microbreccia. The very top of the zone of microbrecciation is the decollement proper (Fig. 1).

Rocks above the decollement in core complexes are always part of the local geologic column of normal country rock. Although allochthonous, they are not exotic, nor do they display the characteristic mylonitic foliation and lineation (Fig. 1). In southern Arizona, rocks above the decollements may be of any lithology and may range in age from Precambrian to mid-Miocene. The structural damage displayed by the so-called "upper-plate" rocks is quite varied. Tertiary conglomerates and interbedded volcanic rocks are homoclinally tilted and broken by imbricate step faults of normal-slip displacement. Where Paleozoic strata rest on the decollement, the strata may simply be homoclinally tilted or they may be dramatically folded and faulted. Precambrian granite in upper-plate position is typically shattered.

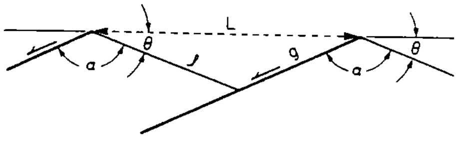
TIME OF FORMATION OF MYLONITIC TECTONITES

On the basis of U-Pb isotopic analysis, it has been shown that Tertiary granitic protolith for mylonitic, augen gneiss is at least as young as about 50 m.y. (Shakel et al., 1977; Anderson, et al., 1980; Wright and Haxel, 1980). Reynolds et al. (1978), Reynolds and Rehrig (1980), and Reynolds (1982) have even suggested that mylonitic tectonites in the South Mountains near Phoenix have been derived from granitic protolith as young as 25 m.y. The basis for their interpretation is Rb-Sr isotopic analysis of a pluton whose upper reaches are transformed into augen mylonite.

KINEMATIC INTERPRETATION

Approach

The evolution of core-complex tectonites, tectonite carapace, and decollement-zone microbreccias can be explained by progressive simple shear within thick shear zones that accommodated normal displacements. The shear zones reflect, in my opinion, a Tertiary stretching of the upper crust. I present this concept in schematic fashion, first por-



$$B = \frac{L}{l} = \frac{\sin \alpha}{\sin(\alpha+\theta)}$$

$$g = \frac{l \sin \theta}{\sin(\alpha+\theta)}$$

Figure 2. Mathematical-geometrical model for crustal stretching along spaced, discrete faults. From Le Pichon and Sibuet (1981).

traying a step-by-step crustal stretching along spaced, discrete, normal-fault surfaces, and then repeating the process, this time replacing the lower reaches of the faults with thick shear zones.

Stretching Accommodated by Discrete Faults

As reviewed recently by Wernicke and Burchfiel (1982), there are many ways by which the upper crust might extend along spaced, discrete, normal fault surfaces. For mathematical and geometric simplicity in preparing illustrative cross-sectional diagrams, [redacted] Compatible values of block tilt, fault dip, and fault translation for different degrees of stretching can be calculated on the basis of mathematical-geometric relationships, such as those presented by Le Pichon and Sibuet (1981) (Fig. 2).

As shown in Figure 3, progressive stretching results in activation of the faults, rotation of strata to steeper dips, and a steadily decreasing fault dip (Fig. 3). Stretching by 10% results in fault translation of 560 m and back tilting of the tilted step blocks by some 4° (Fig. 3B). Fault

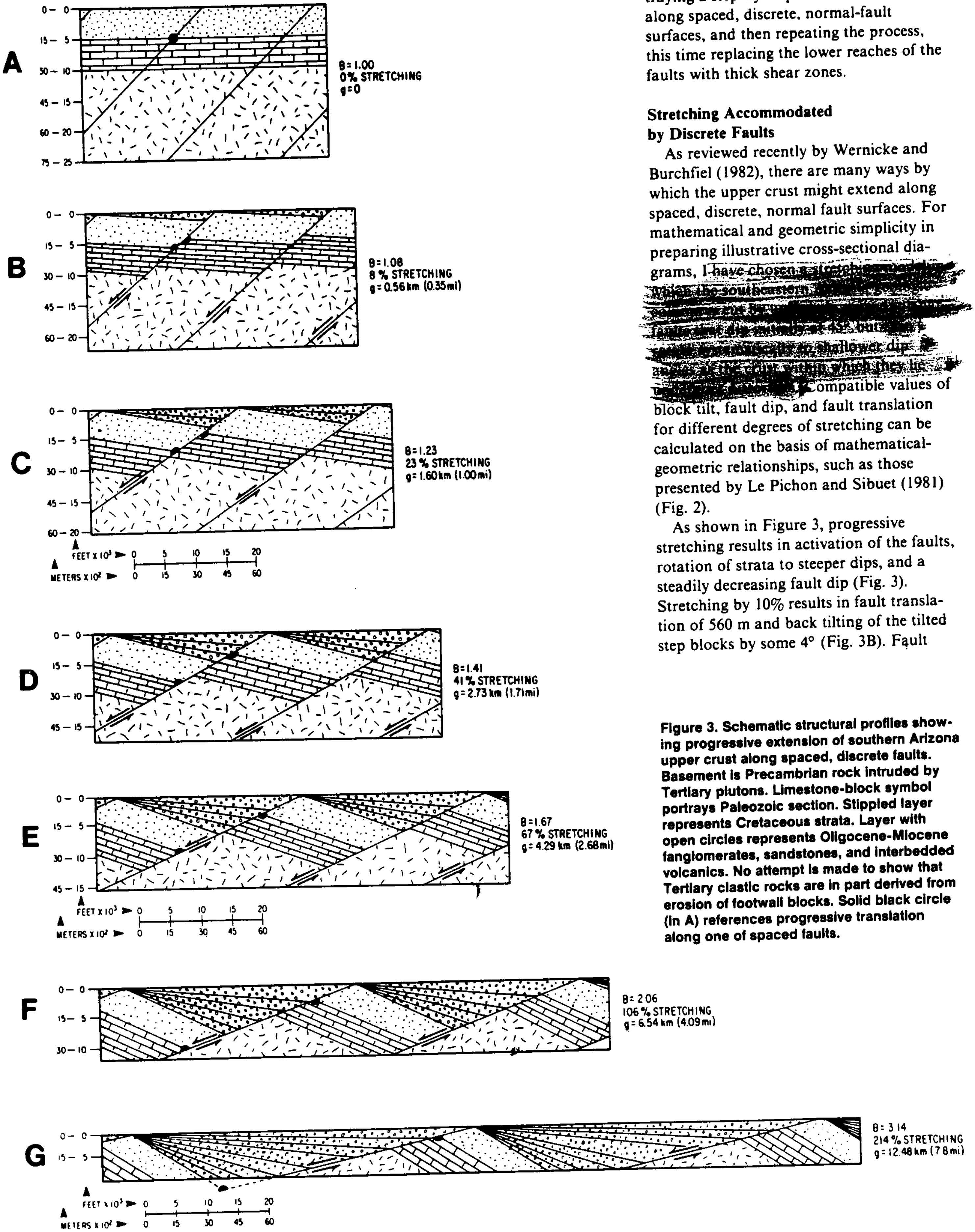


Figure 3. Schematic structural profiles showing progressive extension of southern Arizona upper crust along spaced, discrete faults. Basement is Precambrian rock intruded by Tertiary plutons. Limestone-block symbol portrays Paleozoic section. Stippled layer represents Cretaceous strata. Layer with open circles represents Oligocene-Miocene fanglomerates, sandstones, and interbedded volcanics. No attempt is made to show that Tertiary clastic rocks are in part derived from erosion of footwall blocks. Solid black circle (in A) references progressive translation along one of spaced faults.

offset of what may have been a flat topographic surface forms basins of accumulation of sediment (and volcanic rocks). In the southern part of the Basin and Range, these first-formed gravels would be Oligocene in age, or perhaps even slightly older. For a level of stretching of 67%, individual faults would show displacements on the order of 4.29 km, and strata would be tilted to dips of 20° (Fig. 3D). Tertiary sediments would accumulate to thicknesses of at least 1,800 m, with apparent thicknesses of as much as 3,600 m. Stretching by a factor of 214% (Fig. 3G) is accommodated by fault offsets of 12.48 km and the tilting of beds to dips of about 32°. In this scheme, younger-on-older fault relationships evolve quite naturally. Hanging-wall strata of Paleozoic, Mesozoic, and Tertiary age are sequentially and successively lowered against Precambrian footwall.

Stretching Accommodated by Shear Zones

To better understand the structural significance of core-complex tectonites, tectonite carapace, and decollement-zone microbreccias, it is instructive to replace the lower reaches of the faults shown in Figure 3 with *shear zones,* hundreds of metres thick. Precambrian and Paleozoic rocks cut by the shear zones would be transformed into tectonites by distributed simple shear. Paleozoic strata, displaced by large-magnitude normal offset in zones of distributed simple shear, would be transformed into thin carapace smeared on top of tectonite gneiss derived from Precambrian basement or the Tertiary plutons that intrude it (Fig. 4). The orientation of tectonite foliation within each shear zone would reflect the orientation of the plane of flattening (the XY plane). [redacted]

The concept of progressive simple shear as applied to the core complexes is illustrated in Figure 5, through a sequence of diagrams that shows the contact evolution at some deep level of the extending system. The state of strain is calculated for each increment of progressive deformation. By way of example, Figure 3B shows that a 10% stretching can be accommodated by 560 m of fault displacement along regularly spaced, discrete planar faults. However, when the 560 m of fault slip is distributed across a 600-m-thick shear zone (Fig. 5B), a state of strain develops in which tectonite foliation becomes oriented at 33° to the boundaries of the shear zone. Strain ratio within the shear zone is calculated to be 2.4.

The progressive deformation that ensues during continued stretching from 10% to 214% is interesting indeed. Computed strain-ratio values climb to 453, and the orientation of tectonite foliation rotates to within 3° of the shear-zone boundaries.

The evolution of contacts is portrayed in Figure 5. Young, upper-level crustal rocks are progressively and sequentially brought into low-angle contact with older, deeper level rocks that had already been transformed to tectonites as part of the "stretching" process. The shear-zone model nicely accounts for the evolution of decollement-zone microbreccias. In effect, the tectonic denudation achieved by progressive simple shear elevates early-formed tectonite to higher and higher structural levels (compare B and G in Fig. 5). The upper reaches of the shear zones become more and more vulnerable to a brittle structural overprinting. [redacted]

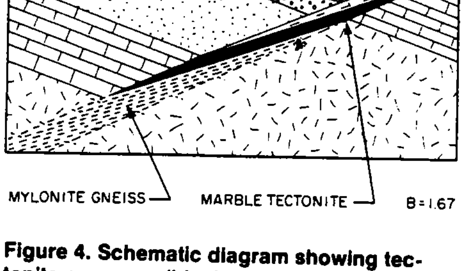


Figure 4. Schematic diagram showing tectonite carapace (black) as product of ductile shear of Paleozoic strata within low-dipping normal-slip shear zone.

SUPPORTING DATA FOR SIMPLE-SHEAR MODEL

The shear-zone model demands a remarkable degree of kinematic coordination of tectonic movements over a long span of time. In particular, the model requires that simple-shear movements responsible for the formation of tectonite are along the same line and in the same sense as the faulting that created the microbreccias and the faulting that emplaced the upper-plate rocks. Such kinematic coordination of movements at all structural levels is reasonably well documented in the Rincon Mountains near Tucson (Davis, 1981; Davis and Hardy, 1981).

Figure 6A, a synoptic stereographic diagram, displays fold-axis orientations in tectonite carapace in the Happy Valley and Redington Pass domains of the Rincon Mountains, based on data from Davis (1975, 1980), Benson (1974), and Lingrey (1982). Fold axes are plotted according to clockwise versus counterclockwise asymmetry. Inferred slip-line orientation based on this plot is southwesterly, specifically S35° W. The inferred slip-line direction is subparallel to the direction of penetrative lineation in the tectonite gneiss of the Rincon Mountains.

Folded Paleozoic and Mesozoic strata in upper-plate locations around the margins of the Rincon Mountains also show southwesterly directed vergence. My earlier interpretation that folds in the cover disclose a radial pattern of movement was incorrect (Davis, 1973, 1975, 1977; Thorman, 1977). When all the fold-axis data for upper-plate rocks are replotted on a single diagram (Fig. 6B), the folds sort into two distinct orientation domains of S-shaped vs. Z-shaped profile forms. [redacted]

As discussed briefly by Davis and Hardy (1981), the direction of translation responsible for emplacement of upper-plate Oligocene-Miocene strata is almost always strictly perpendicular to the average strike of the units. The sense of movement is opposite to the dip direction of the detachment strata. [redacted]

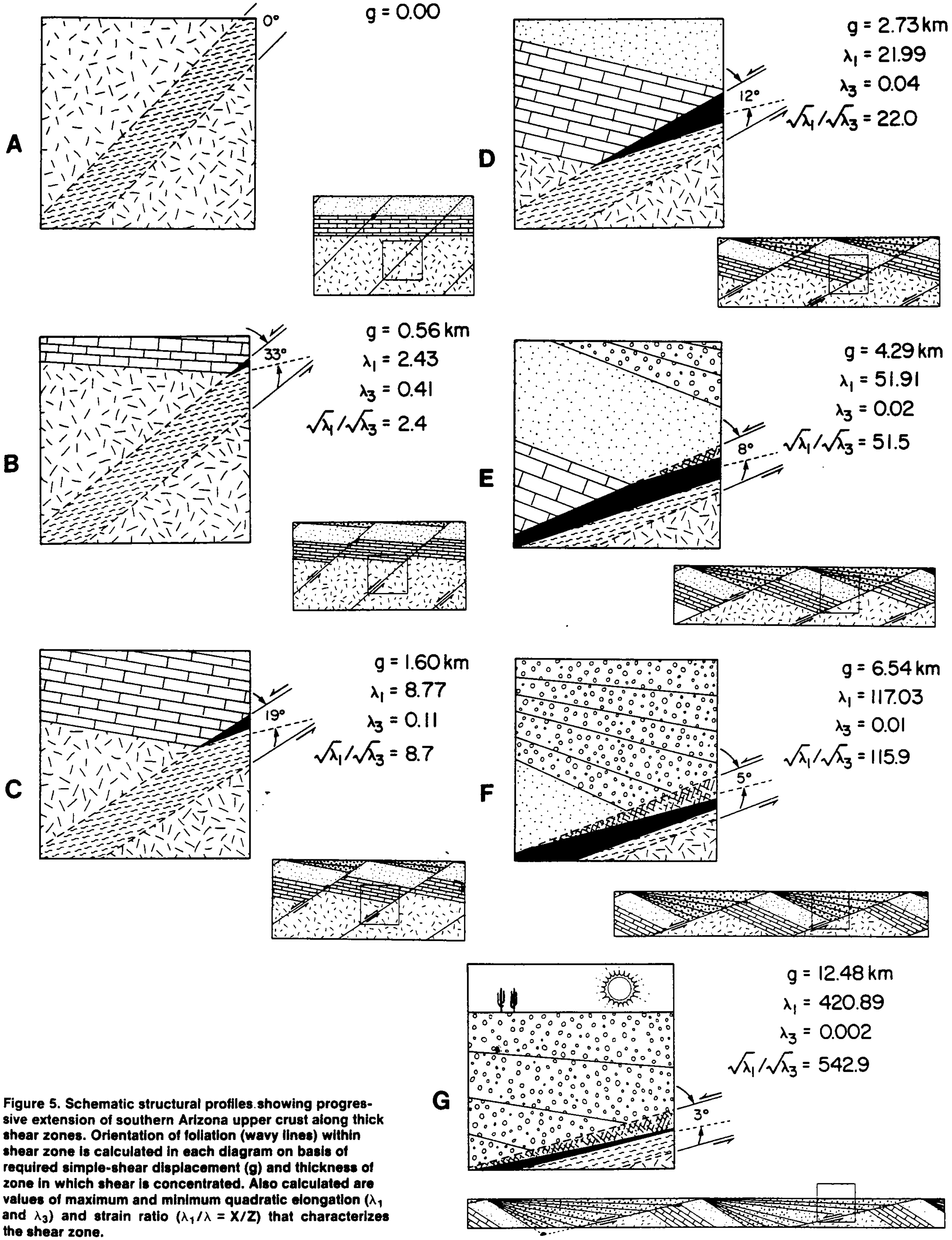


Figure 5. Schematic structural profiles showing progressive extension of southern Arizona upper crust along thick shear zones. Orientation of foliation (wavy lines) within shear zone is calculated in each diagram on basis of required simple-shear displacement (g) and thickness of zone in which shear is concentrated. Also calculated are values of maximum and minimum quadratic elongation (λ_1 and λ_3) and strain ratio ($\lambda_1/\lambda = X/Z$) that characterizes the shear zone.

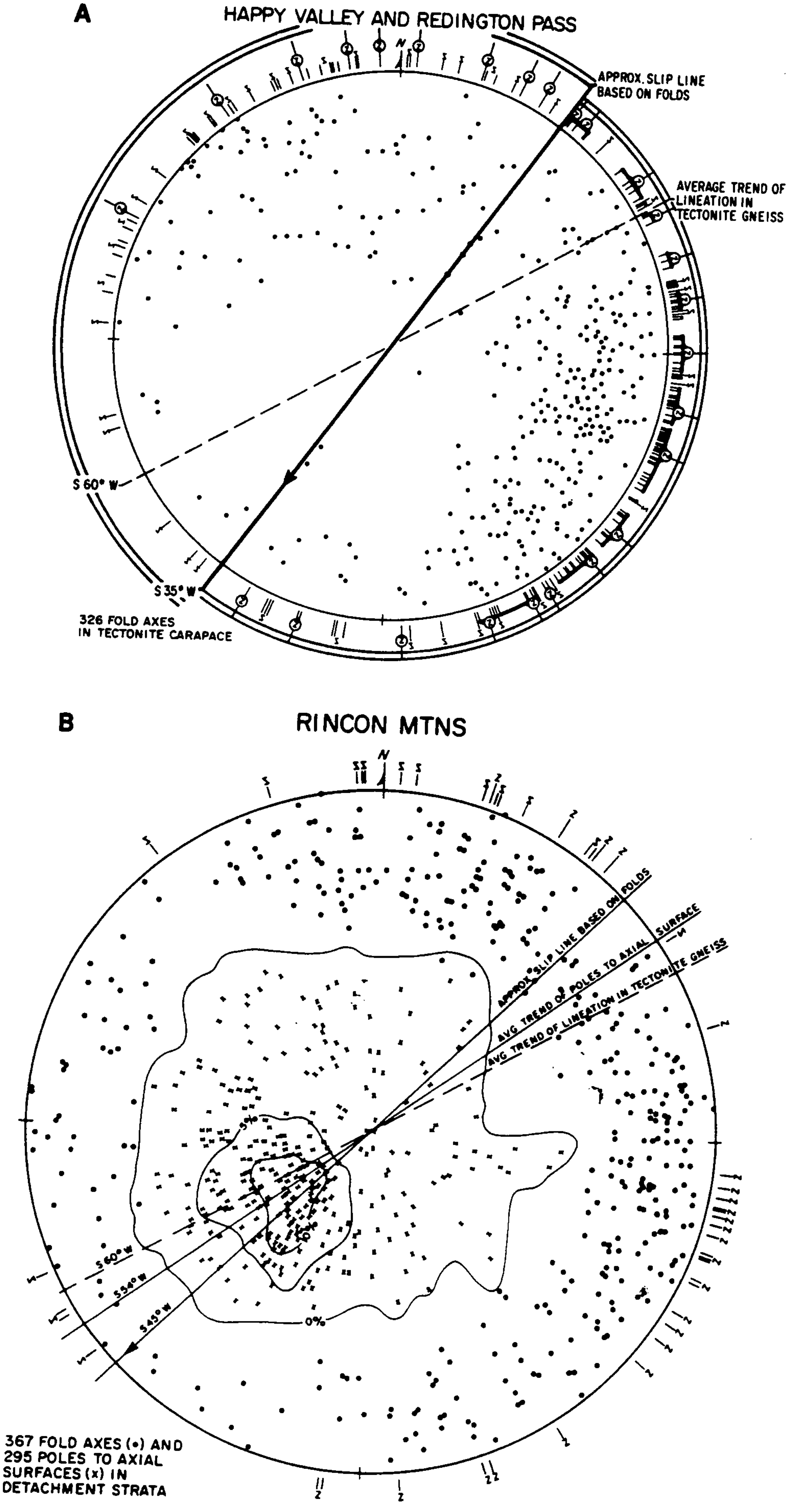


Figure 6. Lower-hemisphere equal-area projections showing (A) fold axis orientations in tectonite carapace plotted according to Z asymmetry vs. S asymmetry, and (B) fold-axis orientations in Paleozoic and Mesozoic detachment strata plotted according to asymmetry.

[redacted] Although speculative, it is possible to interpret the arch-like variation in attitude of foliation, and the variation(s) in intensity of development of mylonitic foliation (Fig. 7A), as expressions of the sigmoidal pattern of internal foliations that commonly mark shear zones (Fig. 7B). Sigmoidal patterns arise when a shear zone gradually increases in thickness as deformation progresses (Ramsay, 1980). Early formed foliations in the middle of such shear zones are rotated by progressive simple shear into near-parallelism with the boundaries of shear (Fig. 8A, B). Late-stage, nonrotated foliations that form near the upper and lower margins of shear zones retain their original 45° angular relationship with the boundaries of shear (Fig. 8C). If indeed the sigmoid-like pattern of foliations in the Rincon Mountains reflects progressive simple shear on a grand scale, the asymmetry of the pattern clearly reflects a southwest-directed normal simple shear. Such a downward "feathering" of foliation in a direction opposite to that of the movement sense of upper-level rocks is not unique to the Rincon Mountains. Similar patterns can be seen in cross sections rendered by Keith et al. (1980) for the Santa Catalina Mountains, by Reynolds and Rehrig (1980) for the South Mountains, and by Davis et al. (1980) for the Whipple Mountains.

CONCLUSIONS

Structures and contact relationships in metamorphic core complexes are expressions of regional shear zones. The shear zones have accommodated many kilometres of displacement of a normal-slip nature along the line of penetrative lineation, a response to crustal stretching in the Tertiary. Foliation attitudes within the shear zones record the XY plane of finite strain. Variations in foliation attitudes record the effects of progressive simple shear. Core-complex tectonites now exposed were formed at great depth, on the order of 10 km. Overprinting of core-complex tectonites by microbrecciation is a natural consequence of the geometry and kinematics of progressive normal simple shear.

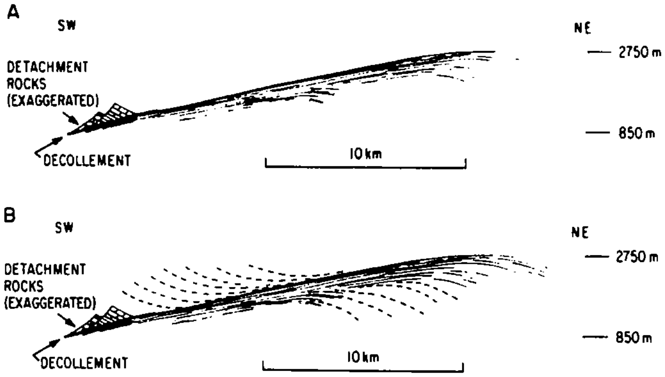


Figure 7. A: Schematic structural profile showing variation(s) in orientation and intensity of development of foliation in core complex tectonite, Rincon Mountains, Arizona. B: Dashed line pattern shows what pattern may have been like before completion of detachment faulting.

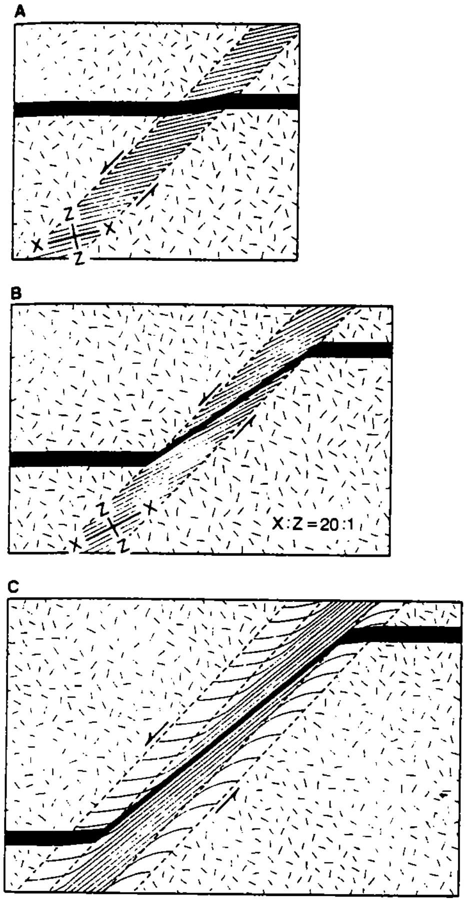


Figure 8. Kinematics of development of sigmoidal foliation patterns within shear zones. A: Plane of flattening is initially oriented at 45° to shear-zone walls. B: Progressive deformation results in rotation of early-formed foliation. C: As shear zone expands, new foliation develops parallel to plane of flattening, 45° to shear zone walls. Overall form of foliation is sigmoidal, reflecting total finite strain.

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