CHAPTER 3

METAMORPHIC CORE COMPLEXES--STRUCTURAL CHARACTERISTICS, KINEMATIC EXPRESSION, AND RELATION TO MID-MIOCENE LISTRIC FAULTING

By

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STRUCTURAL CHARACTERISTICS

Introduction

Cordilleran metamorphic core complexes are deformational systems within the Basin and Range province which owe their distinctive physical expression to superimposition of mylonitic tectonite fabrics and brittle denudational faulting. In the southern part of the western Cordillera, crustal rocks softened by prodigious Laramide magmatism were subjected to a shearing process which gave rise locally to the mylonitic tectonite development. The shearing fashioned thick, regionally continuous, gently dipping zones of lineated tectonite from rocks as young as 55 m.y., but no younger than 25 m.y. (Anderson and others, 1977, 1980; Shakel and others, 1977; Keith and others, 1980; Reynolds and Rehrig, 1980). During the time that the tectonite was forming, large fault-controlled basins developed, and these received growth-faulted accumulations of continental redbeds and volcanics (Davis and Coney, 1979). Regionally extensive mid-Miocene listric normal denudational faulting was superimposed on tectonite and non-tectonite alike, and in such a way that transport along the faults was aligned strictly parallel to lineation in underlying or nearby tectonite exposures.
Comprehensive descriptions of the geologic properties of individual 'Cordilleran metamorphic core complexes' are presented in a memoir by the same name (Crittenden and others, 1980). In this chapter an attempt is made to describe the composite properties of these deformational systems, especially in the context of the regional system of Cenozoic deformation which they comprise. Defining what constitutes the characteristics of metamorphic core complexes is a scale-dependent process. Viewed as regional tectonic elements along the length of the western Cordillera from Sonora to southern Canada, the metamorphic core complexes might be considered 'small' outcrop areas of relatively high topographic relief which comprise arches of distinctively deformed and metamorphosed igneous and sedimentary rocks. The deformed crystalline rocks are separated from unmetamorphosed country rocks by discontinuities (décollement) marking strikingly sharp thermal-strain gradients. Resting on these discontinuities are 'tiny' thin plates of deformed but generally unmetamorphosed rocks. Generally the isotopic systems of core complex rocks disclose a mid-Tertiary thermal disturbance. The complexes are commonly co-spatial with Oligocene-Miocene continental sedimentary sequences and Miocene ignimbritic volcanic rocks.

At the mesoscopic scale, the array of structures in metamorphic core complexes is awesome in its diversity and pervasiveness; tectonites contain low-dipping mylonitic foliation, systematically aligned low-plunging mineral lineation, slickenside striae, normal ductile faults, abundant boudins and pinch-and-swell features, and recumbent to overturned tight ptygmatic folds in aplites and pegmatites. Zones of contact between compositionally (and mechanically) dissimilar tectonites are frequently marked by folded mylonitic schist. Tectonites of marble and quartzite show extreme thinning and attenuation. The common array of structures includes tight isoclinal recumbent to overturned intrafolial folds, axial-plane cleavage, boudins, pinch-and-swell, flattened-stretched pebble metaconglomerate, lineation, and ductile faults. The tectonite fabric is generally overprinted by pervasive fractures. A décollement zone typically marks the uppermost limit of tectonite forming a planar to curviplanar zone of microbrecciated mylonitic tectonite and cataclasite. Within the zone, original foliation and lineation are rotated, overprinted, and locally masked completely by cataclastic granulation. Above the décollement zone, there may be modest amounts of mylonitic tectonite, but generally there are unmetamorphosed but faulted cover rocks characterized by internal folding, bedding-plane cleavage, and faults and shear zones. Although in normal stratigraphic succession, formations represented in the cover rocks are markedly tectonically thinned.
Terminology

In this assessment of structural and tectonic characteristics of metamorphic core complexes, the major components of the deformed terranes are referred to as (1) mylonitic tectonites, (2) décollement zones, and (3) detachments (Fig. 3-1). The term tectonite underscores the fact that all rocks within the zone, regardless of age or composition of protolith, were affected by penetrative slip or flow on newly generated closely spaced foliation and fracture discontinuities. 'Tectonite' places emphasis on the deformed state of these rocks, not simply the metamorphosed state. Misch (1960) recognized the power of the term when he applied it to the infamous marble tectonite below the Snake Range décollement in eastern Nevada. Regional mapping of the tectonites has slowly revealed that they give way downward to country rock from which the tectonite was derived (Compton and others, 1976; Davis, 1977, 1980; Coney, 1980; Davis and Coney, 1979; G.A. Davis and others, 1979; Reynolds and Rehrig, 1978, 1980). This relationship signals the fact that the zone of tectonite is produced at the expense of rocks which are part of the normal upper-crustal geological column for the region. It also reveals that the tectonite is not part of wholesale ductile shearing of all immediately underlying upper crustal rocks. Indeed, the zones are curvitabular, hundreds to thousands of meters thick, and continuous for kilometers (Crittenden and others, 1980).

There are three main field occurrences of mylonitic tectonite. The dominant one is 'tectonite gneiss' (Fig. 3-2a), composed of protomylonitic augen gneiss of granitic to quartz monzonitic composition. In southern Basin and Range examples, the tectonite gneiss is largely derived from granitic basement (Creasey and Theodore, 1975; Banks and others, 1977; Shakel and others, 1977; Davis 1977, 1980; Rehrig and Reynolds, 1977, 1980; G.A. Davis and others, 1980; Reynolds and Rehrig, 1980). Tectonite gneiss is pervaded by a gently dipping and macroscopically smoothly curved foliation which gives expression to awesome dome-like massifs, referred to by some as gneiss domes or magmatic blisters. The Rincon Mountains east of Tucson, Arizona is a good example (Davis, 1980), but an even better expression of this is Mazatan Mountain, east of Hermosillo, Sonora, where a Laramide batholith is partly converted to tectonite gneiss (Anderson and others, 1980).

A second common field occurrence is 'tectonite schist' from phyllonitic overprinting of metavolcanic and/or metasedimentary, schistose protolith (Fig. 3-2b). This class of tectonite schist gives way downward to regionally metamorphosed, foliated, but non-overprinted rocks. Structural kinematics are more difficult to unravel in such terranes as these where two (or more) penetrative deformations have been superimposed. Such tectonites are exemplified by overprinted Jurassic (?) metasedimentary and
Figure 3-1 Schematic diagram showing structural subdivisions of metamorphic core complexes.
Figure 3-2. Chief varieties of metamorphic core complexes. Varieties distinguished on the basis of protolith for mylonitic tectonites. Mylonitic tectonite is derived at the expense of (A) Precambrian granite and Tertiary quartz monzonite, (B) Precambrian Pinal schist (or Mesozoic schist), and (C) younger Precambrian and Paleozoic sedimentary rocks.
Figure 3-3  Recumbent fold in calc-silicate and marble layers within tectonite carapace. Rincon Mountain area, Arizona
metavolcanic rocks in the Papago Indian Reservation west of Tucson (Davis, 1977, 1980)) and in northern Sonora (Anderson and others, 1977, 1980). They are also represented by tectonites formed at the expense of older Precambrian Pinal Schist in places like the Rincon Mountains near Tucson (Drewes, 1978; Davis, 1980) and at South Mountain near Phoenix (Reynolds and Rehrig, 1980).

The third variety of tectonite, and perhaps the most spectacular is derived from unmetamorphosed sedimentary strata and is classically exemplified by the marble tectonite of Misch (1960). This kind of rock is here referred to as 'tectonite carapace', for it typically is expressed by a relatively thin curvitabular, strongly foliated sheet which is plated concordantly to underlying tectonite gneiss or non-tectonite protolith (Fig. 3-2c). Internally it is spectacularly folded (Fig. 3-3). Dominant lithologies are marble, quartzite, phyllite, and stretch-pebble conglomerate. The marble tectonite in the Snake Range of eastern Nevada is plated atop tectonite gneiss derived from Jurassic granite and tectonite quartzite (a part of the carapace) derived from Eocambrian-Cambrian Prospect Mountain Quartzite. The best examples in Arizona are in the Rincon and Coyote Mountains (Davis, 1975, 1977, 1980; Frost 1977; Gardulski, 1980).

Above the mylonitic tectonite there are detachments containing rocks which have not been affected by the tectonite overprint (Fig. 3-1) (Davis, 1977, 1980; Coney, 1979; Davis and Coney, 1979). These lie above the décollement zone. Rocks in the detachments range in age from Precambrian to Miocene, and they are not exotic to the country rock sequence. The upper surface of the décollement zone is a 'planar' fault (décollement). At the scale of a mountain range the décollement may be curviplanar, 'arched' in sympathy with the gross structure of the underlying tectonite foliation (Pasheley, 1966; Drewes, 1975, 1978; G.A. Davis and others, 1979, 1980). Large mullion structures are locally seen at the décollement zone. Below the décollement there is characteristically a conspicuous meter-thick ledge of crushed and granulated but strongly indurated, fine to very fine-grained cataclasite. It is referred to here as microbreccia (Fig. 3-1), and its composition reflects the nature of the underlying tectonite. For example, quartzfeldspathic microbreccia overlies tectonite gneiss derived from granitic rocks; marble microbreccias overlie tectonite marble derived from Paleozoic carbonate (Trevor, M.S. thesis, in prep).

Below the microbreccia, but still within the décollement zone, there are rocks which are excessively faulted, fractured, rotated, comminuted, and altered. These zones display crudely tabular, lens-shaped to wedge-like forms, ranging in thickness from a few meters to at least 50 meters. Until recently these
rocks have been thought of as restricted to décollement zones overlying tectonite gneiss. In such settings the rocks have been described as chlorite breccia (Rehrig and Reynolds, 1977, 1980; Davis, 1980; Davis and Coney, 1979) or, less fashionably, as 'junk-rock' (G.H. Davis and students). Here they are referred to as microbrecciated mylonitic tectonite (Fig. 3-1). The highly fractured, fine-grained, blue-green rocks of this zone weather to light brown/pale green shattered outcrops. In places the original tectonite gneiss fabric is so strongly masked that it cannot be recognized. Where mapped carefully (Reynolds and Rehrig, 1980; Davis and Cardulski, in prep.), the orientation of relict tectonite foliation is seen to be rotated orthogonally to lineation in underlying mylonitic tectonite, and with foliation dips as steep as 90°. The internal structure is surprisingly systematic, even though the rocks are the most deformed within metamorphic core complex terranes. Rocks of the décollement zone do not slowly grade downward into tectonite gneiss, but are separated from gently dipping lineated tectonite gneiss by low- to moderate dipping fault zones. The overall form and geometry suggests that these rocks are made up of imbricate detachments of mylonitic tectonite. Trevor (M.S. thesis, in prep.) has observed in the eastern Rincon Mountains that such rocks underlie an extensive ledge of marble microbreccia and consist of anomalously highly fractured, faulted, rotated, and brecciated tectonite marble. Only the deep blue-green chloritic alteration is absent.

The detachments (Fig. 3-1), in their simplest form, consist of Oligocene-Miocene strata which are rotated to moderately steep or steep dips and rest in low-angle fault contact on microbreccia of the décollement zone (Pashley, 1966; Davis, 1975, 1980; Drewes, 1975, 1978; Davis, G.A., and others, 1979). Bedding strike of the detachment strata is typically oriented at right angles to the trend of lineation in mylonitic tectonite (Rehrig and others, 1980; G.A. Davis and others, 1979). The more complicated and challenging detachments contain pervasively shattered Precambrian granite and spectacularly folded Paleozoic/Mesozoic strata, most of which is non-tectonite (Coney, 1974; Davis, 1975, 1980; Drewes, 1975, 1976, 1978). The décollement zone, then, separates rocks of sharply contrasting mechanical properties and deformational characteristics. It is the contrast between rocks above and below the décollement which has been so puzzling to explain structurally and tectonically (Thorman, 1977; Davis, 1977). Simply stated, how were the tectonites formed without affecting rocks in the detachment plates, whose distance of tectonic transport cannot be very far?? In addressing this question it must be recognized that detachments of the type described lie both within and outside of metamorphic core complex terranes in the southern Cordillera. For example, in the Black Canyon region south of Lake Mead (Anderson, 1971, 1978) and in the San Pedro Valley northeast of Tucson (Creasey, 1965; Cornwall
and Krieger, 1975; Krieger, 1974; Scarborough and Peirce, 1978),
detachments of Oligocene and Miocene strata rest in low-angle
découllement-like fault contact on non-tectonite granitic basement,
with the closest outcrops of lineated mylonitic tectonite kilo-
meters to tens of kilometers away.

Descriptions

Tectonite Gneiss

By far the greatest volume of rocks in the metamorphic core
complexes comprise tectonite gneiss. Tectonite gneiss underlies
exposed surface areas of more than 500 km² within single complexes,
and expresses an exposed vertical relief of as much as 200 m.
Tectonite gneiss undergirds some of the highest summits in the
Basin and Range province. Mylonitic foliation in the complexes
is characteristically low-dipping and commonly defines large
upright, doubly plunging foliation arches or antiforms, half-arches,
upright synforms or troughs, and irregular amoeboid domical struc-
tures. Some of the doubly plunging arches have exceptional physio-
graphic expression (Fig. 3-4). In general, penetrative mineral
lineation within tectonite gneiss is co-axial with axes of arching;
yet there are a number of examples where arching resulted in clear
rotation of the original unidirectional penetrative lineation.

Tectonite gneiss in the southern part of the western Cordillera
is derived in part from medium to coarse-grained Precambrian grani-
tic rocks, approximately 1.4 to 1.6 b.y. old (Creasey and Theodore,
1975; Banks and others, 1977; Shabek and others, 1977; Davis and
others, 1979). In outcrop, the tectonite gneiss thus derived is
relatively dark colored and cut by the penetrative flat to moder-
ately dipping mylonitic foliation (Fig. 3-5). Conformable aplite
and pegmatite veins serve to enhance the foliation, and such sills
and veins commonly display abundant boudinage and pinch-and-swell.
Aplites and pegmatites that cut the foliation at high angles are
almost always ptymatically folded. These folds are axial planar
with respect to low-dipping penetrative foliation and, thus, are
typically strongly overturned to recumbent.

In addition to mylonitic tectonite derived from Precambrian
granitic rocks, abundant tectonite is derived from quartz monzonite,
granodiorite, granite, and alaskite of Phanerozoic age. Many
textural and compositional varieties of these rocks exist, but most
tend to be medium-grained and quartz monzonitic in composition.
Garnet-bearing two-mica granites are not uncommon. As in the case
of the coarse-grained tectonite gneisses, a distinguishing struc-
tural characteristic of these rocks is low-dipping cataclastic
foliation and penetrative lineation. Deformational fabrics with-
in these rocks range from barely recognizable to mylonitic and
schistose. Foliation is typically defined by thin laminae of quartz, parallelism of micas, and aligned augen of cataclastically deformed feldspar. The rocks are cut by abundant pegmatite, aplite, and flat joints. The striking physiographic expression of the penetrative low-dipping foliation and jointing calls attention to these core-complex tectonites from afar.

Establishing the exact age of tectonite-imprinted Phanerozoic plutons has been difficult, for the rocks are characterized by profoundly disturbed Rb/Sr isotopic systems. K/Ar and fission-track ages typically range from 30 m.y. to 24 m.y. for these tectonite gneisses and associated pegmatites and aplites. U/Pb age-determinations on zircons from tectonite gneiss in northern Sonora (Anderson and others, 1977) and southern Arizona (Shakel and others, 1977) reveal that the lineation and foliation-forming process was operative after 55 m.y.b.p. Keith and others (1980) provide a useful summary of the geochronological problems and offer some new interpretations. It is becoming increasingly well documented that the core-complex terranes contain both mid-Tertiary and pre-mid-Tertiary plutons. Recent isotopic data suggest that even some of the mid-Tertiary bodies have been affected by low-dipping foliation and penetrative lineation (Reynolds and Rehrig, 1980). The Tertiary event, whatever its dynamic nature, imposed its thermal-tectonic signature on tectonite gneiss plutons, regardless of whether they existed before the event or were emplaced during the event.

The tectonite gneisses everywhere display low-plunging mineral lineation of a mylonitic nature (Fig. 3-6). The lineation generally is penetrative on the scale of hand specimen, with a delicacy of development dependent in large part on grain size and texture of host rock. The lineation has a variety of forms, but generally is expressed in the plane of foliation of the augen gneisses by the alignment of long directions of inequant feldspar and quartz-feldspar augen, striæ, elongate aggregates and streaks of crushed minerals, and crenulations on quartz ribbons. Additionally, lineation occurs on concordant or discordant low-dipping aplite and pegmatite layers, mylonitic zones, transposition foliation surfaces, and low-angle normal faults. Even in some equigranular hypidiomorphic quartz monzonitic bodies lacking penetrative lineation, the lineation locally occurs on shallow-dipping aplite and pegmatite layers which have served to localize tectonic movements.

Within any given terrane of metamorphic core complexes, lineation is generally remarkably systematic in orientation. In southern Arizona and northern Sonora, with few exceptions, lineation trends N50-70E (Fig. 3-7). In eastern Nevada, western Utah, and southern Idaho, lineation trends systematically west-northwest. In Washington, lineation trends approximately east-west.
Figure 3-4  Northeast-directed, U-2 photo showing distinctive physiographic expression of the Santa Catalina and Rincon Mountains. The city of Tucson lies in the left foreground. High mountain in far-right background is the Pinaleno Mountains, part of which is also marked by metamorphic core complex deformation.
Figure 3-5  Penetrative, low-dipping foliation in mylonitic gneiss derived from Precambrian granite. White augen are feldspar porphyroclasts enveloped by laminae of quartz, biotite, and feldspar. Santa Catalina Mountains, Arizona.
Figure 3-6. Penetrative lineation in mylonitic gneiss. Rincon Mountains, Arizona.
Figure 3-7. Stereographic projections of orientations of penetrative lineation measured within metamorphic core complexes in southern Arizona. (A) Papago domain, west of Tucson. (B) Catalina domain, Tucson and northwest. (C) Pinaléno domain, east of Tucson in the Pinaléno-Jackson Mountain area.
Ductile normal faults are associated with the mylonitic, lineated, tectonite gneiss, and typically result in impressive local thinning. The ductile normal faults are always oriented at right angles to lineation, regardless of absolute orientation. Folds which naturally arise from the ductile faulting are superimposed on intrafolial folds in the mylonitic tectonite. The folds assume the form of upright antiforms and synforms marked by thinning in the zones of maximum inflection. In some cases, the hinge zones of the folds display visible offset, and ductile flexing appears to be superseded by actual normal faulting.

Contact zones between different phases of tectonite gneiss are commonly marked by strongly foliated, folded rocks referred to here as mylonitic schist. These rocks are fine-to very fine-grained and range in color from brown to steel gray to black. White broken feldspar and rock chips, irregular in size and shape, commonly 'float' in the fine grained mylonitic matrix. Deformed concordant aplite and pegmatite layers and veins accentuate the foliation. Penetrative folding is characteristic of these rocks and presumably reflects movements that helped to shape the tectonic gneiss fabric. The folds are intrafolial, tight to isoclinal, overturned to recumbent structures whose axes lie in the low-dipping foliation. Orientations of fold axes range from broadly dispersed to nearly coaxial with lineation. Foliation surfaces are not always marked by the mesoscopically recognizable mineral lineation; indeed, where found, the lineation looks overprinted.

Tectonite Schist

In many core complex terranes in the western Cordillera, the mylonitic tectonite overprint has been superposed on schists. For example, in southern Idaho, in the Albion Range, mylonitic tectonite has been derived in part from schistose rocks metamorphosed during the Mesozoic (at about 150 m.y.b.p.). In southern Arizona, tectonite schist was produced from mylonitic deformation of older Precambrian Pinal Schist (1.6 to 1.8 b.y.), and Jurassic metasedimentary and metavolcanic rocks. The resultant tectonite schist is anomalously highly folded and lineated. Original moderate to steeply inclined foliation is transposed about the new, flat to gently dipping foliation and shear surfaces. Folds are generally strongly overturned to recumbent, and often reclined. Superimposed folding is locally evident. Evaluation of these tectonite schists requires extensive comparative analysis of metamorphism and fabric regionally, in- and outside of the metamorphic core complexes. To date, this variety of tectonite has not been studied in much detail, but it will undoubtedly serve as a focus for structural and petrological analyses in the near future.
Tectonite Carapace

In southern Arizona metamorphic core complexes, tectonite carapace is derived from unmetamorphosed younger Precambrian and lower Paleozoic metasedimentary rocks. Such tectonites are commonly metamorphosed to upper greenschist and amphibolite grade, and form a relatively thin, tabular sheet of marble, quartzite and phyllite, concordantly welded or plated to underlying crystalline rocks. There are many outcrops where not even a crack separates younger Precambrian quartzite or marble of the tectonite carapace from underlying, tectonite gneiss. The tectonite carapace generally rests in low-angle contact on either (1) medium-grained quartz monzonitic tectonite gneiss of Tertiary (?) age or (2) moderately deformed coarse-grained augen gneiss derived from 1.4-1.5 b.y. porphyritic quartz monzonite (Banks, 1977). Thin tectonic slices (<10 m) of the mylonitic gneiss occur from place to place within the lowermost part of the tectonite carapace. On the mesoscopic scale, the base of the tectonite carapace is planar and strictly concordant with the foliation in the gneiss immediately below. Viewed macroscopically, the surface is smooth and gently warped into systematic upright antifoms and synfoms. Rarely, the surface is deformed into surprisingly tight antifoms that project upward in almost tent-like fashion. The vertical relief on such sharp, tight structures is at least 10-20 m. At some locations, granite gneiss below the contact displays tight to isoclinal recumbent folds.

Rocks of the tectonite carapace, wherever found, display very distinct structural characteristics (Davis, 1975; Schloderer, 1974; Waag, 1968; Frost and Davis, 1976; Frost, 1977). Strongly overturned to recumbent folds are ubiquitous (Fig. 3-8). Protoliths for the phyllite, schist, marble, and quartzite have been deformed by transposition into tectonites characterized by intrafolial, commonly rootless tight to isoclinal folds. Depending on mechanical characteristics of the original rocks, the folds may form by passive flow, passive slip, and/or flexural flow. The passive folds typify homogeneous domains of quartzite on marble. The most outstanding flexural forms occur in interlayered calc-silicate and marble. Where the rocks are dominantly marble containing only thin brittle calc-silicate or quartzite struts, the 'competent' layers are typically distended, attenuated, and transposed. Fragments of the originally continuous layers form boudins (Fig. 3-9), isolated fold hinges and assorted tectonic inclusions in the marble matrix, (Fig. 3-10). In the plane of foliation and lithologic layering of calc-silicate and marble, gash fracturing and orthogonally disposed mineral lineation are locally strongly developed.
Conglomerates within the tectonite carapace are transformed into subhorizontally flattened quartzite-pebble units. The flattened pebbles are typically profoundly elongated parallel to the lineation in underlying augen gneiss. Where the pebbles are flattened but not elongate, underlying cataclastically deformed augen gneiss is foliated but not lineated. In the Tortolita Mountains, Davis and others (1975) measured the orientation and dimensions of 86 flattened elongate quartzite pebbles within the Barnes metaconglomerate and compared these to undeformed clasts at a nearby locality in the Santa Catalina Mountains. Axial ratios were computed to be 9:2:1; the plane of flattening is subhorizontal and the direction of elongation, N58°E, is identical to that of the adjoining tectonite gneiss.

Foliation and lithologic layering within the tectonite carapace are generally shallow dipping and strongly developed. Axial planes of tight to isoclinal, overturned to recumbent folds are generally parallel to foliation and layering. The folds are commonly reclined with respect to layering and foliation. Seen on the scale of large single outcrops, the foliation and layering are marked by pinch-and-swell and boudinage, with graceful gentle changes in attitude. Predictably, boudinage and pinch-and-swell are best developed where rocks of contrasting ductilities are juxtaposed.

Individual formations within the tectonite carapace are arranged in normal stratigraphic order, but they are generally tectonically thinned or locally thickened. Specific estimates of the change in thickness are very difficult to make because of the uncertainties inherent in correlating the strongly deformed lithotectonic units with southeastern Arizona stratigraphy. In many places the thinning appears to exceed 75 percent.

Thinning and thickening within the younger Precambrian and Paleozoic sequences have been achieved by passive flowing including transposition (Frost, 1977) of units rendered ductile during the deformational process. On the mesoscopic scale, the mode of thinning is explicitly displayed in the stretched/flattened pebble metaconglomerates, passively folded marble and calc-silicate rocks, transposed schists, and dismembered, attenuated quartzite layers in ductile matrix. Detailed mapping reveals interesting macroscopic adjustments to the 'thinning process,' mainly a heterogeneous distribution of lithologic units of contrasting mechanical properties. Map patterns demonstrate lateral movement and concentration of ductile materials as a response to thinning, but carried out in such a way so as always to bring young rocks over older.
Figure 3-8. Isoclinal fold in tectonite carapace. Folded layers are calc-silicate and marble within Paleozoic rocks. Rincon Mountain area, Arizona.
Figure 3-9. Boudinage showing normal-slip on lozenge-shaped blocks within metamorphosed Paleozoic rocks. Rincon Mountain area, Arizona.
Figure 3-10. Tectonite carapace showing distended and broken 'competent' layers within a matrix of marble. Protolith was Paleozoic strata. Rincon Mountain area, Arizona.
The structural fabric of the tectonite carapace is intimately coordinated with that of the underlying tectonite gneiss. Fabrics of both structural units are marked by profound flattening perpendicular to subhorizontal layering and foliation and by extension parallel to lineation as denoted by boudinage, deformed pebbles, and the ductile normal fault zones. Davis and others (1975) analysed structures in the Tortolita Mountains and showed that the lineated surfaces within fine- to medium-grained quartz monzonite augen gneiss of the tectonite core accommodated vertically directed flattening and profound east-northeast extension; and that the fold and stretched-pebble fabric in the immediately adjacent tectonite carapace formed as a response to the same deforming process. Critical to that analysis was recognition of the coordinated nature of the augen gneiss fabric to that of the tectonite carapace: the modal long axis of pebbles is strictly parallel to lineation in adjacent augen gneiss; the fold axes in the tectonite carapace parallel the lineation orientation; ductile normal faults are orthogonal to lineation. On the basis of the strict compatibility of the normal-slip ductile and brittle faults to inferred principal strain directions inferred from the stretched-pebble data, the 'stretching' of the quartzite pebbles and the development of normal-slip faults were interpreted as the early and late stages respectively of a ductile-to-brittle continuum of extensional deformation. During this deformation no significant shift in principal strain directions took place.

Fold axes in rocks of the tectonite carapace are generally difficult to evaluate in regard to slip-line direction. The fundamental problem is establishing for certain that specific asymmetric folds are indeed first-order folds within the transposed sequences. Furthermore, the fold axes in the metasedimentary rocks generally display a broad range of orientation within the plane of slip or flow. For now it is most important to emphasize that (1) within the array of variably oriented overturned to recumbent folds, reclined folds are commonly the preferred mode, (2) the axes of reclined folds tend to be co-axial with lineation in ductile rocks like marble, (3) mineral lineation in marble is essentially orthogonal to penetrative gash fracturing in mechanically suitable lithologies in the metamorphic carapace, and (4) lineation in underlying tectonite gneiss is parallel to that in marble within the tectonite carapace.

The above observations and inferences are consistent with the interpretation that both the tectonite gneiss and carapace were affected by flattening and extension, and that these processes resulted in profound thinning through flow of the ductile, originally bedded, carapace strata. Flow in the tectonite carapace was parallel to mineral lineation, and during progressive deformation fold hinges rotated partly or wholly into alignment with the
flow direction. The degree of rotation was partly related to the mechanical properties of the deforming sequence.

Décollement Zone

A décollement separates detachments above from tectonite below. The surface separates rocks of remarkably contrasting deformational styles. Most often in southern Arizona examples, the décollement marks the top of the tectonite gneiss and the base of the non-tectonite "cover"; tectonite carapace is generally absent. Below the décollement surface, a 'décollement zone' is usually present and consists of an upper ledge of strongly indurated microbreccia, below which is a thick (up to 100 meters ± ) zone of microbrecciated, faulted, and rotated tectonite gneiss. Although the contact between the cataclasite and overlying detachment rocks is sharp, planar, and conspicuous, the contact between microbrecciated tectonite gneiss and underlying 'normal' tectonite gneiss appears gradational and ill-defined. The décollement zones occur only on one or two flanks of individual metamorphic core complexes.

Décollement zones commonly display striking 'younger on older' fault relations involving tens to hundreds of meters of stratigraphic separation. They typically separate tectonite gneiss derived in part from Precambrian rock, from non-tectonite Precambrian, Paleozoic, Mesozoic or Tertiary cover rocks. This array of structural and petrologic characteristics has prompted many workers to interpret them as thrust faults (Thorman, 1977; Drewes, 1978).

One of the best examples is the Catalina Fault, a décollement zone in the Santa Catalina and Rincon Mountains of southern Arizona. It crops out along a sinuous trace, tens of kilometers in length, on the south and west flanks of the complex. The décollement zone separates tectonite gneiss (below) from a variety of deformed but generally unmetamorphosed cover rocks, including Paleozoic limestone, sandstone, and shale, Mesozoic shale, dolomite, and conglomerate, and Oligocene-Miocene red beds. The dip of the décollement zone is generally less than 15° or 20°. The exposures are commonly confined to the pediment/mountain interface; at no place is the zone known to crop out at a high level on the mountain flank.
Figure 3-11. *The Catalina fault: décollement as separating mylonitic gneisses (below) from unmetamorphosed, non-tectonite Precambrian granite and Paleozoic sedimentary rocks (above).* Rincon Mountains, Arizona.
Viewed at the scale of the complex, the décollement zone forms a smoothly arcuate surface conforming to the macroscopic structural geometry of the tectonite gneiss. Viewed at the mesoscopic scale, the zone may be concordant or discordant to mylonitic foliation in underlying tectonite gneiss.

In outcrop, the extremely altered rocks of the décollement zone weather brown to brownish green, but on fresh surfaces they are seen to be bright blue-green chloritic, fine to medium grained microbreccias. They are pervasively overprinted by shattering along closely spaced fractures. Within the highly deformed rock suite, overprinted lineation and foliation fabrics can still be recognized; but as will be discussed later ('Kinematic Expression'), these are rotated into moderately or steeply dipping attitudes. Clearly, the microbrecciated tectonite gneiss was produced at the expense of mylonitic gneiss, and the microbreccia ledge at the expense of the microbreccia mylonitic gneiss.

The transformation from tectonite gneiss to microbreccia is remarkable. Gardulski (from Davis and Gardulski, in prep.) reports that 'normal' tectonite gneiss derived from Precambrian quartz monzonite consists of large (up to 4 cm) porphyroclasts of rounded to elliptical shapes in a matrix of mainly quartz and feldspar. The feldspar porphyroclasts show pull-apart structures with infilling by quartz and chlorite. Quartz occurs in several modes:—feldspar-free zones of recrystallization in which quartz is undulatary and very fine grained; zones of flattened, elongate, extremely undulose quartz (L:T=20:1) adjacent to feldspar porphyroclasts; and zones of polygonal quartz in 'pressure shadows' next to feldspar augen. Fracturing is not conspicuous and alteration of feldspar is minor in the 'normal' mylonitic gneisses. In contrast, the extremely microbrecciated mylonitic gneisses are marked by extreme fracturing, brecciation, microfaulting, and alteration. The foliation visible in normal gneiss is nearly obliterated by anastomosing bands of microbreccia which cut through the rock. Microfaulting has caused rotation and tilting of micro-fault blocks of up to 60°-70°. Some parts of this kind of rock are so mylonitized that only a dense aphanitic mass remains. Veinlets of chlorite, epidote, biotite, and opaque minerals are abundant and lace the rock in all orientations. Grain size is greatly reduced. Feldspar chips are as large as 0.3 mm, but the average size is 0.01 mm.
The non-tectonite detachments which overlie tectonite in the metamorphic core complexes are interesting and instructive in their gross configuration and interval structure. For the most part, the detachments directly overlie well developed décollement zones of the type already described. Cover rocks above the décollement zone (Catalina fault) in the Santa Catalina and Rincon Mountains form thin plates that include slices of Precambrian, Paleozoic, Mesozoic, and Tertiary formations. Along the front of the forerange in the Santa Catalina Mountains, the zone separates tectonite gneiss from Oligocene-Miocene Pantano Formation, a sequence of red beds, notably mudstone, siltstone, sandstone and conglomerate.

Pantano beds locally rest on the décollement zone on the south and west flanks of the Rincon Mountains; additionally Precambrian rocks and Paleozoic and Mesozoic strata lie atop the zone as well (Drewes, 1978). Completeness (incompleteness?) of stratigraphy in these sections is highly variable. Rocks on the west side of the Rincon Mountains within Saguaro National Monument (East) consist of Precambrian granite and schist, upper Paleozoic limestone, dolomite, and shale, and Tertiary red beds. Along the southeast flank of the Rincon Mountains, Cretaceous shale and limestone with interbedded siltstone, locally lie directly on the décollement. The thickness of the sheet is less than 90 m. At the southeasternmost corner of the Rincons, a 75 m sheet of Paleozoic rocks rests on the décollement zone. Although formations from Cambrian to Permian are represented, the thickness of the sequence is less than 10% of the full Paleozoic section.

East of the Rincon Mountains, the décollement is overlain by detachments of Precambrian granite and younger Precambrian and Paleozoic sedimentary strata, in a stacking which dips homoclinaly (Drewes, 1975; 1976a). The granite is shattered by closely spaced fractures and faults, and it rests directly on tectonite marble and quartzite derived from Younger Precambrian and Paleozoic strata. Enigmatically, specific formations which are strongly deformed tectonites below the décollement crop out within 100 m (!) of their non-tectonite, unmetamorphosed protolith counterparts in the overlying detachment(s).
Structures in the non-tectonite detachments display a wide variety of physical expressions. Precambrian granitic basement rocks form tabular to wedge-shaped, shattered masses. Structures in the sedimentary detachment strata are described by Coney (1974), Davis (1975), Compton and others (1976), and Davis and Frost (1976). Overturned asymmetric folds, detached isoclinal folds, and unbroken cascades of recumbent folds are locally abundant (Fig. 3-12). Most of the folds are transitional between ideal parallel and ideal similar folds and, thus, are characterized by some hinge-zone thickening (Davis, 1975). The scarcity of axial-plane cleavage, the abundance of bedding-plane cleavage, and the obvious influence of layering on the morphology of folds indicate that the folds evolved through slippage between layers and flow within layers.

The dominant structure in the Tertiary detachment strata is moderate to steep homoclinal tilting, and in such a manner that preserves an orthogonal relation between the strike of the beds and the trend of lineation in the closest exposed tectonite. This structural symmetry will be more fully discussed under 'Kinematic Expression'.

KINEMATIC EXPRESSION

Introduction

Interpretation of the kinematic significance of metamorphic core complexes affects our understanding of all aspects of Mesozoic and Cenozoic evolution of the southern part of the western Cordillera. Historically, the physical signatures of metamorphic core complexes have been interpreted in the context of Sevier-Laramide compressional deformation, especially overthrusting (Misch, 1960; Roberts and Crittenden, 1973; Drewes, 1976, 1978; Thorman, 1977). Most recently, DeWitt (1980) has reaffirmed the opinion that Mesozoic metamorphism and Sevier-Laramide compressional deformation were fundamental in shaping the metamorphic core complexes. Yet the geochronologic facts assembled thus far in Sonora (Anderson and others, 1977, 1980) and southern Arizona (Shakel and others, 1977; Keith and others, 1980; Haxel and others, 1979) demonstrate that mylonitic tectonite of core complex affinity formed at the expense
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of granitic plutonic rocks as young as 55 m.y., and perhaps much younger (Reynolds and Rehrig, 1980). Such deformation post-dated the cessation of Laramide compressional deformation and thrusting (Drewes, 1972a, 1972b, 1976b, 1978; Coney, 1978; Rehrig and Heidrick, 1972, 1976). The development of mylonitic tectonite had ceased before mid-Miocene time. The tectonite was at least in part overprinted by brittle fabrics during emplacement of upper-plate detachments as late as mid-Miocene (Davis and others, 1979, 1980; Anderson, 1971; Shackelford, 1977, 1980; Scarborough and Peirce, 1978). The structural facts suggest that both the formation of mylonitic tectonite and the emplacement of the detachments are expressions of extensional deformation in the Tertiary (Davis, 1977, 1980; Davis and Coney, 1979; Coney, 1979, 1980). What remains vague are the dynamic transitions which interconnect classical Laramide tectonism, the formation of mylonitic tectonite, the development of décollement zones, the emplacement of upper-plate detachments, and classical Basin and Range tectonism.

The importance of interpreting the structural geometry and tectonic implications of metamorphic core complexes has emerged recently in a very practical way. Anschutz Corporation has framed a petroleum exploration model for southern Arizona which features interpretation by major regional overthrusting. They have interpreted subhorizontal reflecting horizons at depths greater than 2-3 km to be the expression of Paleozoic and Mesozoic strata beneath what has been considered autochthonous Precambrian basement. Drilling has been initiated at a site directly above a major culmination in the reflectors. The site is within 2 km of lineated mylonitic tectonites exposed in the Picacho Mountain metamorphic core complex terrane, and it lies directly on the projection of the culmination of the Rincon-Santa Catalina metamorphic core complex. Peter Coney and I have suggested that the subhorizontal reflecting horizons might be the subsurface expression of mylonitic tectonite, not sedimentary layering. The possibility exists that the reflection profiles of the Anschutz Corporation might be among the first published records of the 'roots' of metamorphic core complexes.

Interpretation

The kinematic significance of rocks in the zone of mylonitic tectonite has been difficult to explore because so much of the rock is tectonite gneiss derived from mylonitic reduction of granitic or quartz monzonitic plutonic bodies. Where thus deformed, the tectonite usually lacks fold structures which would otherwise help to disclose slip-line paths. Fortunately, the structures in tectonite carapace are kinematically and dynamically coordinated with that of the tectonite gneiss, thus expanding the basis on which the internal movement plan can be evaluated (Davis, 1980).
To date I have emphasized that the tectonite fabric is characterized by profound flattening and extension, as evidenced by a broad array of structures, especially boudinage, ptygmatic folds, stretch-pebble conglomerate gash fractures, and ductile normal faults (Davis, 1977, 1980; Davis and Coney, 1979). Such a fabric system could evolve through pure shear and/or rotational simple shear during progressive deformation. Determining systematic sense of relative slip if such exists emerges as crucial to unraveling the strain and kinematic significance of the zones of mylonitic tectonite.

Based on fold analysis in southern Arizona, systematic simple-shear displacement within zones of tectonite are recognized. In the Pinalêno Mountains near Safford, Arizona, the sense of relative slip is clearly southwest to northeast, as revealed by asymmetric overturned, intrafolial folds which verge down the dip of northeast-dipping tectonite foliation. The line of slip is N40°E, parallel to penetrative lineation in the tectonite. In the eastern Rincon Mountains within Happy Valley, folds in tectonite marble and quartzite show a broad range in axial orientation, but the slip-line direction is westerly. This was reported by Frost and Davis (1976) and by Frost (1978), yet interpretation of this movement sense has never been agreed upon in the context of existing regional tectonic models. Evidence for a southwesterly sense of simple-shear is evident in fold data collected in mylonitic tectonite of the Rincon-Catalina complex as well (see Peterson, 1968; Waag, 1969; Schloderer, 1976). In the metamorphic core complex terrane of the Coyote Mountains, west of Tucson, ductile normal faults and sparse minor folds in tectonite quartzite and marble indicate south to north simple shear. Further west, in the Sierra Blanca Mountains, tectonite schist contains abundant intrafolial folds which together reveal north-northwest to south-southeast directed simple shear. Additionally, the structural data demonstrate that the inferred slip-line and the direction of penetrative lineation are coaxial (Davis, 1977, 1980).

Above and beyond minor fold data, certain large-scale geological relationships suggest that simple-shear deformation produced the mylonitic tectonite. In the Santa Catalina Mountains north of Tucson, coarse-grained augen gneiss derived from 1.4 b.y. quartz monzonite is injected by 'laccolithic', 'lit par lit' medium-grained augen gneiss derived from early Tertiary plutonic rocks. Workers have generally assumed that this geometric geologic relationship is a preserved intrusive contact, overprinted by mylonitic deformation. An alternative interpretation is that the upper part of the Tertiary plutonic system, emplaced in Precambrian basement, was partially 'beheaded' by the southwest-directed simple shearing which seems to characterize the mylonitic tectonite of the Catalinas (Fig. 3 - 13). The kinematics of this model are identical to those described by Ramsay and Graham (1970).
Figure 3-13. Interpretive model that describes a sill-like form of deformed Tertiary quartz monzonite as a product of distributed simple-shear.
The implications of these emerging data are important. First, the mylonitic tectonite acquired its strain during progressive simple-shear rotational deformation and not by pure shear (although pure shear probably occurred locally). Second, the direction of penetrative lineation in the tectonite lies so close to most solutions of slip-line direction based on fold orientations that it seems likely that the mineral-lineation is indeed the slip-line direction. Third, dynamic models for the origin of the tectonites must be capable of explaining simple-shear couples which act in different senses and, locally, in different directions.

With respect to present attitudes, the mylonitic tectonites appear to be zones of ductile normal slip (flow). If so, these tectonites may be partial exposures of ductile normal shear zones of regional extent. Mapping the tectonites as parts of regional ductile shear zones, and mapping both the sense of simple-shear and the slip-line path are necessary to assess the tectonic significance of Cordilleran metamorphic core complexes as a whole. The plan view geometry of the system of regional ductile normal shear zones can be reconstructed in a general way by interconnecting the geographically isolated, partial exposures of tectonite. Subsurface seismic reflection data would perhaps make this job easier and more reliable.

Regional dip of individual subhorizontal zones in some cases can be evaluated through systematic assessment of which rocks within the country-rock column are converted to mylonitic tectonite. In this regard, the Rincon-Santa Catalina complex of southern Arizona is a very provocative example. All along the west and southwest margins of this complex, mylonitic tectonite is made at the expense of Precambrian basement and Tertiary (?) intrusions. The position of the ductile shear zone represented by mylonitic tectonite appears to be well below the great unconformity. Along the northwest-trending 'culmination' (?) of the complex, tectonite was largely produced through penetrative deformation of Younger Precambrian and lower Paleozoic sedimentary rocks, producing tectonite carapace. Further northeast, the zone of tectonite occupies an even higher position in the section, such that tectonite marble and quartzite produced from Paleozoic strata as young as Mississippian-Pennsylvanian rest on non-tectonite basement. Farthest northeast, tectonite derived from Permian and Cretaceous strata rest on non-tectonite lower Paleozoic strata. This apparent migration of the shear zone up-section to the northeast may help explain what has been described as a fundamental asymmetry to metamorphic core complexes. The recognition of such regional dip of the zone of mylonitic tectonite contradicts Davis and Coney's
(1979) interpretation that the top of the zone of penetrative deformation hevers around the great unconformity. This indeed may be the case locally, but it does not appear to be the rule.

The structural characteristics which make the décollement zones so distinctive formed in the late stages of and/or after the formation of mylonitic tectonite. The microbrecciated mylonitic tectonite which makes up most of the décollement was produced during imbricate(?) faulting and rotation of the mylonitic tectonite. In parts of décollement zones where mylonitic tectonite is only modestly overprinted by microbrecciation and faulting, there is bimodality of strike orientation of relict tectonite foliation. For example, in the western Rincon Mountains, foliation is locally 'dragged' into parallelism with north-northwest striking fault and fracture zones. Where the strike of foliation is north-northwest, dip magnitudes are extraordinarily steep. In parts of the décollement zone it is radically changed in orientation. In the Rincon Mountains example, relict foliation strikes north-northwest and dips as steeply as 90°.

Faulting, rotation, and microbrecciation were carried out at a time and at a structural position such that no upper-plate detachment strata became interleaved with microbrecciated mylonitic tectonite in the décollement zone. In essence, the formation of the microbreccia capping ledge, the décollement, and the emplacement of the detachment rocks all post-dated the development of the sub-décollement detachments.

It is suggested here that the detachments in microbrecciated tectonite gneiss are the physical expression of coalescing, imbricate listric normal faults. Rotation of the mylonitic tectonite foliation is viewed as the natural response to normal displacement(s) of tectonite along curved fault surfaces. The steepest-dipping mylonitic tectonite denotes major displacements along a single fault zone and/or multiple movements along superimposed faults. At Saguaro National Monument (East) in the Rincon Mountains, certain low-dipping domains of microbrecciated mylonitic tectonite have relict foliation/lineation attitudes which suggest that the rock has been rotated during faulting perhaps by more than 90° (Davis and Gardulski, in prep.). The rotations may be described as operating around axes oriented perpendicular to lineation in underlying mylonitic tectonite. The problem which has emerged as critically important is determining the sense of fault movement within the décollement zones.
The process of imbricate listric(?) normal faulting must have had the effect of translating upper-level country rock downward and laterally toward the zone of mylonitic tectonite. This tectonic denudation process was probably in part concurrent with formation of mylonitic tectonite (Davis, 1977a). The position of the base of the décollement zone may have been thermally controlled, prescribed by the rheological characteristics of the mylonitic tectonite. Eventually the microbrecciated, rotated mylonitic tectonite was 'truncated' at a level now corresponding to the cataclasite ledge directly beneath the décollement zone. This microbreccia ledge in itself is probably a zone of coalescence of listric(?) normal faults (Shackelford, 1977), but what controlled its exact structural position is not known. Above it, the nontectonite detachment rocks are found. The stacking of structural units -- mylonitic tectonite, sub-décollement detachments, microbreccia ledge, and upper-plate detachments -- is a profound example of 'disharmonic faulting'.

MID-MIOCENE LISTRIC NORMAL FAULTING

by

G.H. Davis and J.J. Hardy, Jr.

Introduction

The emplacement of the upper-plate detachments is a composite product of (1) an early tectonic denudation associated with formation of mylonitic tectonite and of the décollement zone, and (2) a mid-Miocene low-angle normal faulting which is now regarded as an integral part of the regional tectonic strain of the southern part of the western Cordillera. To understand the denudation contribution afforded by the mid-Miocene faulting, it is useful to examine in some depth the structural characteristics and terranes in which the detachments are mainly composed of sedimentary and volcanic strata of Miocene age. The following account is directly from the work of Davis and J.J. Hardy, Jr. (submitted for publication).

Views regarding the origin of the upper-plate detachments are changing in accord with new facts derived from careful studies of the mid- to late-Tertiary record. Armstrong's (1972)
success in discriminating between Cenozoic and pre-Cenozoic low-angle faults in the Basin and Range of western Utah and eastern Nevada provided a glimpse of extensive Tertiary 'denudational' faulting which had largely gone unnoticed. Anderson's (1971, 1977, 1978) brilliant mapping and synthesis of structures in the region south of Lake Mead in Arizona and Nevada yielded salient geological details regarding one class of denudational faults, namely a listric faulting which he regarded as having accommodated thin-skin distension of the crust in an east-west direction. The fundamental relationship which he observed repeatedly is one of faulted and rotated Miocene strata separated from underlying Precambrian granitic basement by listric normal-slip faults (Fig. 3-14). The important conclusion which Anderson (1971) emphasized was that the listric normal faulting pre-dated the high-angle faulting which blocked out the present basins and ranges. According to Anderson (1971) listric normal (growth) faulting took place mainly between 15 and 11 m.y., whereas the high-angle faulting proceeded approximately between 10 and 5 m.y.

The deformational system which Anderson (1971) described is an integral and representative component of regional tectonic strain in the southern Basin and Range. G.A. Davis, E.G. Frost, J.L. Anderson, T.J. Shackelford, and their co-workers have shown this to be true in southeastern California and westernmost Arizona. P.E. Damon, S.C. Creasey, M.H. Krieger, H.W. Peirce, W.A. Rehrig, S.R. Reynolds, R.B. Scarborough, and M. Shafiquilah independently reached the same conclusion in west central and southeastern Arizona (see references which follow).

MIocene LISTRIC FAULTING AND METAMORPHIC CORE COMPLEXES

Evaluating the nature and origin of mid-Miocene denudational faulting in the Basin and Range is almost inseparable from trying to unravel the tectonic evolution of metamorphic core complexes (Crittenden and others, 1978, 1980; Davis and Coney, 1979). Metamorphic core complexes owe much of their physical distinctiveness to the superimposition of (1) formation of thick zones of foliated mylonitic tectonite, and (2) extensional faulting of Tertiary age, including mid-Miocene denudational listric faulting. Tectonite and non-tectonite are separated by the distinctive low-angle décollement (see Crittenden and others, 1980), and striking contrast between rocks above and below such structural discontinuities has been very puzzling to explain.

The presence of detachments (i.e., upper plate, hanging-wall rocks in low-angle fault contact on structurally deeper footwall rocks) which were emplaced in mid-Miocene are not unique to the
Figure 3-14. Structural-profile of listric-fault relationships in Black Canyon region, northwestern Arizona. Figure is modified from Anderson (1978).
metamorphic core complexes as defined by Davis and Coney (1979); rather they may be found both within and outside of them. Away from the metamorphic core complexes, the low-angle faults separate non-tectonite steeply rotated detachment strata from underlying non-tectonite basement. The basement rocks are commonly highly fractured and marked by chloritic and ferruginous alteration along the faults, but there is a compatibility of brittle behavior between structures in the hanging-wall and footwall rocks. In these field occurrences, workers have never felt compelled to introduce terms like décollement to describe the contacts. 'Low-angle (normal) faulting' has adequately identified these relations. Within metamorphic core complexes, however, the décollement sharply separates underlying lineated mylonitic tectonite from overlying, mainly non-tectonite detachment strata. The mid-Miocene (approximately 18 to 14 m.y.) denudational faulting is physically superimposed on the tectonite fabric. In décollement zones the lineated tectonite fabric is shattered and rotated by movements related to the denudational faulting. Such facts confirm that the faulting, at least in part, post-dated the development of lineated tectonite (Coney, 1974; Davis, 1975; Davis and Coney, 1979).

The paradox which confronts workers who are interested in evaluating the relationship between the mid-Miocene faulting and the evolution of metamorphic core complexes is in reconciling the following facts:

1. mid-Miocene faulting post-dates the formation of lineated tectonite
2. everywhere in the southern Basin and Range, the slip-line direction which describes extension in the detachment strata is virtually parallel to penetrative lineation in underlying or nearby tectonite.

Regional Occurrences of the Listric Fault Systems

Major Geologic Characteristics

Rocks in the detachments range in age from Precambrian to middle Miocene, and they are always made up of rocks derived from the local geological setting. Some structures within the detachments evolved in those rocks prior to the tectonic denudation, but most of the conspicuously brittle deformation appears to have attended the detachment process itself. In their simplest form, the detachments contain moderately to steeply dipping Oligocene(?)-Miocene strata which rest on expansive flat to gently dipping faults. Davis and Coney (1979) suggested that the continental sediments and associated volcanics which comprise a great portion of the Oligocene-early Miocene detachment strata were deposited in
extensional basins which grew as a response to the formation of lineated tectonite at depth. These strata are presumed to be characterized by growth-fault structure/stratigraphic patterns. Such patterns would be older than the mid-Miocene faulting of interest to us here.

In California and Arizona examples, the footwall rocks on which the detachments rest are typically composed of Precambrian rocks, although any relatively old, relatively deep component of the local geological column might compose the footwall. Workers generally agree that the footwall blocks are autochthonous. Rotation of strata in the detachments was accompanied by brittle fracturing, and in all probability was accomplished by listric normal faulting and coordinated tear faulting. Bedding strike of hanging-wall strata are typically oriented at right angles to the direction of greatest finite strain in the detachments. Regionally, there are broad structural domains of homoclinal detachment strata, each of which is characterized by (1) uniform dip direction of hanging-wall strata and, thus, (2) uniform sense of bedding rotation. Rehrig and Heidrick (1976) first called attention to the regularity of dip direction of Oligocene/Miocene volcanic and sedimentary rocks in the Basin and Range of Arizona. Furthermore, they clearly recognized that the regional pattern was produced by 'thin-skinned, rotational faulting and tilting' (Rehrig and Heidrick, 1976, p. 217).

The descriptions which follow are taken from studies in which the mid-Miocene timing for faulting can be proved and/or convincingly argued. Whether this faulting is simply a continuation of the faulting which produced décollement zone fabric is not known. Treating the mid-Miocene faulting as a discrete event may or may not be valid. Readers are referred to the original references for details regarding the stratigraphic and lithologic characteristics of the detachment strata and for geochronological facts. The work by Eberly and Stanley (1978) provides a regional description and interpretation of Cenozoic stratigraphy and faulting in southern Arizona. They contributed significantly in pioneering an awareness that mid-Miocene faulting is a distinctive tectonic episode which preceded 'late Miocene block faulting'. The papers by Scarborough and Peirce (1978) and Shafiqullah and others (1978) are all landmark papers which underscore the fact that major extensional faulting of a thin-skinned and rotational nature affected the region during the Miocene, before the classical Basin and Range disturbance.

Black Canyon Region, Northwestern Arizona

The type locality for the style of structures being considered here is that mapped by Anderson (1978) south of Lake Mead in the Black Canyon region of the Colorado River (Fig. 3-15). The
Figure 3-15. Location map for geographic areas referenced in discussion of mid-Miocene faulting.
geological framework there consists of Precambrian granite overlain nonconformably by Oligocene(?)-Miocene volcanic and sedimentary rocks. As a result of mid-Miocene denudation, the Tertiary strata within a 1000+ km² area are moderately to steeply tilted eastward within a succession of imbricate, west-southwest-dipping, listric normal faults. The direction of greatest finite strain is N70°E/S70°W, as revealed by abundant striae and by the uniform north-northwest strike of detachment strata. The dip direction of the detachment strata, combined with the listric nature of the faulting, demands that the sense of movement for the fault system was S70°W. East-west-trending tear faults, referred to by Anderson (1979, pers. comm.) as marginal shear zones, served to coordinate the internal movements of structural lobes within the regional mass. Some of the marginal shear zones have been shown by Anderson to be structures where the soles of the listric faults 'shoal up' to near-vertical attitudes.

Cross sections which Anderson (1977, 1978) presents clearly show that the faults are growth faults. Older rocks within the Tertiary column tend to show greater displacements than younger ones. Hanging-wall strata for a given unit on a given fault tend to be thicker than strata of the same unit immediately below the fault. The youngest Tertiary strata affected by the faulting locally display nonconformable contact relations with underlying Precambrian granite.

Anderson has demonstrated that the listric normal faults commonly penetrate the Precambrian basement, but they are very difficult to map. Parts of the 'autochthonous' Precambrian basement may actually be allochthonous detachments. Directly below the system of faulted Tertiary strata, the Precambrian rocks are locally intensely fractured and altered. In fact, at one location along the western margin of Black Mountain, there is a décollement-like zone of resistant, iron-stained micro brecciated rock, not unlike that found along the margins of metamorphic core complexes.

According to Anderson (1979, pers. comm.), it is the vitrophyre in the Tertiary strata that took up much of the strain of accommodation to the listric faulting and marginal shearing. Matrix of ash flows in the Tertiary strata has locally been converted to tectonite. Within the bold exposures of Black Canyon, the attenuation and stretching of the Tertiary strata are clearly seen, not only in the form of brecciation and shearing, but in the coalescing of faults to produce boudin-like, lozenge-shaped fault blocks as well as local draping of strata over low-angle normal faults.

Anderson (1971) has interpreted this array of structures as the response of upper crustal rocks to extreme distension brought
about by batholithic emplacement and crustal extension at depth. Gastil (1979) has developed such a model of crustal distension in some detail.

Southeastern California–Western Arizona

To the south of the Black Canyon region, G.A. Davis and his students have mapped the internal structure and stratigraphy of Tertiary strata in the Whipple, Buckskin, and Rawhide Mountains (Fig. 3-15) and have described the physical relationship of these rocks to lineated tectonite of core-complex affinity. The deformed terrane is fully 3000 km² in area, 100 km long in a northeast-southwest direction (G.A. Davis and others, 1980). Virtually all of the detachment sheets are separated from autochthonous footwall by a regional, subhorizontal detachment fault which they call the Whipple detachment fault to the west, Buckskin detachment fault in the central part, and the Rawhide detachment fault to the east (Shackelford, 1977; G.A. Davis and others, 1979).

The upper plate detachment rocks consist of Oligocene(?) to middle Miocene sedimentary and volcanic rocks as well as Precambrian and Mesozoic(?) crystalline rocks, and Paleozoic metasedimentary and metavolcanic rocks. Footwall rocks are both non-lineated, non-mylonitic rocks and lineated quartzo-feldspathic gneisses (Shackelford, 1977; G.A. Davis and others, 1977, 1979).

Imbricate listric normal faults, and some marginal tear faults, are the major structures within the detachments (Shackelford, 1977; Davis and others, 1979; Anderson and others, 1979). The faults are growth-fault in nature (Frost, 1979). The slip-line direction for faulting is N40°E to N60°E, as deduced by striae and bedding strike, and the sense of movement is in that same direction (G.A. Davis and others, 1977, 1979; Shackelford, 1977). Strata dip southwest as a result of back-tilting along the northeast-dipping normal faults. The tear faults helped to accommodate differential upper-plate distension. The same structural patterns and relationships have been observed by Davis and others (1979) to the north in the Chemehuevi, Sacramento, Homer, and Dead Mountains (Davis and others, 1979) and to the east in the Mohave and Artillery Mountains (Frost, 1980, pers. comm).

Detachment faulting is interpreted to have taken place in mid-Miocene, (Shackelford, 1977; Davis and others, 1977). Davis and others (1979) have concluded that 'regional mylonitization' significantly predated Oligocene(?)–Miocene detachments events 'and that' field relations indicated that the mylonitic rocks, at least at levels near the basal detachment surface, were kinematically 'dead' and cold, or at least cooling, at the onset of
of detachment faulting. Davis and others (1979) explain the detachment faulting as a regional, northeast-directed gravity gliding over a non-extending lower plate.

West-Central Arizona

To the southeast of the region studied by G.A. Davis and his students, there is a well defined and extensive belt of metamorphic core complexes which trends northwest-southeast through most of Arizona (Fig. 3-15). In the Harcuvar and Harquahala Mountains, Rehrig and Reynolds (1977, 1980) report the presence of moderately to steeply tilted mid-Tertiary volcanic and sedimentary rocks which rest on a gently east-dipping dislocation surface. Beneath the dislocation surface are chloritic, mylonitic gneisses which contain N60°E- trending cataclastic lineation. Formation of the dislocation surface pre-dates 10 to 13 m.y. basalts. "Activism of the dislocation surface, deposition of coarsely clastic sedimentary wedge deposits, and rotational faulting were nearly coincident processes" (Rehrig and Reynolds, 1980). Rehrig and Reynolds (1980) note the kinematic coordination between the east-northeast direction of extension implicit in the listric-normal faulted blocks of mid-Tertiary volcanics and conglomerates. Although they are aware that the chlorite breccia and dislocation surface are imposed on already-formed mylonitic foliation and lineation, they postulate that the 'upper plate' rocks now represented by listric fault blocks of Miocene strata were distended above a thin, sub horizontal zone of extreme extension and flattening, now represented by mylonitic gneiss.

The coordination of the mylonitic fabric and the orientation of normal faults and rotated upper-plate strata are beautifully pictured by Rehrig and others (1980). They reported structural and geochronological relationships in a terrane of denudational faulting just southeast of the Harcuvar and Harquahala Mountains, in the Vulture, Big Horn, and Eagle Tail Mountains. They suggested that east-northeast/west-northwest crustal extension affected the entire area, producing rotational normal faulting of late Oligocene/early Miocene conglomerate and mid-Miocene volcanics. Faulting took place between 20 m.y. and 16 m.y. and produced "shingled prismatic crustal blocks bounded by downward flattening fault planes" (Rehrig and others, 1980). Footwall granitic and gneissic rocks became intensely brecciated. Detachment strata are oriented perpendicular to the east-northeast direction of crustal stretching. The sense of rotation of upper plate strata is homogeneous over large expanses. From the northern part of the Big Horn Mountains through the Vulture Mountains (and nearly to the Bradshaw Mountains), the upper plate strata are tilted eastward on gentle west-dipping faults (Rehrig and others, 1980). From the southern end of the Big Horn Mountains through the Eagle Tail Mountains, strata are tilted westward on east-dipping listric faults. Rehrig and others (1980)
specifically comment that in all respects, the faulting is comparable to that described by Anderson (1971).

Further southeast, on the west outskirts of Phoenix, Reynolds and Rehrig (1980) mapped and studied the geochronology and structure of South Mountains. They concluded that mylonitic lineated gneiss was derived in part from cataclastic reduction of a pluton which they regard as late Oligocene to early Miocene in age. Age determinations were based on Rb-Sr whole rock isochrons. Chloritic breccia overlying mylonitic granodiorite is well exposed there. Relict mylonitic foliation within it is rotated out of the normal northeast strike to northwest to the perpendicular direction of mineral lineation.

Southeastern Arizona

North-northeast of Tucson in San Pedro Valley (Fig. 3-15), M.H. Krieger, S.C. Creasey, and H.R. Cornwall (see references) have mapped quite a number of detachments of Oligocene (?) - Miocene strata which are separated by low-angle faults from footwall Precambrian granite. The structural properties of the system are very similar to those described by Anderson (1971). The upper-plate strata in these detachments are moderately to steeply tilted, with strike attitudes (north-northwest) orthogonal to lineation orientation (N60°E) in tectonites which lie kilometers to the west and south. The strata dip southwestward, indicating northeastward tilting along southwest-dipping listric (?) normal faults. The domain of this tilting occupies at least 2000 km². Precambrian granite, below or more rarely within the detachments, is generally shattered and altered close to the faults. Locally it is converted into a macrobreccia. A few tear-fault boundaries have been recognized. For example, Krieger (1974) mapped such a boundary along the eastern edge of the Tortilla Mountains. There, steeply tilted younger Precambrian and Miocene strata are dragged in left-slip fashion along a northeast-striking high-angle tear fault, southeast of which is (exclusively) Precambrian granite. Minimum left slip is 2 km.

Upper-plate rocks above décollement zones in metamorphic core complexes of southeastern Arizona are generally more heterogeneous and structurally complicated than detachment rocks in the San Pedro Valley examples (Davis, 1977, 1980). These detachments locally contain mid-Miocene strata, but additionally there are Precambrian, Paleozoic, Mesozoic, and early to mid-Cenozoic rocks. The largest and most continuous exposure of a décollement in southeastern Arizona is the Catalina fault which crops out along the south base of the Santa Catalina Mountains and the western and southern margins of the Rincon Mountains (Pashley, 1966; Drewes, 1975, 1978; Banks, 1976; Creasey and Theodore, 1975). It dips 15° to 25° in
a southerly or westerly direction. Chlorite breccia is commonly well developed below this décollement, and the chlorite breccia in turn is underlain by hundreds of meters of mylonitic gneiss. Recent work by Davis and Gardulski (in prep.) reveals that relict, overprinted foliation and lineation within the chlorite breccia is systematically rotated perpendicular to lineation in underlying mylonitic gneiss. Drewes (1978) has pointed out spectacular polished fault mullion on the Catalina fault which trend N60°E.

Movements on the Catalina fault are multiple and superimposed. The full structural history includes development of linedated tectonite, listric normal faulting and formation of the décollement zone. At some locations, like Happy Valley on the east side of the Rincon Mountains, the detachment strata of unmetamorphosed homoclinal Paleozoic strata rest in fault contact on tectonite with the same simplicity and geometric regularity as described for detachments in the aforementioned San Pedro Valley examples. In other cases, like Saguaro National Monument (East) or Colossal Cave (Davis, 1975; Davis and Frost, 1976; Davis and others, 1974), detachment strata contain spectacularly and sometimes complexly folded Paleozoic-Mesozoic strata, and the total deformation cannot be related to a single, simple movement plan of mid-Miocene faulting. The variety of physical structures in such systems, and the nature of progressive deformation through time, is presented in Davis (1980).

West of Tucson, in Papago country, there is a recently discovered array of core complex terranes which are unique in that lineation in the tectonites trends approximately north-south, not N60°E (Davis, 1977; 1980). In the eastern Comobabi Mountains, linedated tectonites of core-complex affinity as well as décollement-zone rocks crop out adjacent to a major outcrop area (50 km² +) of Miocene continental sediments. Noteworthy is the fact that Haxel and others (1978) have mapped on orthogonal relationship between tectonite lineation and (1) bedding strike of the moderately dipping sediments, and (2) strike of the (low-angle) normal faults which separate the sediments from underlying older, mainly crystalline bedrock.

The Eagle Pass Detachment, Southeastern Arizona

Introduction

The Eagle Pass detachment northeast of Tucson near Safford, Arizona, (Fig. 3-16) displays a structural style of deformation which both conforms and adds to our understanding of the mid-Miocene denudational systems. The Eagle Pass structure is the easternmost known detachment in southeastern Arizona. Its geological location is especially instructive for it lies on undeformed
Precambrian quartz monzonite, even though lineated tectonite derived from the Precambrian protolith crops out only several kilometers to the east (Davis, 1977, 1980).

The Eagle Pass detachment occupies a broad, high pediment-saddle between the imposing Pinalêno Mountains to the south and the Santa Teresa Mountains to the north. These mountains, taken together, may be thought of as a typical 'range' of the Basin and Range province. The pre-Basin and Range origin of the detachment is partly indicated by its presence within the range. Precambrian quartz monzonite crops out over most of the saddle between the Pinalêno and Santa Teresa Mountains, but toward its western edge a low semi-circular ridge demarcates upper-plate lower and middle Miocene strata which rest in fault contact on the basement. Still further west, major westward-draining canyons carve into the faulted rock system and afford special views of its anatomy.

General Geology

The Eagle Pass detachment is underlain by a fault surface which displays a curved, convex-northeast trace which is approximately 11 km in length (Fig. 3-17). The footwall is everywhere Precambrian basement, predominantly composed of the medium- to coarse-grained porphyritic quartz monzonite. The quartz monzonite is (probably) part of the regional 1.4 to 1.5 b.y. anorogenic quartz monzonite suite (Silver and others, 1977). For the most part the quartz monzonite is light tan to off-white in color. It has decomposed to the extent that much of the landscape is covered by grus. Within the quartz monzonite there are scattered small patches of older Precambrian Pinal Schist. Northeast-striking, vertical dikes of rhyolite and rhyolite porphyry comprise a swarm which intrudes the quartz monzonitic footwall rocks. The dikes do not cut the upper-plate strata. Rehrig and Reynolds (1980) report a 25 m.y. K-Ar age based on analysis of biotite from these dikes. The value '25 m.y.' has almost become a signature marking proximity to metamorphic core complex terranes (Davis and Coney, 1979).

The detachment proper occupies 25 km$^2$ and consists of Miocene volcanic and sedimentary rocks. Three major units were identified by Blacet and Miller (1978) and these were 'carried' in our mapping. The oldest is composed of numerous reddish-brown porphyritic andesite flows containing phenocrysts of randomly oriented to radiating plagioclase laths. Its maximum thickness is approximately 945 m. This rock is known to workers in southern Arizona as the 'turkey track porphyry', and it is thought of as a guide rock of uppermost Oligocene/lower Miocene. Overlying the andesite is a middle unit which consists mainly of a rhyolitic welded ash-flow tuff with thin rhyolite and rhyodacite flows. It also contains intercalated rhyolite breccias and coarse sedimentary breccia. The thickness of
Figure 3-17. Geologic map of Eagle Pass study area. Map prepared by J.J. Hardy, Jr.
Figure 3-17
this middle unit is approximately 550 m. The andesite and rhyolite, taken together, are undoubtedly part of the Galiuro Volcanics (Cooper and Silver, 1964; Simons, 1964; Creasey and Krieger, 1978) whose type area is in the next range west. The Galiuro Volcanics are nearly 1900 m thick in the central Galiuro Mountains. Creasey and Krieger (1978) report 11 K-Ar age determinations for the formation, and these range from 22 to 28 m.y. The youngest unit in the detachment is a very thick (4485 m), red-brown, well indurated, poorly stratified fanglomerate and mud-flow breccia composed of heterogeneous boulders and cobbles of angular to subrounded andesite and rhyolite. Clasts range in length from several centimeters to more than 5 m. This coarse clastic sequence may be correlative with the Hell Hole Conglomerate (Simons, 1964), the type locality of which is on the east flank of the northern Galiuro Mountains. Its age is uncertain, although in the Galiuro Mountains it depositionally overlies the Galiuro Volcanics. All of the detachment strata dip moderately to steeply to the southwest. They are overlain unconformably by very gently dipping, moderately well indurated conglomerate of Plio-Pleistocene(?) age.

Structural Geology

The trace of the Eagle Pass fault is markedly sinuous. Although the fault zone is continuous and curvilinear, it is convenient to think of it as composed of a number of segments which are distinctive in attitude. Along the northwest margin of the Eagle Pass detachment, the fault zone strikes N50°E and dips steeply southeast. In the vicinity of Underwood Canyon, the fault assumes a very low angle of dip (less than 15°) and swings in strike from northeast through southeast to south-southwest. From the vicinity of Eagle Pass to the south end of the study area, the fault strikes north-northeast and maintains a low-angle dip. When plotted stereographically, the attitudes of fault segments disclose that the fault has a conical form, reflecting a trough-like fault morphology converging northeastward. The axis of the trough plunges 12°S 58°W.

The form of the Eagle Pass fault has profoundly influenced the orientation and style of deformation of both upper-plate and footwall rocks. Bedding within the detachment strikes consistently N50°-55°W and dips moderately to steeply southwest, except along the northwest margin of the detachment. There, the volcanic rocks swing into parallelism with the fault, conforming both in strike and dip to the fault-zone attitude. This shift in bedding attitude close to the fault resulted in elevated strain as expressed by an unusually high degree of fracturing, abundant striae reflecting adjustments along bedding and faults, and the mechanical breakdown of the volcanic units into discontinuous structural lenses.
Notably, along the northwestern and northeastern parts of the fault, the rhyolitic unit is locally juxtaposed directly against basement granite, without intervening andesite.

The fanglomerate is not as sensitive as the volcanic rocks to changes in fault attitude. The fanglomerate strikes N50°-55°W and dips steeply southwest throughout the area, except within tens of meters of the northwest margin of the detachment. There, the fanglomerate is locally dragged and faulted into parallelism with the northeast-striking, steeply southeast-dipping volcanic rocks, and with the fault zone itself.

Applying J. Hoover Mackin's (1950) down-structure method for viewing geologic maps proves to be a powerful approach to grasping the structural significance of the fault bedding relationships in the Eagle Pass area. When viewed southwest down the gently dipping slope of the fault plane, the geologic map is transformed into a provocative structure section (Fig. 3-18). The upper surface of the quartz monzonite footwall is seen to be a deep trough or groove, mullion-like in terms of its macroscopic structural significance (Wright and others, 1974). The northwest wall of the trough is especially steep and has served to localize subparallel fault zones in the detachment strata. Control for the location and orientation of the steep northwest trough-wall originally may have been afforded by one of the 25 m.y. rhyolite dikes. Along the northwest wall, detachment strata are steeply dipping and attenuated. Locally, rhyolite abuts directly against the quartz monzonite. The footwall quartz monzonite is severely fractured along that margin for a distance of several hundred meters, and ferruginous alteration in the zone of intense fracturing has converted the terrain into one of rich red-orange hues. Along the base of the fault trough there is a distinctive keel below which (10 m +) the footwall quartz monzonite has been profoundly fractured, mylonitized, and altered. Alteration is both chloritic and ferruginous. Planar surfaces in the fault zone look like 'boiler plates' with alteration-derived metallic gray/black tones embellished with tectonic polish. Just southeast of the keel, the andesite unit is attenuated and faulted in such a way that rhyolite again rests directly on granite. A few meters to tens of meters below the fault, the Precambrian quartz monzonite is absolutely undeformed and unaltered.

Movement Plan and Deformational Characteristics

A number of lines of evidence indicate that the upper-plate detachment strata were faulted into position by northeast-directed translation. The translation was accompanied by rotation of strata to steep southwest dips, and during faulting the upper part of the autochthonous footwall quartz monzonite became highly fractured.
Along the keel of the detachment, the footwall rocks were converted into a rind of mylonite. Although there are data which suggest that the upper-plate strata were extended during faulting, there is no evidence in the footwall rocks for such northeast-southwest elongation. Rather, the footwall rocks appear to have been stationary and rigid when they were overridden by the detachment strata. Loci of heavy alteration in the footwall quartz monzonite are positioned along the keel of the fault and along the steep northwest trough-wall. These locations were vulnerable to migration of hydrothermal solutions along the detachment strata/fault interface and (then) into fractured and mylonitized quartz monzonite.

Data which suggest that the line of fault movement was N40°E/S40°W include (1) the orientation of the axis of the trough-like form of the fault, (2) the uniform N50°W orientation of bedding strike in the tilted detachment strata, and (3) grooves and striae in deformed quartz monzonite, especially in the keel of the fault. The important logical argument (assumption) is that detachment strata were rotated and thus tilted during faulting. The axis of the fault trough and the average strike of bedding are beautifully coordinated in an orthogonal way. Grooves and striae measured mainly at the Big Spring locality are convincingly northeast-southwest in azimuth, with a great-circle distribution oriented N50°E. There is scatter in the trend of striae, and it is emphasized that striae display a dispersal which reveals a complex internal movement plan. Indeed, one gains the impression that faulting was accompanied by converging/diverging path movements which were highly dependent on local boundary conditions. The range of the striae azimuth is quite unlike the tight lineation clustering which typifies tectonites in metamorphic core complexes. Large mullion-like structures (elongate ridges, 10 to 20 m long, faceted by polished, stained, and striated surfaces) are present in quartz monzonite at the Big Spring locale, and their orientations are northeast-southwest. The form of these structures is identical to those mapped by Drewes (1978) along the Catalina fault in the Rincon Mountains. Joints were measured on 'boiler plate' outcrops in the fault zone at Big Spring, and although they cannot be used to evaluate movement plan, it may be significant that the stereographically plotted patterns are symmetrical with respect to a N40°E/S40°W line of movement.

Striated surfaces in the upper-plate detachment strata are not particularly abundant, except along the northwest faulted boundary of the plate. Thus, it is difficult to corroborate the N40°E/S40°W inferred movement plan on the basis of upper-plate minor structures. A notable exception is a series of keystone fault blocks in rhyolite in Section 27 in the north central part
of the area. Normal-slip faults mark the borders of several rotated blocks of rhyolite. These structures lie 20 m above the Eagle Pass fault. Their presence discloses that some degree of northeast-southwest elongation attended translation during faulting. Faults in the andesite and rhyolite are difficult to find because of the poor quality of many of the hill side exposures. Certainly these rocks are highly fractured. The fanglomerate is beautifully exposed, but faults are absent except along the northwest border of the detachment. Jointing in the fanglomerate is mild to almost non existent.

The main evidence that the sense of translation on the Eagle Pass fault was northeast-directed is an extraordinary zone of tear-faulting on the northwest boundary of the detachment. Evidence for strike-slip faulting is conspicuously displayed by horizontal striae on polished fault, fracture, and bedding surfaces in rhyolite. The rhyolite forms a wall of steeply dipping strata which were dragged into parallelism with the trough-wall of quartz monzonite. The andesite, a much weaker rock than the rhyolite, was severely attenuated within this zone and is generally absent. Where it does crop out, exposures are poor and striae are not generally evident.

Nowhere along the northwest tear-fault boundary of the detachment do the volcanic units display their normal N50°W strike. The volcanic rocks are plated against the footwall quartz monzonite along the fault. In contrast, the fanglomerate maintains N50°W strike attitudes until within tens of meters of the tear-fault boundary. At that point, the layers are dragged abruptly westward and/or the rock is transformed to flattened-pebble tectonite along zones of penetrative simple shear. The drag effects clearly reveal left-slip of the detachment along the fault interface. The development of tectonite at the expense of 20 m.y. of fanglomerate containing competent rhyolite clasts is shocking. The zones of simple shear are up to ten meters wide and are separated by intervening zones of approximately the same width where the fanglomerate is highly faulted and fractured, but not converted to tectonite. The tectonite fabric is instructive in that it must have formed under dry, cool, relatively shallow conditions of deformation. The strain characteristics of the simple-shear zones are identical to those discussed by Ramsay and Graham (1976). Movement of the fanglomerate detachment strata northeastward past the footwall of quartz monzonite must have been met by profound frictional resistance to movement. This is yet another indication that the quartz monzonite footwall was stationary and rigid.

One of the most peculiar structural relationships along the tear-fault boundary is the presence of a 'stratified' monolithic breccia which is sandwiched between the highly fractured/shattered
quartz monzonite footwall and steeply dipping, northeast-striking andesite. Layering within the breccia is concordant to that of the andesite. The exposure is approximately 200 m in trace length, and the thickness of the breccia is about 30 m, maximum. Virtually all of the clasts and matrix material of the monolithologic breccia are derived from the adjacent quartz monzonite. Clasts are as large as 1/2 m in size, and the layering in the breccia is primarily due to size-sorting of fragments and matrix. Although the rock appears to be a water-lain conglomerate/breccia, two factors suggest that the rock may be a kind of tectonite derived from comminution of the footwall. First, there is no rock like this anywhere in the detachment stratigraphy outside of the tear-fault zone. Its position within the tear-fault zone is suspicious in that it lies at an abrupt bend in the major fault. The form of the bend, combined with the left-slip nature of movement on the fault, demands that the location of this breccia formation must have been a site of significant compressive stress. Secondly, the andesite and rhyolite just southeast of the monolithologic breccia are extremely highly fractured and faulted, yet most of the breccia is absolutely devoid of fractures, even joints. Only in a few places are single, through-going fractures evident, and these tend to offset breccia clasts by small displacements. Additionally, the clasts of quartz monzonite are so internally shattered that they could not possibly have been physically transported to their present sites in their present condition. These observations suggest that penetrative comminution, granulation, and dry flow superceded regular fracturing and shattering of the quartz monzonite. Thin-section study of the monolithologic breccia has not yet resolved the problem. This rock is still under study, and preliminary results suggest that monolithologic breccia may be a legitimate strain facies of detachment terranes. Krieger (1974) has mapped macrobreccias of Precambrian granite along the margins of some detachments in the San Pedro Valley.

A final slip-line indicator is a single asymmetrical overturned fold, 2 m in amplitude, found in highly deformed andesite just a meter above the Eagle Pass fault in the southeast order of the map area. The fold trends N40°W, and is unambiguously overturned northeastward.

Structural Interpretation

Rehrig and Reynolds (1980) examined in reconnaissance the Eagle Pass fault zone and reached the conclusion that deformation was achieved by a listric normal faulting which produced southwest-to northeast transport of a upper-plate strata. Only listric faulting along a northeast-dipping fault zone could explain (easily)
the moderate to steep southwest dip of the upper-plate detachment strata. We agree with their interpretation totally and regard the data and relationships presented herein as a rather definitive proof. We believe that the Eagle Pass fault is the sole of a large, regional, listric normal fault zone whose upper reaches are simply not exposed, that the fault zone was curved is an inference born simply from the reality of rotated strata. We infer that the fault was originally flat or gently east-dipping, but was rotated to its present attitude by arching of the Pinalêno Mountains and/or Basin and Range faulting.

Movement indicators certainly support the interpretation of northeastward transport. The marginal tear-fault boundary is perceived as a zone of accommodation to differential relative movement within the larger mass. The volcanic rocks and fanglomerate in the detachment are identical to Galiuro and Hell Hole stratigraphy in the Galiuro Mountains, and this too strongly supports a westward provenance for the detachment. The detachment mass carried on the system of listric faults may have been enormous, for a detachment exists 30 km south-southeast of the Eagle Pass area which appears, from its small-scale geologic map portrayal, to display macroscopic relationships identical to those discussed.

The volcanic and sedimentary rocks in the Eagle Pass detachment may have been 'plucked' by faulting from a country rock sequence characterized by the Miocene strata in horizontal and non-conformable contact with underlying Precambrian granite (Fig. 3-19A). Such an undisturbed relationship is preserved in the central part of the Galiuro Mountains. The listric normal fault zone could have cut through the Tertiary volcanic and sedimentary rocks, curving into the discontinuity marked by the nonconformity (Fig. 3-19B). Alternatively, the fault could have cut downward and through the unconformity, thus allowing Precambrian granite to occupy an upper-plate detachment position (Fig. 3-19C). We cannot distinguish with confidence between these possibilities, although after significant field effort we have eliminated in our minds the possibility that any of the shattered Precambrian quartz monzonite occupies an upper-plate detachment position at Eagle Pass. In any case, progressive faulting resulted in lowering of the sedimentary and volcanic rocks onto Precambrian quartz monzonite footwall. By the time that the andesite and rhyolite reached the level of basement, the sole of the fault was already marked by significant curvature and irregularity, notably the large, mullion-like trough. The volcanic rocks were plated (smeared) concordantly to the southeast flank of the mullion as the detachment moved in left-slip fashion past the rigid quartz monzonite footwall. Dragging of the volcanic rocks along the keel of the sole may have been responsible for the decrease of dip of the volcanic layering.
Figure 3-19. Schematic diagrams of listric faulting. (A) Listric faulting that mainly affects rocks above the great unconformity. (B) Listric faulting that penetrates the basement.
The fanglomerate exposed along the northwest margin of the Eagle Pass detachment is believed to express a stage of the faulting in which that rock first felt the effects of interference with the basement obstruction. As the fanglomerate was lowered down on the mullion, only the closest fanglomerate layers responded to the frictional resistance to steady northeastward movement. The northeast transport must have been on the order of kilometers. Thus it is not surprising that extreme granulation and mylonitization of quartz monzonite were locally achieved.

DYNAMIC INTERPRETATIONS

During the Laramide in the southern part of the western Cordillera, rocks were subjected to strong northeast-southwest compression. The cause of the compression has been attributed to rapid convergence of the North American plate against oceanic plates to the west (Coney, 1978; Burchfiel and Davis, 1975; Armstrong, 1968a). The effect of the compression was northeast-southwest shortening of upper crustal rocks. Shortening was achieved by monoclinal folding and associated basement-involved uplift(s) in the Colorado Plateau (Kelley, 1955). Along the western edge of the Colorado Plateau in southwestern Utah in the vicinity of the hingeline, Laramide monoclines and basement-cored uplifts were superposed on earlier, thin-skinned Sevier thrusts of a décollement type. In southeastern Arizona, the gross structural geometry of shortening is not agreed on. Drewes (1973, 1976, 1978) believes that shortening was accommodated by regional, northeast-directed overthrusting, involving translation of upper-plate rocks for distances in excess of 100 km. In the context of descriptions presented earlier, he regards the folded tectonite carapace as a product of dynamic metamorphism of 'lower-plate rocks' during overthrusting. The rocks here described as locally-derived detachment rocks, including shattered Precambrian granitic rocks and overlying non-tectonite Phanerozoic sedimentary rocks, are thought to have been brought from the southwest to their present site by overthrusting, although gravitational adjustments in the Tertiary determined their specific 'final' locations (Drewes, 1976, 1978). Thorman (1977) supports this model and regards the penetrative lineation in mylonitic tectonite as a Laramide signature recording the direction of overthrusting. By way of contrast, Davis (1979) views the Laramide structural framework of southeastern Arizona as a foreland setting comprised of Wyoming-type basement-cored uplifts, the margins of which were partly pre-determined by locations of major Jurassic and perhaps Precambrian faults. Shortening in rocks along the margins of such uplifts took place by tight upright to overturned folding, thrust faulting, cleavage development, and local formation of tectonite. The Anschutz model for the Laramide framework is the most extravagant presented to date.
It portrays the well-known southeastern Arizona country rock framework as wholly allochthonous and overlying two repeated sections of Precambrian, Paleozoic, and Mesozoic strata.

The ambiguity expressed by these multiple hypotheses forms a confusing backdrop with which to evaluate the dynamic significance of metamorphic core complexes. However, most workers agree that the deformation by crustal shortening, whatever its nature, was completed by 55 m.y. (?), for plutons and dikes in the age-range 70-50 m.y. cut already-deformed strata. The presence of 'core complex fabrics' in rocks 55 m.y. old suggests that the formation of the core complexes was temporally separate from the main regional shortening event.

The effect of major plutonic invasion into the upper crust in the early Tertiary may have set the stage for the unusual style of penetrative deformation recorded in metamorphic core complex terranes. Gordon Haxel (Pers. comm., 1979) drew this conclusion during his southern Arizona mapping, and T.H. Anderson (pers. comm., 1980) has independently reached the same conclusion regarding terranes in Sonora, Mexico. The thermal input, in effect softened the country rocks, more in some places than in others. The rheology of the cooling plutons and the locally heated country rocks made the systems vulnerable to ductile flow. There are few localities where metamorphic core complexes lack any sign of known or inferred Tertiary intrusive bodies. The regional system, consisted of domains of cool rigid rocks and contrasting domains of hot, ductile rocks. Furthermore, the upper crustal rocks were not marked by lateral continuity of lithotectonic units. Instead, the combination of Jurassic and Laramide faulting led to domains of Precambrian basement juxtaposed laterally against domains of Paleozoic and/or Mesozoic layered strata; or domains of folded, thrusted strata juxtaposed against domains of homoclinal strata; or domains featuring complete sections of Precambrian-Paleozoic-Mesozoic rocks juxtaposed against domains where Cretaceous strata rests nonconformably on Precambrian basement. The combined effects of thermal and mechanical anisotropy may have profoundly influenced the location and nature of individual core complex terranes.

Given the thermal and mechanical condition of the upper crustal rocks, what regional tectonic movements gave rise to the penetrative componental movements which produced mylonitic tectonite? Based on relationships presented here and elsewhere (Davis, 1977, 1980; Davis and Coney, 1979; Davis and others, 1975), the mylonitic tectonite fabric is considered to be a flattening/extension fabric, with direction of extension parallel to penetrative mineral lineation. The fabric seems best explained by ductile normal shear within gently dipping curvitabular zones of simple-shear. The
The net effect was to produce younger-on-older separation relations. The absence of older-on-younger displacements suggests that the formation of mylonitic tectonite did not accompany regional shortening.

If it is true that the mylonitic tectonite expresses normal simple-shear, then it suggests that the regional tectonic movements stretched the upper-crustal rocks producing giant pull-apart. The cause of the stretching is not known.

As a response to stretching, the heterogeneous upper crust was partitioned into an array of rigid blocks with ductile margins. The boundaries between adjacent rigid blocks were largely determined by locations of hot, ductile crustal rocks. It was in these zones that a major percentage of the regional upper crustal stretching strain was accommodated. The 'megaboudin'-like rigid crustal units became marked by shoulders and necks of normal shearing characterized by profound thinning and flattening. At depth, these zones of normal shearing were marked by thick zones of mylonitic tectonite made at the expense of Precambrian basement. Upwards, these zones became thinner, converting Paleozoic and Mesozoic strata into tectonite. Perhaps the projection of the zones to the surface was marked by distributed, imbricate normal faulting, producing growth-fault basins of sediment accumulation. Downward, the zones may project into horizontal, lithospheric to aesthenospheric regimes of lamellar flow.

As cooling of the system took place, and as the 'zone' of brittle/ductile interface slowly descended, some already-formed mylonitic tectonite was disrupted, rotated, and microbrecciated by closely spaced, mesoscopically penetrative, normal-slip listric faults. This process was probably an upper-level, brittle counterpart of still-active mylonite-tectonite formation at greater depth. The kinematic coordination is perfect. While mylonitic tectonite and microbrecciated mylonitic tectonite were being formed, hanging-wall, upper-plate rocks continued to move downward and laterally, bringing rocks once far removed from the normal shear zones to positions directly above the mylonitic tectonite. This tectonic denudation largely fashioned the dramatic contrast between rocks of the mylonitic tectonite zone and rocks above.

Abrupt cooling of the mylonitic tectonite rocks of the metamorphic core complexes throughout the western Cordillera south of the Snake River plain is recorded in mid-Tertiary K-Ar and fission-track ages (about 25 m.y.). Most workers have ascribed this cooling event to 'uplift'. The structural implications of such uplift are not clear. A speculative interpretation is that the 25 m.y. ± cooling ages record development of the décollement and its ledge of microbreccia by major imbricate listric normal faulting. The major translation can be thought of as an 'unroofing'
in some respects, thus promoting cooling. The normal faults coalesced at or near the uppermost level of mylonitic tectonite, in some cases within, in other cases below the microbrecciated mylonitic tectonite. The positioning of the décollement zone may have been pre-determined by mechanical and not thermal factors. The trigger for this listric faulting collapse may have been the brittle rifting of rigid megaboudin units and/or boundaries between units. The rifting prompted greater extensional strain in the upper crust as a whole. Ignimbritic volcanics (25 m.y. ±) exploded out of the deeply rifted crust throughout the entire belt of metamorphic core complexes.

It is shocking to realize that all of the events which proceeded from 55 m.y. (?) to 25 m.y. may have accompanied and/or may have been produced by the concurrent formation of mylonitic tectonite (at some depth). However, the emplacement of detachments in post-25 m.y. time, largely mid-Miocene, must have had a cause which is not directly related to the formation of tectonite, even though the slip-line direction for translation of the detachments identically parallels the trend of penetrative lineation in nearby or underlying tectonite.

The mid-Miocene component of emplacement of the detachments may have been sensitive to and triggered by the inferred earlier normal-slip descent of hanging-wall terranes above zones of mylonitic tectonite. For the pure mid-Miocene detachments, i.e., those containing only mid-Miocene strata, were translated perfectly parallel to the direction of the penetrative lineation in the closest mylonitic tectonite, and apparently in the same sense of slip as that of simple-shear in the tectonite. The structure profiles of such mid-Miocene detachments convey the properties of slump- or toreva-block tectonics. Tempting as it is to explain the listric fault profiles as the result of stretching of brittle multilayers atop a ductile stretching medium, the geologic facts disclose that the listric fault blocks now rest on footwall which shows no sign of penetrative flow movements. Taken together, the relationships suggest that deep upper-crustal slumping took place in the mid-Miocene. In essence, the stability of rocks at the highest structural levels was weakened by the cumulative effect of normal-slip displacements during tectonite and décollement zone formation. Those rocks nearest the margins of the boudin-like lithospheric blocks 'felt' a removal (or weakening) of lateral support, and were translated along curved normal faults in the direction of the earlier stretched and descended terranes. The event represents the upper crustal brittle collapse of rocks occupying the outer margins of megaboudins. The composite symmetry of the deformatonal system is striking.
All of these events preceded the classic Basin and Range high-angle faulting. Such faulting was initiated 10 to 15 m.y. ago, and its dynamics of origin seems to bear no relation to the earlier Tertiary deformations. The surprising turn of events is that the Basin and Range province owes most of its distinctive and unusual tectonic characteristics to the development of metamorphic core complexes and to mid-Miocene listric normal faulting, not to the simpler imprint of high-angle normal faults.