

**Structural reconnaissance of lower-
plate rocks along the Catalina-
Rincon range front, Pima County,
Arizona**

by

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Context of this study

History and status of structural studies. The Santa Catalina and Rincon Mountains of southeastern Arizona (Fig. 1) were seminal in the development of the concept of metamorphic core complexes (Davis and Coney, 1979). The first steps in this development were the recognition and description of low-angle normal faults (Pashley, 1966) and mylonitic rocks (Ted Theodore and Norm Banks *in* Banks, 1974) all along the sinuous range fronts (Fig. 1). Because early workers in these areas noted a striking parallelism and identical vergence of mylonitic fabrics and structurally overlying detachment faults (Davis, 1980; Wust, 1986; Reynolds and Lister, 1990), these two features became married as deep ductile and shallow brittle aspects, respectively, of extensional tectonics (e.g., Spencer and Reynolds, 1989). The Catalina-Rincon metamorphic core complex became a "type" example partly by virtue of its early description.

Below gently south- and west- dipping detachment faults are mylonitic gneisses with southwest-plunging lineation, defined in part by quartz rodding. In the range-front area, fabrics in these gneisses show top-to-southwest relative motion. These rocks were semi-ductile during deformation--quartz was ductile but feldspar was brittle. Flattening is most pronounced parallel to lineation. Protoliths of the mylonitic gneisses are Proterozoic through early Tertiary igneous rocks (Keith and others, 1980). Mylonitization and detachment, however, are mid-Tertiary in age (Spencer and Reynolds, 1989).

The areal information on which these concepts are locally based, however, has always been sparse (Fig. 1). Banks (1974), Drewes (1977), and Thorman and Drewes, 1981) provided geologic maps that include the range-front area but which were intended for other purposes. That by Creasey and Theodore (1975) is sketchy in the range-front area. Dickinson (1999) provided the most recent map of the detachment system as seen from the Tucson basin. The map in Force (1997) of the east-central Catalinas is the seed from which the current study grew.

The correspondence of detachment to mylonitic structure along the range front has proved to be fortuitous in part. North and east of the range-front areas, detachment structures extend over the main crests of the ranges, whereas the main belt of mylonitic fabrics show an anticlinal dip reversal, and dips under the main ranges (Reynolds and Lister, 1990; Force, 1997). In detail, departures of detachment and mylonitic geometries and histories occur even in the range front (Force, 1997). Such departures may provide clues to the evolution of core-complex exhumation. Map relations presented in this report suggest both similarities and differences in geometry and genesis between mylonitic fabrics and detachments. The nature of the relation is not yet completely explained, but the two are neither fully separate nor fully linked.

Physiography. The morphologies of metamorphic core complexes are quite dissimilar to those of typical basin-and-range mountain ranges, even though they occur in the basin-and-range province (Pain, 1985; Spencer, 2000). Metamorphic core complexes are apparently shaped mainly by the detachment faults that overlie them; that is, the mountain-pediment boundary is most commonly the detachment trace. The detachments are generally warped into gently plunging mullion-like shapes, so the mountain front is generally sinuous. The mountain surfaces themselves may closely reflect the former position of the detachment, as if erosion virtually stopped as soon as unresistant upper-plate rocks and underlying fault breccias and sub-fault chloritic breccias were stripped off (Pain, 1985).

The Catalina-Rincon core complex exemplifies these physiographic features; the northern Rincon Mountains and Agua Caliente Hills (Fig. 1) in particular are enormous whalebacks closely outlined by

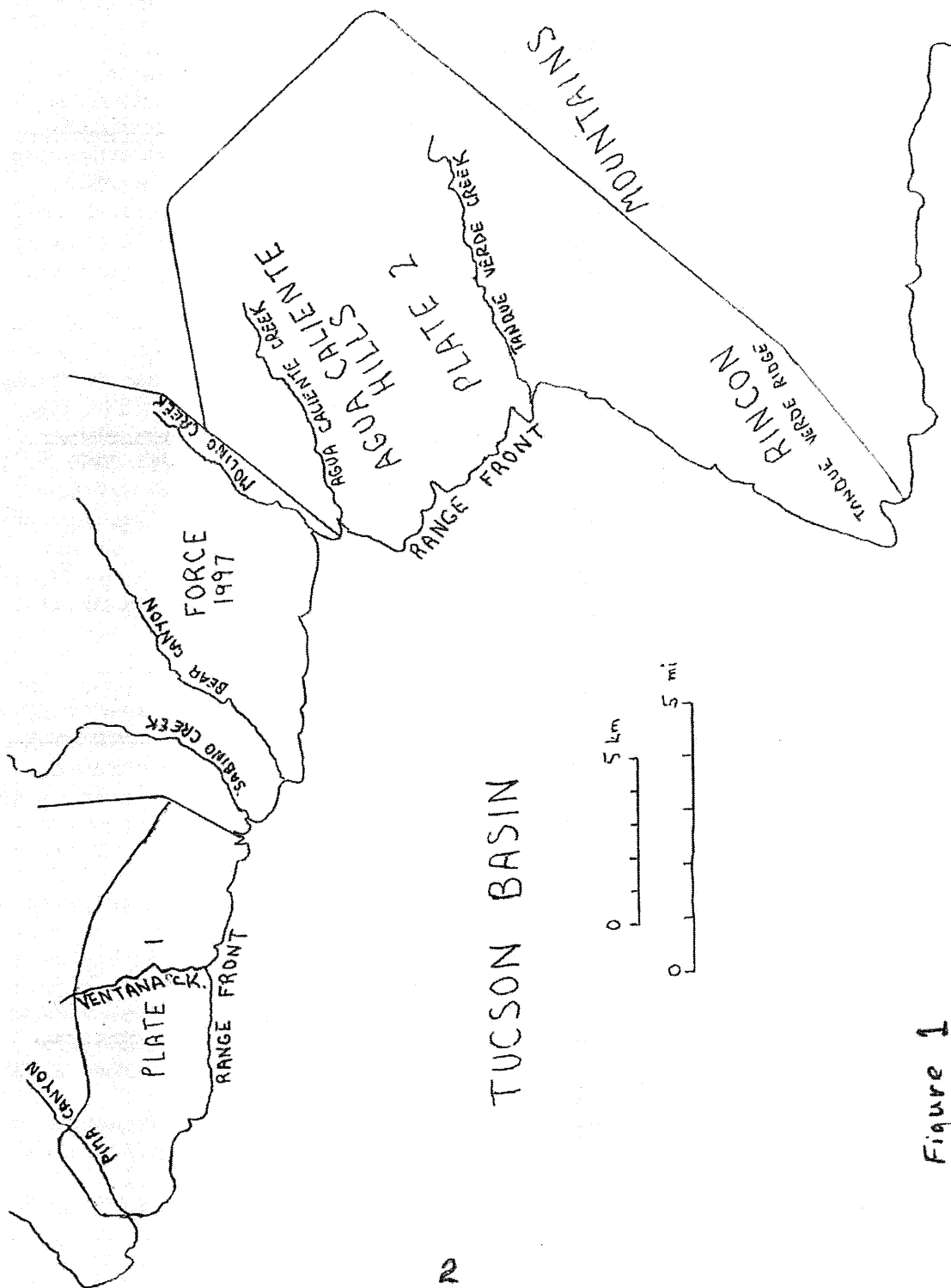


Figure 1

detachment traces, the surfaces of which must approach the eroded detachments, based on the distribution of various superposed allochthons. Given the age of detachment, about 20 Ma, this is remarkable, and deserving of further study. This report contributes some structural context to permit such study.

The morphology of the Catalina segment of the range front is controlled in part by the Pirate fault on its west side (Dickinson, 1994). Post-detachment uplift on this fault has produced entrenched canyons that deepen toward the fault.

This study. My intent was to broadly summarize the geology of lower-plate rocks (i.e. below the detachment) in the Catalina-Rincon range front area. Two areas that flank my previous mapping (Force, 1997) were chosen—one extending to the west (Fig. 1, Sheet 1) as far as Pima Canyon in the western Catalina forerange, and one extending southeast (Fig. 1, Sheet 2) as far as Tanque Verde Ridge in the Rincon Mountains, and including the Agua Caliente Hills. Both areas update previous maps (Banks, 1974 in the western Catalinas; Thorman and Drewes, 1981 in the Agua Caliente Hills; and Drewes, 1977 in the Rincons) with more modern concepts of extensional tectonics.

However, the two areas prove to illustrate quite different aspects of range-front geology. The Catalina segment (Sheet 1) is of interest especially for the nature of the protoliths of mylonitic rocks and the igneous-structural relations among them, whereas the Rincon segment (Sheet 2) is of interest mostly for the structural control of detachment traces and variations in mylonitic fabric. Both areas display a sequence of structural features as a function of structural level in lower-plate rocks, but in different ways. Despite their differences, the aggregate continuity (including Force, 1997) along the range front for a total of over 40 km permits a comprehensive view of range-front geology in a metamorphic core complex.

About the map plates. Neither of the two maps (Sheets 1 and 2) are completely conventional. In both, contacts that can be precisely located are shown solid whether observed or not. A dotted convention is used in maps and cross-section to show a unit's position prior to intrusion or faulting. Surficial units are not shown.

Sheet 1 (at 1:24,000) emphasizes the protoliths of mylonitic gneisses, particularly the older ones, and thus minimizes Eocene leucogranites. Pinal Schist is shown, for example, if Pinal is the dominant pre-leucogranite protolith even where leucogranite forms as much as 70 percent of the protolith assemblage. The LG unit consists of at least two intrusions; note that unit LG2 does not pinch out but the intrusive sheet dips under Pima and Finger Rock canyons. All three leucogranite units are mostly-concordant sheets except in the area shown.

Sheet 2 (at 1:48,000) does not show protoliths—protolith variation is too irregular and the map is already too complex. The main features of this map are variations in mylonitic deformation, faults separating these domains, axes of folds in the deformation features, and structure contours showing the lowest possible position of semi-breccias below the detachment fault. These contours are controlled by semi-breccia outcrops, and constructed so as to graze hills formed by unbrecciated lower-plate rocks.

Protoliths of mylonitic gneiss

Summary. Mylonitic gneisses of the Catalina-Rincon range front are derived mostly from Eocene 2-mica leucogranites and pegmatites (the Wilderness Suite), forming large sills and intricate stockworks, and from their older host rocks (e.g., Banks, 1980; Keith et al., 1980). Several types of leucogranite are present (Force, 1997), varying in composition and texture (with more local differences in deformational fabric).

In the Catalina range front, middle Proterozoic Oracle-type porphyritic granites and early Proterozoic Pinal Schist are the most extensive older rocks (Sheet 1). Others include fine- to medium-grained equigranular Laramide biotite granodiorite and middle Proterozoic diabase. Three or more leucogranite sheets, which vary in texture and/or relative abundance of garnet, muscovite, and biotite, cut boundaries among the older protoliths. These sheets generally form separate bodies but locally are amalgamated. In the area of greatest interest the sheets are concordant to each other and to mylonitic foliation, but toward the north and east the leucogranites become highly discordant.

In the Agua Caliente Hills and northern Rincon Mountains (Sheet 2), the equigranular Laramide

biotite granodiorite and Oracle-type granite are the most common older rocks. Leucogranites are as diverse as in the Catalina segment; locally small aluminous leucogranite bodies cut mylonitic fabrics in other leucogranites. In this area, however, the intricacy and scale of relations between subequal Oracle Granite, granodiorite, and leucogranite precursors discouraged protolith mapping in favor of other features. Except at the northwestern end of the Agua Caliente Hills, where the Gibbon Mountain body can be recognized, garnet content of leucogranites appear to be largely proportional to the size of the leucogranite body.

Mid-Tertiary mylonitic fabrics are commonly weak to absent in the Agua Caliente Hills (Sheet 2), but both Oracle and granodiorite commonly show a foliation cut by younger leucogranite, reminding the observer that Laramide fabrics preceded mylonitic fabrics throughout the range-front area. Laramide fabrics, though variable, are dominated by E-W-striking foliation. Lineation is generally absent, and this characteristic, the variability of Laramide foliations, differences in lineation trend, and differing relations relative to Eocene leucogranites, are sometimes needed to differentiate Laramide from mylonitic mid-Tertiary fabrics.

Discussion. Syn- to post-mylonite rocks described in the lower plate include Catalina Granite (about 26 Ma; Keith and others, 1980) west of the study area (Fig. 1) and a leucogranite unit of the southern Rincons (Gehrels and Smith, 1991). The Knagge Granite of the northeastern Santa Catalina Mountains, supposed by Force (1997) to be mid-Tertiary (syn-mylonitic) has instead proved to be post-Wilderness but pre-mylonite (George Gehrels, written comm., 2000). Except at structural levels below mylonite, described below, the post-mylonite leucogranites encountered in this study are few and small, mostly occurring in the Rincons and Agua Caliente Hills. Some small massive microdiorite dikes in the Rincons (Sheet 2), commonly near faults, also cut mylonitic rocks.

In the western Catalinas, Banks (1974) showed all Eocene leucogranites as a single map unit (Tsqm). In the east-central Catalinas, it is possible to map the leucogranites as discrete sills (Force, 1997). Sheet 1 shows that in the western Santa Catalina Mountains also, subdivision of the leucogranite map unit into separate bodies reveals more sill-like shapes than is apparent in Banks's (1974) map. In an intermediate area occupying the heads of Romero and Esperero Canyons (and north to Cathedral and Rattlesnake peaks), large discordant leucogranite bodies are common. This area may be the intrusive center from which the sills diverged. One sill, the Gibbon Mountain body of Force (1997), apparently extends along (indeed, forms) much of the range front as a single concordant body. Its trace as shown in Sheet 1 is based largely on physical continuity, supported by coarse porphyroclastic texture and rarity of garnet throughout. However, the body apparently has a higher ratio of biotite to muscovite toward the east.

I also subdivide basement protoliths in this area, where Banks (1974) showed all such protoliths as Oracle Granite (Yo). Though granodiorite (probably related to Leatherwood granodiorite) and metadiabase occur as protoliths here as in the eastern Catalinas, the greatest benefit of splitting up the Yo unit of Banks is the recognition of a folded belt (Sheet 1) of Pinal Schist. The Pinal here can be recognized by abundance of finely bedded, coarsely muscovitic pelitic beds interbedded with meta-sandstone and minor meta-chert, and by refolded recumbent folds. Oracle Granite occurs as sills and dikes forming as much as 50% of the Pinal-bearing belt. Oracle-Pinal contacts are commonly obscured by later intrusions of Eocene leucogranite and pegmatite. The E-W fold in this contact as shown in Sheet 1 is probably Laramide in age, based on its tightness at both outcrop and map scale, and its orientation. To the north, where these rocks are undeformed, contacts between them are nearly north-south and steep (Force, 1997).

Banks (1974) noted the presence of Apache Group in some areas of his Oracle Granite unit. The sequence I show as Pinal, however, (1) contains distinctive Pinal lithologies such as meta-chert, (2) lacks conglomerate near Oracle contacts (and all other distinctive Apache Group features), (3) forms xenoliths in Oracle, and (4) shows a greater number of pre-mylonite deformational fabrics than the Apache Group. In addition, Apache Group pinches out toward this area in the Catalinas (Force, 1997) and formerly-nearby mountain ranges (Lipman, 1993). Thus Banks is apparently mistaken in calling these rocks Apache Group. The sequence I show is probably continuous toward the NW with Pinal Schist in the

Alamo Canyon (Pashley, 1963) and Montrose Canyon areas. The presence of significant amounts of Pinal Schist in this area may have implications for mineral potential (i.e. Precambrian massive sulfides, etc.) and for the petrogenesis of Eocene leucogranites of peraluminous composition.

On the other hand, Pinal Schist is probably not as common as shown by Drewes (1977) in the northern Rincon Mountains. Some at least of the rocks he showed as Pinal prove to be foliated fault gouges.

Structural elements in vertical sequence

A characteristic sequence of structural features underlie detachment faults in lower-plate rocks. Some are well-known; a few others are described here for the first time. The vertical sequence presented here builds on relations in the literature and ignores (for the time being) lateral variations. From the top the elements are:

Brecciation. Chloritic breccias adjacent to detachment faults are a common and well-described feature of lower plates (e.g., Davis, 1980; Rehrig and Reynolds, 1980; Spencer and Reynolds, 1989). Generally these are fewer than ten meters thick. I find these are an upper component of a thicker zone that is sufficiently disrupted to destroy or rotate mylonitic lineation, but that shows little recrystallization and commonly is bleached. Outcrops of these lower breccias are lumpy to scabrous and generally lack planar joints. Original rock textures are commonly disrupted, but larger features such as xenoliths may retain nearly original shapes.

Such rocks are here called semi-breccia. Semi-breccia blocks are most commonly leucogranite and pegmatite. Large coherent domains within semi-breccia show back-rotated lineation. Locally, fracture sets (described below) in relatively coherent domains are rotated also. Though rock types are all those of the lower plate, the lithologic mix is locally different from that in intact lower-plate rocks directly beneath.

Subsidiary detachment faults are locally observed at the base of the semi-breccia zone (Sheet 2), as noted nearby by Davis (1987). Thus there is a sense in which these rocks form an intermediate plate. Different lithologic mixes across these faults demonstrate offset and locally suggest movement direction. Elsewhere, however, semi-breccia may possibly grade into intact lower-plate rocks.

The thickness of the semi-breccias varies widely. In parts of the Agua Caliente Hills, it is more than 160 m thick. Its locus of greatest thickness there seems to match one of the synforms in the detachment surface (structure contours of Sheet 2). Where semi-breccia thickness is constrained, its distribution provides some control on the former positions of eroded detachment faults.

Fractures. Steep fractures striking N20-40W (cf. Miksa, 1993) are common in mylonitic lower-plate rocks, mostly below the semi-breccia zone, throughout the range-front area. Density of such fractures ranges from less than one to greater than ten per meter. They are especially dense where the reconstructed detachment location is less than 200 m above; in a few places such as Pontatoc Canyon where vertical relief allows, they are observed to decrease downward. In the deepest canyons of the western Catalinas, the fractures are apparent in only a few intervals.

Both plates show where such fracture sets were observed at densities of 6 or more per meter. Other fracture sets may be present in the same outcrop but are not shown. The fractures locally correspond to lineaments of considerable length, perhaps best expressed on the northern flank of Tanque Verde Ridge.

Small movements are commonly observed on the fractures. Locally, oppositely dipping anastomosing fractures form little horsts and grabens. Elsewhere, whole domains follow the same sense, most commonly down-dip to the southwest. Where dip is moderate, slickensides trend parallel to mylonitic lineation; steeply dipping fractures, however, commonly have oblique slickensides.

Thin micro-breccias fill some of the fractures. Mineralization in the fractures varies from Fe-Mn-oxides to chlorite-epidote-quartz. Remarkably, the higher-grade assemblages, as along Tanque Verde Ridge, seem restricted to higher-level structural positions, as do most micro-breccias. Also on this ridge, micro-diorite dikelets intrude some fractures. Where the fracture system is strongest, mylonitic lineation

is obscured.

Unidirectional shear zone. I have little to add to the classic descriptions of mylonitic gneisses in these mountains (e.g. Davis, 1980), except to observe that these shear zones have finite thicknesses (~600m), whose bases are marked by transitions to fully-ductile rocks with a large component of pure shear (Force, 1997), and that relict older fabrics are re-deformed by unidirectional shear. A relation of ptygmatic folding to mylonitization is suggested where S-(flattening) surfaces have been folded, but C-(shear) surfaces remain parallel to the regional orientation across the fold.

Older pure shear. Where anticlines and domes expose rocks under mylonitic gneiss, these are fully-ductile penetratively deformed gneisses with ptygmatic folds marked by leucogranite. In some exposures, such as the Maiden Pools area of Ventana Canyon, some but not all of the garnet-muscovite leucogranites cut the gneissic fabric, suggesting syn-Eocene fabric development. Lineation in these gneisses is roughly parallel to those in overlying mylonitic gneisses. Pre-Eocene Laramide deformation, though probable throughout the range front (Force, 1997), forms fabrics at different orientations.

Thus some fully-ductile Eocene deformation is suggested by mutually cross-cutting relations with garnet-bearing leucogranites and apparently results in some of the NE-trending lineation. The ptygmatic folds in overlying mylonitic gneisses are apparently these older features, overprinted but incompletely destroyed by modest unidirectional shear. Perhaps deformation at sufficiently great depth was fairly continuous in time but not orientation and sense from the Laramide into the Oligocene. Perhaps the deeper, more ductile deformation is more widespread than the unidirectional shear zone that locally captures and overprints it.

Discussion. The relative age of these elements seems to become progressively younger toward the top. Starting at the base, unidirectional shear appears to be an overprint on deeper pure shear. The NW-striking joints cut quartz rodding in older mylonitic gneiss. However, these joints appear to be older than the overlying semi-brecciation zone, based on the few back-rotated joints in the semi-breccia.

The sequence is also toward upward-increasing brittle behavior, from fully ductile pure shear, through semi-ductile mylonitic gneiss, to brittle joints and breccias. Ductility presumably records deeper-crustal conditions, so the sequence is an age-depth record of uplift that accompanied tectonic denudation (e.g., Davis et al., 1986).

The above-described sequence, though generally applicable in all parts of the study area, shows variations in degree among different parts of the study area. The thickness of semi-breccia zones, for example, is greater in the Agua Caliente hills than elsewhere. Also in the Agua Caliente-northern Rincon area (Sheet 2), an extensive intermediate-level sheet of weakly- to non-mylonitic rocks is apparently present, commonly with foliated gouge at its base and along its flanks separating it from mylonitic gneiss. The evidence belongs to the following section.

Geometric relation of structural elements

The Agua Caliente Hills (Sheet 2) present the best opportunity to study the geometric relations among various structural features. Among these are the shape of the detachment surface, folds in mylonitic fabrics, variations in degree of mylonitization, and various types of sub-detachment faults.

Geometry of detachment surface. In the Agua Caliente Hills, the presence of a sinuous detachment trace and two upper-plate allochthons in addition to some near-detachment features in a lower plate with considerable topographic relief, allows the construction of a structure contour map (Sheet 2). The contoured surface is the base of semi-breccias below the detachment, as that surface is far better constrained at the range front than the detachment itself. However, where semibreccia is thin or lacking the surface is controlled by the detachment itself, and the shape of the contoured surface should be that of the detachment.

Contouring is constrained considerably by current land-surface relief, i.e. the contoured surface has to be above hills entirely composed of unbrecciated lower-plate rocks. In order to touch down at the Italian Trap allochthon, for example, the detachment surface has to clear several higher lower-plate hills between there and the range front. Unmapped but common semibreccia outcrops between the Italian Trap

and Bellota Ranch allochthons make contouring in that area ambiguous.

The warps apparent in the contoured detachment surface resolve themselves into two sets of structures (Sheet 2). An ENE-trending set (T1) links the two individual allochthons to two range-front synforms in the detachment trace, separated by a medial arch over Agua Caliente Hill, and flanked by lower-plate Santa Catalina and Rincon mountains. A NNW set (T2) links the two allochthons in a synform and controls the shape of the range front. The geometry resulting from interference of the T1 and T2 sets forms an egg-box pattern. Neglecting the Santa Catalina and Rincon Mountain flanks, the vertical relief on both trends seems to be about 300 m.

The T1 set is probably an original feature of the detachment system, as its trend is that of tectonic transport. It presumably formed as great mullions on the fault surface. The T2 set, on the other hand, probably formed by later arching of the detachment system, as we shall see.

The warps in the detachment surface are closely related to mountain morphology; the synforms form valleys and saddles, and the antiforms form ridges. The T1 synforms together form the angle in detachment trace between the Catalina and Rincon Mountains (Fig. 1), as well as the low country between them. The correspondence of structure and physiography is probably due to extensive erosional exhumation along detachment surfaces (Pain, 1985).

Geometry defined by mylonitic fabrics. The Catalina-Rincon range front seems everywhere to show an arch in mylonitic fabric that roughly parallels the range front and the trace of detachment faulting. Mylonitic lineation retains a near-constant ENE trend except on the northern limb of the arch in the Catalina forerange (Force, 1997), but the plunge reverses to define the arch. The axis of arching trends NW-SE the length of the Catalina forerange but more N-S through the Rincons (Drewes, 1977; Thorman and Drewes, 1981). Sheet 2 shows its continuation in the Agua Caliente Hills, which intervene.

The arch in mylonitic lineation is a little ambiguous in parts of the Agua Caliente Hills where mylonitic fabric is absent (Sheet 2). Even here, however, its position is constrained by sporadic lineation.

The axis of the detachment arch parallels but does not coincide with the arch in mylonite lineations (Sheet 2), being separated by about 3 km. That is, lineation plunge defines a T2 feature. Some separation could be expected because the most apparent lineation feature is in S-surfaces rather than C-surfaces; a C-surface arch should be farther east.

The vertical relief on the sub-detachment arch is at most 300 m (Sheet 2). In comparison, the arch in mylonitic structure probably has 500-600 m of structural relief, based on limb width and lineation plunge. Thus the magnitude of arching of mylonite is significantly greater than the probable magnitude of arching of detachment. However, the parallelism is suggestive of a relation between them.

To the NE beyond the two allochthons, the detachment must rise toward the NE again because the allochthons close. Mylonitic lineation, however, continues to plunge NE in this direction (Thorman and Drewes, 1981). In this area, detachment and mylonitic structure must depart (as they apparently do in the Catalinas; Force, 1997).

Intersecting the T2 lineation arch and plunging away from it is a ENE-trending synform parallel to mylonitic lineation (Sheet 2) along Agua Caliente Creek. It is defined by mylonitic foliation and by compositional banding formed by flattened leucogranite intrusions in older host rocks. Synform axes as determined by mylonitic fabrics and by the detachment surface appear to be coincident, i.e. mylonitic fabrics share one T1 feature with the detachment surface. No corresponding synform in mylonitic fabrics was detected under the southern T1 detachment synform, however, possibly because some fabrics there predate the mid-Tertiary.

Variations in mylonitic fabric. Though older rocks are deformed throughout the study area, mylonitic deformation of leucogranite is extremely varied in the Agua Caliente Hills and northern Rincons (Sheet 2). In several areas, one of considerable size, leucogranite is basically undeformed; in others its deformation is weak to sporadic. The pattern of such occurrences is difficult to interpret. This intricate variation in mylonitization is currently undescribed, and quite anomalous in the midst of a metamorphic core complex range front characterized by post-leucogranite semi-ductile extension.

Within the little-deformed areas shown in Sheet 2, only Laramide and older rocks are severely deformed, and these older fabrics commonly lack lineation and show foliation independent of those in

mylonitic rocks. Muscovite-garnet leucogranite and pegmatite are little-deformed. Mylonitic fabric where present in leucogranite shows large angles between C and S elements, i.e. strain is not great. Locally, a weak fabric in leucogranite is discordant to a preserved stronger fabric in the older rocks. NW-striking steep joints and fractures are weakly developed. There is commonly a thin sheath of typical strongly mylonitic gneiss in the highest structural positions, against semi-breccia. This seems to be only as much as 50 m thick. Plunge of sporadically developed lineation is as in adjacent domains.

Three factors are possibly involved in the observed distribution of mylonitic fabric in the leucogranite. First, in some areas the predominant leucogranite may be post-mylonite. In support of this factor, two leucogranites, one pre- and one post-mylonite, are observed at a few localities. However, more commonly all leucogranites either are or are not deformed together, and the following observations in the little-deformed areas severely limit the importance of this factor:

1. Strong deformation fabrics in these areas are limited to Laramide and older rocks, are generally totally ductile, commonly lack lineation (mostly consisting of isoclinal fold axes where present), and generally consist of steep foliations with strikes varying from E-W to S70E, i.e. quite different from mylonitic lineations and trends thereof. That is, there is little evidence of mid-Tertiary extension affecting older rocks.
2. Mylonitic fabric is locally present but weak in leucogranite, showing for example large angles between C and S elements. That is, mid-Tertiary extension where present is generally not obscured by later intrusion.
3. Strength of mylonitic fabric grades from the upper thin sheath into lower rocks without change of leucogranite type. That is, the leucogranites in these areas are not too young to be mylonitic.
4. In some parts of the panel there are no deformation fabrics at all, though a spectrum of rock ages are represented. That is, if no deformation occurred, no mid-Tertiary deformation occurred.

A second factor is that some loci may represent thresholds of quartz ductility, and separate brittle from semi-ductile behavior. Some gradual transitions do seem to occur in map unit nss of Sheet 2. However, most commonly the transitions from little- to severely-deformed leucogranite is abrupt. Thus this factor too is insufficient to explain most variation.

The third factor, structural juxtapositions of different fabrics (as well as different protolith assemblages), is observed at a great number of lower-plate localities, and can explain the pattern, especially in conjunction with some variation due to the first two factors. Two types of structural juxtaposition are observed and are described in the next section.

Faults. Abrupt boundaries separating areas of weakly and strongly deformed leucogranites quite commonly correspond to fault gouges. Many of these gouges seem to be related to moderately to steeply dipping faults, forming nearly straight lines on air photos. In the northern Rincon Mountains there are apparently swarms of such faults (Sheet 2). The faults generally dip north; some of the gouges are foliated and sub-horizontal rodding is characteristic.

Less frequently exposed in this area are gently north-dipping gouges, but they are an important clue to the most important fault style and to the nature of the mylonitic fabric distribution. Weakly deformed rocks are found above these faults and more strongly deformed rocks below them. Both are lower-plate rocks relative to the main detachment, but I think the gently dipping faults are themselves lower-plate detachments. The distribution of mylonitic fabrics, then, is a collage contributed by a few young granites, a few mylonitic thresholds, and many steep faults, complicating a basic detachment geometry.

Except for a few of the steeply dipping faults that may be of minor importance, the fault gouges being described here are locally foliated. Thin section examination and megascopic quartz rodding show that some quartz in some of them is ductile; that is, they formed at depths and at times appropriate to carry rocks being slightly mylonitized over or along strongly mylonitic ones.

Sub-horizontal lineation is characteristic of both the lower-plate detachment(s) and the more steeply north-dipping faults. Movement directions for the fault rocks and nearby mylonitic lineations are not perfectly parallel, however; the fault rocks tend to plunge NE more steeply than lineation by an average of about 10 degrees. This gives a slight dip-slip component to movement. This lineation in both

fault rocks and mylonitic gneiss was then arched along the same T2 trend.

In contrast to the complex southern boundary of non-mylonitic domains, the northern boundary seems to be a single fault, called the Cat Track fault on Sheet 2, thus making the non-mylonitic domains highly asymmetric. This fault was traced from a range-front sub-detachment to a probable extension of the Romero Pass fault (of Force, 1997), both of which are apparently younger. The plane of the Cat Track fault is foliated, and contains sub-horizontal quartz rods in planes dipping moderately to steeply northward.

On the southern boundary, non-mylonitic terranes are bounded by three main fault systems. Probably the most important is the gently north-dipping lower-plate detachment (Sheet 2), whose plane was seen in four places (and in one thick zone, five readings were made). It dips north 10 to as much as 40 degrees. It is locally foliated; plunge of mullions and quartz rodding is shallow, but away from the T2 arch in plunge of mylonite lineation. Top (or north) is everywhere to the southwest. The lower-plate detachment must also be present on the north wall of Tanque Verde Canyon, where it separates mylonitic rocks in the canyon from non-mylonitic leucogranites just north of it (Sheet 2). However, the fault plane was not seen there, nor in some other places where its presence is suspected.

A shear zone with two main branches apparently offsets the lower-plate detachment, up to the south, so that non-mylonitic leucogranite occurs to the north. A southern branch that I'll call the falls branch, as it passes through Bridal Wreath and Chivo Falls, is cataclastic; its dip is unclear. A northern, more throughgoing branch that I'll call the tank branch, as it passes through Aguila, Mica, and Mesa del Oro Tanks, ranges in dip from almost flat to steeply north-dipping. Its plane was seen at six localities; it is locally ductile, with subhorizontal rodding (plunge direction depending on relation to T2 arch). Chlorite and epidote are elsewhere seen in brittle fault-rock. The north side moved southwest. Note that this fault zone forms the southern boundary of the Italian Trap allochthon (Sheet 2).

Another fault, well-exposed near the Saguaro Park loop road, is apparently brittle and steep. It is apparently down to the south, bringing the lower-plate detachment below the surface again, based on non-mylonitic leucogranite to the south. The steeper attitude of this fault relative to the falls-tank fault, and the opposed apparent offset, suggests a horst-like relation of mylonitic rocks between for the slight dip-slip component of movement. However, the southern fault may be younger as it is less ductile.

Discussion. It seems fairly clear that a post-detachment faulting event could not have produced all these faults and the offsets of mylonitic domains. Evidence includes the ductile component of deformation in the fault zones, the folded fault lineations, and the absence of offsets of range-front detachment faults or semi-breccia zones in conjunction with the evidence of strike-slip motion based on subhorizontal rodding and mullions.

Instead most of the faults seem to be related to a lower-plate detachment extension regime. The movement vectors on the lower-plate detachment faults themselves suggest they were a deeper component of the same extensional system as the overlying more brittle detachment faults. The ductile component of movement on the steeper faults, together with their strikes parallel to extension and the evidence of strike-slip movement, suggests that they served an accommodation function for these lower-plate detachment faults. That is, they allowed the mylonitic zones to function semi-independently (in all but transport direction) in much the same way that accommodation zones allow detachment faults to function semi-independently. The falls-tank fault zone that forms the southern margin of the Italian Trap allochthon shows that an accommodation function for the sub-detachment system led to an accommodation function for the detachment system.

There must be a complex history to the fault system as a whole. Apparently an older set of extensional boundaries between mid-crustal mylonitic domains, formed in a late stage in the development of those domains, later and locally became the locus of an accommodation zone in a detachment system in a shallow-crustal environment. A near-continuum of structural features may exist, from the lower-plate detachments and their accommodation zones, through sub-detachments at the base of the semi-breccia zones, to more conventional detachment faults.

Some features of the Agua Caliente Hills area suggest the form of relations between the mylonitic and detachment regimes. For example, accommodation functions seem inherited from the slightly-ductile

to the brittle environment (but not necessarily from more ductile environments). The T2 arches in mylonitic lineation and detachment surface are parallel but not coincident (unless C-surface arching occurs 3 km east of S-surface arching). A T1 synform in mylonitic lineation coincides with the northern of two such synforms in the detachment surface, but no such correspondence is apparent in the southern T1 detachment synform, indeed an arched lower-plate detachment occurs there. These comparisons suggest that despite common basic geometries, much continued evolution separated the older mylonitic from the detachment generation of features.

The T2 arch in mylonitic lineation presumably originated from tectonic unloading and consequent crustal rebound associated with extensional processes (e.g. Spencer, 1984; Reynolds and Lister, 1990); original lineations must have been colinear but are now deformed. Thus the arch probably postdates the T1 NE-SW trending antiforms and synforms in the mylonitic fabric and detachment surfaces, which are original extensional features. The arch apparently also postdates the ductile component of fault zones bounding the weakly mylonitic domains, i.e. quartz rodding in these faults is itself arched. As the arch is defined by a plunge reversal of features whose distribution and orientation is variable, and which is a product of isostatic rather than compressive tectonic factors, we might expect that the axis of arching could curve and the magnitude of arching be variable, as seems to be the case.

Comparison of the arch in lineation with that of the detachment surface suggests a history. That is, the offset axis and greater magnitude of lineation arching suggests that lineation arching began prior to inception of detachment faulting. Probably mid-crustal extension required some pre-detachment isostatic response.

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