Fault and fault-rock characteristics associated with Cenozoic extension and core-complex evolution in the Catalina-Rincon region, southeastern Arizona

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ABSTRACT

Cenozoic extensional deformation in southern Arizona included (1) a Neogene phase of Basin and Range deformation recorded by high-angle normal faults and (2) an earlier phase of detachment faulting and brittle-ductile crustal shearing associated with tectonic denudation of metamorphic core complexes. In the Catalina-Rincon region, exposed fault zones produced at different crustal depths during successive extensional episodes display differing fault geometries and types of fault rocks formed during progressive crustal extension. Detachment faults are associated with both mylonites produced by ductile shear and cataclasites produced by brittle shear. Younger faults formed at shallower depths are associated with less intense cataclastic deformation and with brittle fracturing that includes transtensional phenomena at the shallowest crustal levels represented. Qualitative measures of net displacement along individual fault zones are provided by (1) the nature of contrasts among successively overprinted fabrics and internal structures in the footwall and (2) the degree of contrast between fabrics and structures of footwall and hanging-wall rocks. Footwalls of the oldest structures display varied brittle overprints of ductile fabrics and are juxtaposed across gouge zones along detachment surfaces with stratal successions cut by multiple brittle shear surfaces. Footwalls of younger structures formed at shallower depths display multiple generations of cataclastic features, including brecciation of variable intensity and cataclasite dikes, but are juxtaposed against hanging-wall strata that are only moderately deformed by subsidiary faults. The shallowest fault zones lack either structural overprints in their footwalls or any significant contrasts between footwall and hanging-wall deformation. Exposures of mid-crustal rocks within the core complexes reflect successive exhumation and uplift of fault footwalls during sequential episodes of deformation. The present high elevation of mylonitic rocks in the Catalina-Rincon metamorphic core complex reflects dip slip and isostatic foot-wall flexure during Basin and Range deformation as well as tectonic denudation during detachment faulting. Net uplift of core rocks resulted from multiple phases of deformation.

Keywords: core complex, crustal extension, detachment fault, fault rock, normal fault.

INTRODUCTION

Cenozoic crustal extension in southern Arizona was the product of superposed deformational regimes separable in both timing and style (Davis, 1980; Dickinson, 1991, 2002). Late Oligocene to early Miocene extension was accommodated at exposed crustal levels by subregional brittle-ductile shear zones, expressed as metamorphic core complexes and associated gently dipping detachment faults. Postdetachment early Miocene extension involved motion on normal faults that originated at high dips but were progressively rotated to lower dips as adjacent fault blocks tilted in domino fashion during continued deformation. Additional post-middle Miocene extension produced high-angle Basin and Range normal faults that offset the basin fill of structural depressions. Basin and Range extension was most rapid before initiation of seafloor spreading in the nearby Gulf of California near the end of Miocene time, but continues at reduced rates.

Because all the younger generations of faults offset middle Cenozoic detachment faults, there has been a tendency to focus on a simple dichotomy in deformational style between low-angle and high-angle normal faults. We here call attention instead to progressive changes in fault behavior and fault-rock character as crustal extension evolved through multiple extensional episodes involving deformation at different depths and varying extension directions. Mylonitic rocks now exposed 2–3 km above sea level within the Catalina-Rincon metamorphic core complex were raised in increments from mid-crustal levels during a succession of deformational phases, including isostatic and flexural responses to each. Net rock uplift during each stage of structural evolution was a function of relative fault displacement in relation to changing elevations of the ground surface as erosion proceeded.

Our primary focus during this study was on post detachment fault systems that to date have received much less study than the detachment system and associated mylonitic rocks. We then assess the influence of successive phases
of extensional deformation on the exposed morphology of the Catalina-Rincon core complex. The fault geometries and fault rocks associated with sequential phases of deformation can be considered jointly to develop an integrated picture of crustal extension as it affected different levels within the crust. The influence of changing geothermal gradients on crustal rheology probably supplemented the effects of simple depth control on the style of faulting, but is more difficult to quantify with confidence.

**STUDY SITES**

Faults exposed around the periphery of the Catalina-Rincon metamorphic core complex (Dickinson, 1991) formed at various times and at a range of depths. Our knowledge of the structural geometry of the core complex led us to select four key study sites (Fig. 1), discussed in order of increasing age of faulting, where structural features associated with each successive phase of extensional deformation can be examined to best advantage.

Two study sites involve high-angle Basin and Range faulting, for which extant descriptions of physical characteristics are scanty because exposures of Basin and Range faults are commonly masked by aggradational Neogene alluvium deposited against range fronts. At the Cascabel study site, intrabasinal Basin and Range faulting (6–4 Ma) in the San Pedro River valley east of the Rincon Mountains proceeded at a depth of <1 km within disrupted basin fill. At the Dead Hawk Gulch study site along the Pirate fault, range-front Basin and Range faulting (12–6 Ma) delimited the western margin of the Santa Catalina Mountains along the flank of Oro Valley where the pre-offset depth of exposed footwall rock was 3–4 km.

Two generations of older low-angle normal faults are present within the Catalina-Rincon region (Dickinson et al., 1987, 1995; Dickinson, 1991, 1993, 1998a, 1999; Force et al., 1995; Force, 1997). The Catalina detachment fault, which is gently inclined and forms the southwest front of the Catalina-Rincon metamorphic core complex, controlled tectonic denudation of mylonitic core rocks in its footwall (Davis, 1980). Rotated normal faults of somewhat younger age that dip beneath the core complex and locally displace strands of the detachment system are exposed within the San Pedro trough, a synformal downwarp (Spencer, 1984) in the detachment system lying between the uplifted core complex and its breakaway zone.

The other two study sites focus on the two different generations of low-angle normal faults. At the Cottonwood Wash study site, the pre-offset depth of exposed footwall rocks adjacent to the rotated San Manuel fault north of the Santa Catalina Mountains was 2–3 km during pre-Basin and Range but postdetachment normal faulting (19–16 Ma). At the Martinez Ranch study site, the pre-offset depth of exposed footwall rocks was 8–12 km (Dickinson, 1991; Force, 1997) during mylonitic shear and detachment faulting (28–20 Ma) along the Catalina brittle-ductile shear zone at the southeast corner of the Rincon Mountains.

**CASCABEL STUDY SITE**

Along the San Pedro River at the east flank of the Little Rincon Mountains (Fig. 1), moderately to steeply dipping (65°–85°) normal faults offset upper Cenozoic alluvial deposits of the Quiburis Formation and its correlatives (Dickinson, 1991, 2003), as well as older units (Drewes, 1974). South of Cascabel (Fig. 1), Lingrey (1982) mapped a system of high-angle normal faults, striking north and spaced 100–400 m apart; individual trace lengths are up to 7 km. Along strike, the faults converge and diverge, creating trace intersections at angles of 10°–30°. Most are locally east-dipping, but the overall system of Basin and Range faults in the Little Rincon Mountains and the San Pedro River valley includes important west-dipping normal faults as well (Dickinson, 1998a, 1998b, 2003). The north trend of the system is consistent with the widely accepted view that Basin and Range faulting in southern Arizona was a response to east-west regional extension (Menges and Pearthree, 1989).

Multiple faults exposed in a cliff face near Cascabel offset subhorizontal conglomeratic horizons of the Quiburis Formation (of post-middle Miocene age), which forms the basin fill of the San Pedro trough (Dickinson, 1998a, 2003). Displacements of a pink, sand-rich layer (~3 m thick) within an otherwise homogeneous succession of buff, pebble to cobble conglomerate record fault offsets clearly. None of the faults in the cliff face offset bedding more than 20 m, but we assume that the physical characteristics of the exposed faults are similar to those of unexposed, greater-displacement faults mapped nearby by Lingrey (1982). The faults near Cascabel strike northeastward, at an angle to the overall north regional trend of Basin and Range faulting. We interpret this departure from the expected orientation as the expression of an oblique transfer zone between en echelon eastward-dipping normal faults striking more nearly due north.

**Outcrop Observations**

The main structure in the cliff exposures near Cascabel is a graben, trending N35°–40°E and bounded by normal faults that dip 70°–75° inward (Fig. 2A). Each of the graben-bounding faults is exposed for a height of ~30 m (Fig. 2B), but their projected intersection lies below the base of the cliff. The pink marker bed (Fig. 2A) within the graben has been down dropped ~20 m from its position outside the graben on the cliff face. The faults cut across, rather than curving around, rigid clasts of the host conglomerate. All the faults at the Cascabel study site are marked by thin zones of powdery and clayey gouge up to 3 cm thick. The gouge is silvery white, making the fault surfaces conspicuous in outcrop. The gouge along each fault forms a layer of uniform thickness, bounded on each side by parallel planar fault walls bearing polish and slickenlines. Penetrative strain of the clayey gouge during fault movement is recorded by closely spaced cleavage dipping more gently than, but in the same direction as, the fault surfaces.

Above a subtle bend in the fault surface, the uppermost exposed segment of the northwestern (southeast-dipping) graben-bounding fault shifts to a slightly shallower dip than observed lower in the cliff face. Immediately above the angle in the fault surface, there are two hanging-wall normal faults, one synthetic but dipping more steeply than the master fault and the other antithetic and northwest-dipping (Fig. 2C). These two faults, in combination with the master fault, create a fanning pattern. Higgs et al. (1991) described a similar fault-fanning pattern associated with a change in the dip of a prominent splay of the Sevier (Basin and Range) fault near Mount Carmel in southern Utah. The dip change in the graben-bounding fault at the Cascabel site coincides with the base of the 3-m-thick pink sandstone marker bed in the footwall and probably reflects a change in mechanical properties of the dominantly conglomeratic Quiburis succession.

In the footwall beneath the southeastern (northwest-dipping) graben-bounding fault at Cascabel, there are two synthetic footwall faults, striking N45°–50°E and dipping 75°–85°NW, which display normal offsets of ~3 m. Variations in the attitudes of these footwall faults stem from grooves in the fault surfaces with wavelengths of ~10 m. Slickenlines and grooves on both the master graben-bounding faults and the subsidiary faults record normal
oblique slip, with net extension approximately east-west, as expected for Basin and Range deformation (Menges and Pearthree, 1989).

Fault Interpretations

We interpret the conjugate oblique-slip normal faults as an expression of faulting in a three-dimensional strain field (Reches, 1978; Krantz, 1986; Watterson, 1999) along a displacement-transfer zone linking two larger-displacement faults. The conjugate angle between the major graben-bounding faults in the cliff face is 30° to 40°, suggesting that faulting occurred in the transtensive field (Suppe, 1985; Davis and Reynolds, 1996) as a combination of mode I (jointing) and mode II (shear fracturing). To assume that faulting was controlled by strict Coulomb failure would require an angle of internal friction for Quiburis conglomerate of 50° (coefficient of internal friction > 1), which far exceeds reasonable values for natural rock materials (Byerlee, 1978; Suppe, 1985; Davis and Reynolds, 1996).

No intensive fracturing, brecciation, or veining is apparent in wall rocks of the faults at Cascabel. Deformation mechanisms were restricted to fault breakage and frictional sliding accompanied by minor grain-scale cataclasis and perhaps fault-zone dilation. Small-scale normal faulting is not pervasive within the Quiburis Formation, and the total extension accomplished by Neogene faulting was small. Areal mapping of widely spaced faults cutting the Quiburis Formation of the San Pedro trough (Dickinson, 1998a) indicates that Basin and Range normal faulting internal to the Quiburis Formation accommodated east-west extension of <5%.

The depth of faulting at the Cascabel study site was <750 m, the approximate combined maximum thickness of exposed and buried Quiburis Formation (Dickinson, 1991, 2003). Remnants of a prominent paleosol that was developed on the aggradational surface at the stratigraphic top of the Quiburis Formation just prior to its dissection by post-middle Pliocene erosion stand only 350–450 m above river level at the base of the cliff-face fault outcrops (Dickinson, 2003), and suggest a depth of faulting of <500 m. As the residual remnants of the paleosurface capping the Quiburis Formation lie along the flanks of the San Pedro trough, and slope at an angle of ~1° toward the San Pedro River (Dickinson, 2003), the burial depth of the faults at the Cascabel study site was probably <250 m. The age of the faulting is difficult to constrain as closely, but ca. 6 Ma tuffs and mammalian faunas are present in Quiburis fluvial and lacustrine facies correlative with the conglomerates cut by the faults, and dissection of faulted Quiburis basin fill was under way no later than middle Pliocene time (Dickinson, 2003). These constraints imply faulting mainly during the interval 6–4 Ma; the younger age bracket is uncertain.

DEAD HAWK GULCH STUDY SITE

The Pirate fault, which dips 50°–65° at the surface (Dickinson, 1994; Spencer and Pearthree, 2002), delineates the western flank of bedrock exposures in the Santa Catalina Mountains (Fig. 1). The fault strikes N10°E at its northern end, curving abruptly to a strike of N45°E to the south (Fig. 3). The fault trace crosses modern topography, including mountain spurs, without offsetting any geomorphic features, although preferential erosion along the fault zone locally controls the positions of some stream segments. Where projected southward beneath alluvial cover, the fault apparently truncates the Catalina detachment fault as exposed along the southern flank of the Santa Catalina Mountains.

Inferred ages of sedimentary units within Oro Valley suggest that displacement along the Pirate fault occurred during the interval 12–6 Ma (Dickinson, 1994). At the northern
end of its exposed trace, the Pirate fault is overlapped by a dissected alluvial fan built across the fault trace by the ancestral Cañada del Oro (Fig. 3). Fan remnants form benches of the Pleistocene Cordones surface (McFadden, 1978, 1981) standing 125–250 m higher in elevation than modern wash floors. Farther south, a dissected pediment carved into granitic bedrock east of the Pirate fault trace is delimited uphill by steep relief at the modern range front, which marks the limit of headward incision into the footwall block by pedimentation after faulting slowed or ceased (Bull et al., 1990).

The Pirate fault separates syntectonic but subhorizontal Neogene basin fill of Oro Valley in the hanging wall from crystalline bedrock in the footwall (Dickinson, 1994). Proximal facies of basin fill adjacent to the fault trace contain megaclasts as coarse as 1–5 m in diameter (Dickinson, 1994). The fault contact is marked by a thin seam of clay-rich gouge (1–5 cm thick) between variably but moderately dislocated basin fill and highly fractured to brecciated crystalline rock in the immediate footwall. Mapping of the entire fault trace (Dickinson, 1994) indicates that the outcrops that most fully display the physical character of the fault zone occur at Dead Hawk Gulch (Figs. 1, 3), a tributary to Cañada del Oro where erosional exhumation of the sediment-bedrock contact has produced a local fault-line scarp ~5 m high. Dead Hawk Gulch breaches the scarp and dissects fault rocks lying within the adjacent footwall to expose the internal geometry of footwall deformation in fractured bedrock (Fig. 4A) for a distance of ~200 m along strike. The footwall is Catalina Granite (ca. 26 Ma), intrusive into Middle Proterozoic Pinal Schist exposed nearby (Fig. 3).

Outcrop Observations

The fault surface at the sediment-bedrock interface (Fig. 4B) is slightly curved and scored by abundant slickenlines and grooves. Some of the slickenlines occupy Riedel shears that dip westward at 60°–70°, slightly steeper than the main fault surface (dipping at 50°–55°). Exposed fault-zone features at Dead Hawk Gulch can be subdivided into five structural domains (Fig. 4A), in order downward into the footwall as follows (Davis et al., 1994): (1) the fault surface itself, (2) a thin sheet (~10 cm) of compact breccia lying parallel to the fault surface, (3) a thick zone (~180 m) of cohesive breccia (brecciated granite) displaying semibrittle cataclastic foliation throughout and cut by abundant cataclasite dikes, (4) a diffuse zone (~40 m) of “fracture grid work” (Hancock, 1994) consisting of orthogonal fracture sets, invaded locally by cataclasite dikes, within unbrecciated granite, (5) undeformed Catalina Granite.

The compact breccia sheet adjacent to the fault surface (Fig. 4C) is resistant to erosion and forms flatirons along the fault-line scarp. Clasts within it range upward to ~10 cm in diameter and are set in a matrix of massive cataclasite without throughgoing fractures. By
contrast, the cohesive breccia structurally below the compact breccia sheet is internally ruptured and contains throughgoing fractures up to 10 m in length. Individual clasts of granite, equant but faceted or elongate, range from 1 to 10 cm in diameter. Although the Catalina Granite protolith for the cohesive breccia is gray, the breccia is uniformly red to red-purple, in part because most of its fractures are coated with hematite and also because perva-sive cataclasite dikes (Fig. 4D) are rich in hematite as well. The variably oriented cataclasite dikes crosscut protolith and fault-rock fabrics that were dilated but not offset laterally across the dikes. In addition to fractures and cataclasite dikes, the cohesive breccia is cut by hematite-coated fault surfaces scored by slickensides and slickenlines and by foliated shear zones formed by entrainment of finely comminuted granite protolith (Fig. 4E). Displacements across discrete faults and more diffuse shear zones are recorded by offset of (1) markers such as aplite dikes, inclusions, and schlieren in the granite protolith and (2) fault surfaces, shear zones, and cataclasite dikes formed earlier during progressive deformation by faulting and brecciation.

Deeper into the cohesive breccia, shear-zone foliation ultimately disappears, although brecciation and cataclasite dikes persist downward structurally for another 30–40 m (Fig. 4A). Brecciated rock passes eastward over a narrow (<1 m) zone of transition into Catalina Granite laced by orthogonal joints filled with thin (up to 2 cm), hematite-rich cataclasite dikes. In general, these joints strike both parallel and perpendicular to the trace of the Pirate fault, isolating blocks of Catalina Granite that are ~1 m on a side. Stewart and Hancock (1994) described similar structures in limestone of the footwalls of normal faults in Turkey and Greece as “grid-work fracturing.” The contact between the zone of grid-work fracturing and undeformed Catalina Granite is sharp, marked by an abrupt face of resistant granite standing ~2.5 m in steep relief for at least 150 m parallel to the Pirate fault trace. In detail, the configuration of the prominent step in local topography is controlled by throughgoing joints that strike N10°E and dip 55°W, parallel to the Pirate fault surface.

**Microstructural Features**

Microstructures of Pirate fault rocks as viewed in thin section provide information on the deformational mechanisms that accommodated fault displacement. Cataclasite bodies collected from the domain of grid-work fractures and from cataclasite dikes display mode I (tension) fractures containing at least one, and in some instances two or three, generations of cataclasite fill (Davis et al., 1998a). The contacts between cataclasite dikes and undecomposed Catalina Granite are everywhere sharp. Different generations of cataclasite dikes are discernible from crosscutting relationships, and the different generations of cataclasite fill commonly display empirical contrasts in the sizes of residual clasts, 0.25 to 2.5 mm in diameter, which include angular to subangular fragments of K-feldspar, quartz-feldspar aggregates, and biotite flakes set in a dark, fine-grained matrix. The domain of cohesive breccia showing traces of shear foliation contains similar hematitic cataclasite fracture fillings separated by shear surfaces from microbrecciated and cataclastically foliated granite (Fig. 4E). Fragments of intact but internally deformed Catalina Granite are in part brecciated and in part cataclastically foliated, and their grain sizes have been reduced by microfracturing. The edges of some granite fragments are sharp, whereas others are diffuse, marked by mixing with breccia matrix.

**Fault Interpretations**

The combined petrographic and outcrop observations lead us to interpret deformational mechanisms during Pirate faulting as brittle to semiductile; they include cataclastic flow, Coulomb faulting, frictional sliding, and tension fracturing accompanied by cataclasite dike formation. Repetitive motions along the fault zone may have formed the band of compact crush breccia adjacent to the fault surface. We regard the band provisionally, however, as the cohesive counterpart of shallow-level noncohesive breccia belts formed where synfaulting fragmentation, brecciation, and frictional sliding of fault-precursor shatter zones are produced by stress imposed on rock ahead of propagating fault tips (Stewart and Hancock, 1994). In this view, deformation spatially ahead of a developing fault plane is accommodated by intense local fragmentation.
CENOZOIC FAULT AND FAULT-ROCK CHARACTERISTICS, SOUTHEASTERN ARIZONA

Figure 4. Pirate fault zone at Dead Hawk Gulch. Location shown in Figure 1. (A) Line drawing of fault-zone features (see text) exposed in stream transect normal to fault trace (Fig. 3). (B) Fault surface with figure for scale (view south). (C) Close-up of fault surface (view east) showing cataclasite (light-colored clasts of Catalina Granite 5–10 cm across) forming compact breccia sheet (field of view ~0.5 m wide). (D) Close-up (field of view ~5 cm wide) of cut slab showing cataclasite dike intruding fractured granite of cohesive breccia zone. (E) Photomicrograph (field of view ~5 mm wide) of foliated cataclastic fabric in sheared granite (communited fragments white).

and brecciation of a precursor shatter zone. Later propagation of the fault plane through fault-precursor breccia concentrates deformation along the fault plane and reconstitutes the fault-precursor breccia into attrition breccia or fine gouge. Where exposed by erosion, attrition breccia forms an indurated carapace (compact breccia sheet) adjacent to the fault plane and provides a measure of protection for underlying fault-precursor breccia that is less resistant to erosion.

Oro Valley Gravity Modeling

Bouguer gravity modeling was used to delineate the subsurface geometry of the Pirate fault system as reflected by the thickness and configuration of basin fill in the Oro Valley half graben (Fig. 5). A single basin transect was modeled by using the gravity data of Budden (1975) combined with an assessment of expected basin-fill density and the mapped attitude of the Pirate fault at the modern land surface. Station spacing on the transect is ~330 m, and the observed gravity data were reduced by using meter drift, latitude, free air, Bouguer, and terrain corrections (Budden, 1975). The resultant Bouguer anomaly associated with the Oro Valley half graben, after removal of the regional gradient, is ~14 mgal, with steep gradients on both sides of Oro Valley. Modeling calculations were performed with a version of the standard two-dimensional program (Talwani et al., 1959).

Subsurface data from two deep wells in the Tucson basin were used to establish the variation of density with depth in basin-fill sedimentary rocks of the Catalina-Rincon region. Subsurface data were derived from compensated neutron density (FDC-CNL) logs for Phillips Petroleum Company Redondo State A#1 and Humble Oil and Refining Company State 32#1. Both wells show a gradual increase in density with depth, from 2.2–2.3 g/cm³ at shallow depths (<1000 m) to ~2.6 g/cm³ at a depth of ~2500 m. The latter density closely approaches the density of underlying granitic bedrock and reflects the effect of compaction on coarse basin fill derived from granitic parent rocks.

Subsurface densities inferred from the Tucson basin well logs compare closely with those derived from surface rock samples and borehole data from Tertiary grabens in western Montana (Constenius, 1988). Density determinations for surface samples of Tertiary strata in western Montana indicate that sandstones and conglomerates have average densities of 2.3 g/cm³ and 2.5 g/cm³, respectively. In Oro Valley, the density of basin fill composed of coarse granitic detritus is accordingly inferred to be 2.3 g/cm³ or greater near the surface, with higher densities prevalent at depth (Fig. 5). The background density used for modeling was 2.65 g/cm³, a value representative of granitic bedrock on the basis of well control. Figure 5 depicts the structural configuration of the Oro Valley half graben derived from our best-fit gravity model. Although the configuration of the structural keel of the half graben, where sediment densities approach bedrock density, is not well constrained, the Pirate fault is interpreted as a west-dipping listric normal fault, flattening from a dip of 55° on the outcrop to a dip of 25° at a depth of 2.5 km below the ground surface. The minimum dip-slip displacement inferred from the model is 4.4 km. The minimum fault throw is ~2.6 km, and it is probably ~4.0 km if the average bedrock relief of ~1.4 km on the adjacent range front is taken into account.
Flexural Uplift

We infer that isostatic footwall uplift accompanying Pirate faulting contributed to the upward translation of rock masses lying within the Catalina-Rincon metamorphic core complex relative to surrounding basins. King and Ellis (1990) described other examples of large relative uplifts in the immediate footwalls of large-displacement high-angle normal faults, and attributed the phenomenon to isostatic response of elastic upper crust as footwall blocks are unloaded by displacements along dipping faults. The apparent effect of isostatic flexure is seen in the topography of the Santa Catalina and Rincon Mountains where the loci of highest elevations occupy proximal footwalls of the Pirate and Martinez Ranch faults (Fig. 6). The crestal region of the Santa Catalina Mountains, composed of footwall core rocks lying structurally below the Catalina detachment fault, widens and rises in elevation westward toward the Pirate fault. The crestal region of the Rincon Mountains has a similar configuration, but in reverse, rising toward the Martinez Ranch fault, another Basin and Range structure, with at least 1.5 km of throw downward to the east (Dickinson, 1998b). We infer that the broad topographic saddle (Redington Pass of Fig. 6) between the Santa Catalina and Rincon segments of the Catalina-Rincon metamorphic core complex is the passive product of relative footwall uplifts related to movements on the Pirate and Martinez Ranch faults on opposite flanks of the core complex (Fig. 7).

COTTONWOOD STUDY SITE

The San Manuel fault, best exposed at the Cottonwood Wash study site (Fig. 1), is a low-angle normal fault of early Miocene age, slightly younger than the detachment fault that defines the Catalina-Rincon metamorphic core complex, which lies within the hanging wall of the San Manuel fault. The fault, which strikes approximately N30°W and dips ~25°SW at Cottonwood Wash, separates tilted conglomerate beds of the lower Miocene San Manuel Formation in the hanging wall from highly fractured and hematite-stained Precambrian Oracle Granite (ca. 1425 Ma) in the footwall (Fig. 8A). The homocline containing the San Manuel Formation at the study site occupies the uppermost stratigraphic levels of a half-graben tilt panel that exceeds 6 km in northeast-southwest outcrop breadth (Creasey, 1965, 1967; Hansen, 1983; Dickinson, 1991, 1993). The trace of the San Manuel fault is repeated at Cottonwood Wash by offset of the fault surface across a steeper Basin and Range normal fault also striking N30°W (Fig. 8A).

Less than 5 km northwest of Cottonwood Wash, Lowell (1968) showed that the San Manuel fault beheaded the San Manuel porphyry copper orebody and displaced its detached extension (the Kalamazoo orebody) ~2.5 km in the direction S50°–55°W. Lowell (1968) and Lowell and Guilbert (1970) further indicated that the San Manuel and Kalamazoo orebodies have been tectonically rotated, about a subhorizontal axis, in a manner compatible with rotational tilting of the San Manuel Formation and the San Manuel fault about the strike of the latter during or after faulting. Although the amount of net rotation is still controversial (Guilbert and Lowell, 1995; Dickinson et al., 1995), Force et al. (1995) showed from both field relationships and paleomagnetic data that a rotation of 33° satisfies all known geologic constraints. Back-tilting by that amount would restore bedding in the San Manuel Formation to subhorizontal and steepen the present outcrop dip (25°–35°) of the San Manuel fault to an initial dip of 60°–65°, an attractive attitude for initiation of extensional slip. The fault is therefore inferred to have rotated domino-style to its present shallow dip during fault displacements.

Along Cottonwood Wash, 2250–2500 m of San Manuel Formation are truncated by the San Manuel fault (Fig. 42 of Dickinson, 1991, 1993). Conglomerates of the San Manuel Formation record syntectonic early Miocene growth-fault deposition of alluvial fans and braidedplain aprons shed from uplands in both the footwall and the hanging wall (Dickinson, 1991). Approximately 3 km north of Cottonwood Wash, uppermost horizons of the San Manuel Formation lying 2750–3000 m stratigraphically above its base overstep the fault to rest depositionally on the footwall (Dickinson, 1993) and place an upper limit on the amount of fault displacement. From these stratigraphic relationships, we infer that footwall rock at the Cottonwood Wash study site lay 2–3 km below the ground surface when faulting and deposition of the San Manuel Formation began.

The age of the unfossiliferous San Manuel Formation is poorly known, but from regional relationships is younger than 22–21 Ma and older than 15–12 Ma (Dickinson, 1991). An air-fall tuff bed intercalated with conglomerate near the top of the exposed section in Smelter Wash (~1 km south of Cottonwood Wash) has yielded an apatite fission-track age of 18.5 ± 3.5 Ma (Dickinson and Shafiqullah, 1989). We infer that movements along the San Manuel fault at the Cottonwood Wash study site occurred mainly during the interval 19–16 Ma, in the immediate aftermath of slip along the Catalina detachment fault.

Outcrop Observations

Undeformed Oracle Granite exposed in nearby unfaulted areas is broken only by joints spaced at intervals of 2–5 m. In the immediate footwall of the San Manuel fault, however, Oracle Granite is broken for hundreds of meters by randomly oriented but
Figure 6. Morphology of Catalina core complex showing highest elevations and steepest relief of lower-plate core rocks (below detachment fault) adjacent to Pirate and Martinez Ranch (MRf) faults (HV—Happy Valley Neogene basin fill). Fault traces dashed where masked by alluvium. Topographic form lines are generalized contours (erosional incision restored) on exposed core rocks at intervals of 1000 feet (≈ 300 m; metric contour maps unavailable at appropriate scale). Major peaks of Santa Catalina (ML, MB) and Rincon (MM, RP) Mountains: MB—Mount Bigelow; ML—Mount Lemmon; MM—Mica Mountain; RP—Rincon Peak. Other faults: BRf—Banco Ridge; BSf—Buehman Spur; CLf—County Line; PCl—Paige Canyon; R Pf—Romero Pass; SRf—Soza Ranch. Extensional allochthons within compound detachment synform of Redington Pass: BRa—Bellota Ranch; ITa—Italian Trap. Modified after Dickinson (1991, his Fig. 13) with information from more recent mapping (Dickinson, 1993, 1994, 1998a, 1998b, 1999).
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Figure 7. Topography along profile A–A’ (Fig. 1) obliquely across Catalina-Rincon metamorphic core complex (no vertical exaggeration).

Figure 8. San Manuel fault in Cottonwood Wash. Location shown in Figure 1. (A) Local geologic map, with squares on hanging wall of low-angle San Manuel normal fault and barbells on hanging wall of Basin and Range high-angle normal fault offsetting San Manuel fault (strike-and-dip symbols denote bedding in San Manuel Formation and arrows denote fault dip). (B) North side of Cottonwood Wash in the northeast corner of Figure 8A (view north), showing tilted Miocene conglomerate (thin white lines, bedding; heavy white lines, fault surfaces) in fault contact (half arrows) with Precambrian granite along San Manuel fault (topographic relief in view is ~75 m). (C) Close-up of extensional duplex faulting in hanging wall of San Manuel fault (Fig. 8B, center), with bedding in San Manuel Formation inclined downward to right.

closely spaced fractures and diffuse brecciation. Few fracture-bound blocks of internally unfractured granite exceed 20 cm in maximum dimension. Typical red-orange coloration reflects pervasive hematitic alteration.

Tilted hanging-wall strata of the San Manuel Formation are less disrupted than footwall granite where exposed in cliffs forming the north wall of Cottonwood Wash immediately adjacent to the San Manuel fault (Fig. 8B). Conglomerate beds of the San Manuel Formation strike on average N25°W and dip 15°–55°NE (average, 30°–35°NE). Extensional duplex structure is evident across a structural thickness of ~8 m (Fig. 8C). Well-polished and slickenlined floor and roof faults, which parallel the San Manuel fault itself, are interconnected by more steeply dipping subsidiary faults bounding extensional duplex panels ~2 m thick and ~8 m long (Fig. 8C). Faults bounding the extensional duplexes strike N30°–60°W and dip 45°–75°SW, with slickenlines trending S35°–S40°W. Cleavage that dips more gently than the faults, but in the same direction, is present in places within clayey gouge along fault strands.

Hanging-wall deformation of the San Manuel Formation is not restricted to the immediate vicinity of the fault. Over a structural thickness of 50 m or more, there are spaced extensional faults, of modest displacement (generally <1 m), which helped accommodate distortion of the hanging-wall strata and created local variations in bedding dip within the San Manuel Formation. Similar multiple faults are exposed in roadcuts ~1 km along bedding strike northwest of Cottonwood Wash (Hansen, 1983). Many such faults are marked by gouge zones with cleavage similar in style and orientation to the gouge cleavage observed at Cottonwood Wash (Hansen, 1983). At greater distances from the San Manuel fault, normal faults are uncommon within the San Manuel Formation.

Fault Interpretations

At several places within the San Manuel fault zone at the Cottonwood Wash study site,
within the field of view of Figure 8B, steeply dipping small-scale reverse faults are associated with small-scale normal faults and appear incompatible with extensional deformation, but are interpreted as rotated faults that formed originally as high-angle normal faults during concomitant layer-parallel extension of untilted strata. Rotation through the vertical to the present anomalous attitudes occurred as tilting of the San Manuel fault proceeded. Assuming that the reverse faults were initially normal faults cutting and displacing essentially horizontal bedding, the normal faults originally dipped 70°–80°SW, comparable to the dip of shallow-level Basin and Range normal faults at the Cascabel study site.

From the nature of mesoscopic structures in outcrop, we infer that deformational mechanisms at the Cottonwood Wash study site were Coulomb faulting and frictional sliding accompanied by grain-scale cataclasis along narrow gouge zones. Assuming Coulomb failure, the angle of internal friction for the San Manuel Formation at the time of faulting was 25°–30° (coefficient of internal friction, ~0.5). We view gouge cleavage dipping more gently than fault surfaces as a record of flattening strain during normal-sense shear.

We attribute pervasive fracturing of the footwall Precambrian granite, as compared to the relatively minor fracturing and faulting within the hanging-wall San Manuel Formation, in part to greater mechanical strength of the granite and in part to greater net slip of the footwall rocks, with consequent greater net intensity of brittle shearing. Whereas fault offset of the Precambrian rocks began as soon as the San Manuel fault was initiated, the exposed upper horizons of the San Manuel Formation—deposited within the half graben adjacent to the fault—were not deposited until later in the history of faulting. We infer accordingly that Precambrian granite in the footwall was already strongly fractured before continuing fault movements placed the deformed footwall against the upper horizons of the San Manuel Formation that are now in fault contact with the footwall at the study site. Net displacement of the footwall was ~2.5 km, but stratal relationships along strike to the north, where the uppermost San Manuel Formation depositionally overssteeps the San Manuel fault, indicate that the San Manuel strata juxtaposed against the footwall at the study site were displaced only ~0.5 km.

**MARTINEZ RANCH STUDY SITE**

The oldest structures associated with Cenozoic tectonic denudation of the Catalina-Rincon metamorphic core complex are well exposed for >3 km along strike within the Martinez Ranch study site (Fig. 1). A brittle detachment fault structurally overlies and overprints the upper structural levels of a mylonitic shear zone flanking the core rocks. Mylonites and microbrecciated mylonites derived from granitic rocks of the core are capped, across the master detachment fault, by a textonically thinned upper-plate succession of Precambrian basement and Paleozoic to Mesozoic cover (Drewes, 1977; Spencer et al., 2001b). Transformation of granitic protolith first to mylonite and ultramylonite and then to cataclasite and ultracataclasite along the detachment fault is recorded by microstructures displayed in thin section (Davis et al., 1998b). The Martinez Ranch fault, a major Basin and Range high-angle normal fault (Fig. 6), truncates the detachment fault and associated structures on the east.

The upper plate of the detachment system consists of internally deformed, fault-bounded slices of Precambrian basement and Paleozoic cover that are discontinuous along strike because of stratal truncations by younger-overolder displacements along subsidiary faults subparallel to the master detachment. Individual Paleozoic formations in the upper plate are thinned to structural thicknesses only 15%–25% of their original stratigraphic thicknesses by multiple imbricate normal faults that internally disrupt the stratigraphic units. The Precambrian strata typically dip to the north or northeast, back-tilted with respect to the southwestward direction of tectonic transport along the Catalina detachment fault (Dickinson, 1991). Oligocene–Miocene red beds (conglomerate and sandstone) of the Pantano Formation (Drewes, 1977) form part of the upper plate; they rest in fault contact on upper Paleozoic sedimentary rocks and form an undisrupted tilt panel that strikes east and dips north. Deposition of the Pantano red beds accompanied detachment faulting in both time and space (Dickinson, 1991).

**Outcrop Observations**

At the Martinez Ranch study site, the Catalina detachment fault strikes east and dips 10°–20°S, separating nonmylonitic and noncataclastic upper-plate rocks from structurally underlying cataclastic and mylonitic rocks (Fig. 9). The detachment fault crops out as a smooth surface capping an indurated ledge of brown or gray cataclasite 1–2 mm thick. Gouge zones as much as 10 cm thick are locally present directly above the detachment surface where they formed at the expense of upper-plate rocks. Typical gouge is cohesionless powdery silt, and clay. Gouge formed from Precambrian granite locally contains residual faceted clasts of granite as much as ~10 cm in diameter. Despite overall structural thinning of the upper plate by internal extensional faulting, some Paleozoic units of the upper plate display mesoscale overturned folds vergent to the south or southwest, in the direction of relative tectonic transport of upper plate over lower plate, with axial surfaces inclined to the north or northeast.

The indurated cataclasite along the Catalina detachment surface was derived from mylonitic rocks of the lower plate and has a random internal fabric that ranges in detail from protocataclasite to ultracataclasite. The intensive superposed fracturing that formed the cataclasite was accompanied by hydrothermal alteration to produce thin yellow, green, and black seams of fine-grained limonite, chlorite-epidote, and pyrolusite, respectively. Residual feldspar porphyroclasts, derived from parent mylonitic rock and set in random orientations, are locally as large as ~5 mm in diameter in protocataclasite, but are more commonly <2 mm in diameter; those porphyroclasts within narrow bands of ultracataclasite are <0.5 mm in diameter. Relict mylonitic foliation and lin-
eation are also preserved locally within the cataclastic rocks.

Less intense cataclastic deformation disrupts mylonitic rocks for a structural thickness of ~25 m below the Catalina detachment fault. Approximately one-third of the distance (5–10 m) through the zone of more subdued cataclasis lies another discrete fault surface that we term the “subdetachment” fault (Fig. 9). Structurally above the sub detachment fault, cataclastic rocks tend to be relatively coarse grained, and their protoliths are discernible as mylonite or ultramylonite overprinted by cataclasis. Directly beneath the sub detachment fault, over a distance of several meters, disrupted rock is reduced to fine-grained cataclasite and ultracataclasite similar to the fault rocks lying directly beneath the Catalina detachment surface itself. Detachment and sub detachment faults were evidently twin loci of intense cataclasis during Catalina detachment fault displacements. As structures within the zone of cataclasis include discrete fault surfaces that interconnect to define extensional duplexes, the sub detachment fault may connect downdip with the main Catalina detachment surface as part of an anastomosing array of fault surfaces forming the detachment system.

The thickness of cataclasite lying structurally below the sub detachment fault varies along strike, but the base of cataclastic deformation is marked by a comparatively sharp transition, over distances of 2–3 m, to mylonitic rocks not overprinted by cataclasis. The base of the zone of cataclasis is sinuous in outcrop and undulose in down-plunge view (Fig. 10), normal to the fault-slip vector, to define a surface geometrically analogous to an undulating fault with millions and grooves. Structurally beneath the zone of cataclasis, quartzose mylonites containing local enclaves of protomylonite and bands of ultramylonite were derived, as elsewhere within the core complex (Dickinson, 1991; Force, 1997), from two main protoliths: (1) porphyritic granite of Precambrian Oracle type; (2) finer-grained and more voluminous, muscovite-bearing peraluminous granite of Eocene Wilderness type. The mylonitic rocks all display strong foliations and lineations distinguished by feldspar porphyroclasts in a foliated matrix of stretched quartz, biotite, muscovite, and finer-grained feldspar, the latter granulated by brittle fracturing. Protomylonites contain feldspar porphyroclasts up to 10 mm in diameter, but counterparts are <5 mm in diameter in mylonites and ultramylonites. Mesoscopic mineral lineation in the mylonites and ultramylonites plunges gently S50°W, and strongly oriented mica flakes associated with S-C fabrics, best developed in the mylonites derived from muscovite granite, record top-to-the south sense of shear. Within the interior of the Catalina-Rincon metamorphic core complex, mylonitic fabrics structurally below the zone of cataclasis give way downward in turn to nonmylonitic protoliths (Force, 1997), and small pockets of nonmylonitic rock are present within the Martinez Ranch study area where granitic rocks locally escaped mylonitic shear.

At the eastern extremity of the Martinez Ranch study area, the Catalina detachment system is offset downward below the ground surface by the Martinez Ranch fault. Deformed quartzite and marble in the upper plate of the detachment system are in sharp contact with fault breccia along the Basin and Range structure. Both mylonitic foliation in lower-plate rocks and bedding in upper-plate rocks are dragged into parallelism with the Martinez Ranch fault surface over a span of 25–50 m adjacent to the fault; observed dips range from 50° to 75° toward the fault.

Fault Interpretations

Structural features and geologic relationships at the Martinez Ranch study site are consistent with lateral displacement of the detached upper plate by 25–30 km across the Rincon Mountains (Dickinson, 1991). Deformation mechanisms within the detachment system ranged from ductile to brittle, reflecting the large-magnitude displacement accommodated along the Catalina brittle-ductile shear zone. The deepest levels of shearing are represented by mylonites and ultramylonites, whereas upper-pluge gouge zones reflect the shallowest levels of faulting and intermediate levels of faulting and brittle shear represented by cataclasites display fabrics that overprint mylonitic foliation and lineation. We interpret discrete fault surfaces—such as the sub detachment fault—within the zone of cataclasis to represent some of the youngest shear-zone ruptures that survived without overprinting by further cataclasis when movements along the Catalina detachment system ceased. Vertical displacements associated with lateral translation of upper-plate rocks placed middle Cenozoic basin fill against mid-crustal granitic basement. Mylonites and cataclasites were later carried farther toward the ground surface by Basin and Range Martinez Ranch faulting.

CORE-COMPLEX EVOLUTION

Combining our observations for post detachment phases of faulting in the Catalina-Rincon region with previous analyses of detachment faulting and associated mylonitic deformation allows appraisal of the contributions of successive episodes of extensional deformation to net core-complex evolution. Figure 11 shows schematically the inferred time vs. elevation path followed by mylonitic rocks of the Catalina-Rincon metamorphic core complex during late Oligocene to early Miocene detachment faulting and subsequent post-middle Miocene structural and erosional development.

Thermochronological analysis of isotopic and fission-track dating indicates an episode of rapid tectonic denudation, by an estimated 6–8 km (Spencer and Reynolds, 1989), during detachment faulting within the interval 28–20 Ma in Oligocene–Miocene time (Dickinson, 1991). Slower post-middle Miocene erosional exhumation, by 1.7–1.8 km, accompanied Basin and Range normal faulting (Davy et al.,
CENOZOIC FAULT AND FAULT-ROCK CHARACTERISTICS, SOUTHEASTERN ARIZONA

Figure 11. Summary diagram of incremental (left to right) exhumation and uplift of mylonitic rocks in Catalina-Rincon metamorphic core complex (see text discussions for controls on changing elevations of ground surface and burial depths of mylonitic rocks); sediment thickness in Tucson basin after Eberly and Stanley (1978) and Houser and Gettings (2000).

Following tectonic denudation of the core complex by Oligocene–Miocene detachment faulting (Fig. 11), we infer gradual reduction in the elevation of the local ground surface as erosion and resultant isostatic uplift of underlying rock masses proceeded during Miocene time (Fig. 11). Basin and Range faulting along the Pirate fault (Figs. 6, 11) offset mylonitic rocks that are structurally contiguous with bedrock of the Tortolita Mountains (Fig. 6) from the floor of the Oro Valley half graben to the crest of the Santa Catalina Mountains. The keel of the Oro Valley half graben is almost as deep structurally as the floor of the Tucson basin, which covers the downfaulted upper plate of the detachment system (Fig. 11).

From the curves of Egan (1992) for isostatic deformation adjacent to normal faults dipping 30°–60°, we infer ~1.25 km of flexural footwall uplift affecting the crest of the Santa Catalina Mountains adjacent to the Pirate fault (Fig. 11). Comparable footwall uplifts are observed along the flanks of grabens and half grabens of the East African rift sys-
tem (Ebinger et al., 1991). Flexural isostatic uplift may have been assisted by the buoyancy of a local crustal root beneath the Santa Catalina Mountains (Wallace et al., 1986; Holt et al., 1986; Myers and Beck, 1989). Flexural analysis implies that locales more than ~20 km from the Pirate fault (Fig. 6) would not be affected by flexural footwall uplift (Egan 1992). Accordingly, the broad topographic swale at Redington Pass occupies a synform with the ground surface at the same elevation as the Tortolita Mountains (Fig. 11). The topographic crests of the Santa Catalina and Rincon Mountains rise higher to either side because of flexural footwall uplift adjacent to the Pirate and Martinez Ranch faults, respectively (Fig. 6).

CONCLUSIONS

Our case studies shed light on the geometry of faulting and the deformational mechanisms associated with different phases of the incremental exhumation and uplift of mylonitic rocks now exposed in the Catalina-Rincon metamorphic core complex. Present elevations of high-standing mylonitic core rocks are not a function of detachment faulting alone, but stem in part from postdetachment normal faulting, flexural footwall uplifts associated with Basin and Range faults, and isostatic uplift during prolonged erosion. The present morphology of the core complex stems in part from detachment faulting, but also in part from the later effects of Basin and Range faulting after a change in the prevailing direction of crustal extension.

In general, older faults exhumed from greater depths are more gently inclined than younger faults formed at shallower levels. Strands of the middle Cenozoic detachment system, active at a reconstructed paleodepth of ~10 km at the Martinez Ranch study site, dip 20° or less. The postdetachment but pre–Basin and Range Manuel fault exposed at the Cottonwood Wash study site dips 25°–35°, although its dip was probably 60°–65° before domino-style tilting. Gravity modeling suggests that the Basin and Range Pirate fault at the Dead Hawk study site is a listric structure decreasing in dip from ~55° at the surface to ~25° at a depth of 2.5 km. The Basin and Range Martinez Ranch fault also dips ~55° where exposed along the eroded eastern face of the basement-cored Rincon Mountains, but steepens to ~70° at a shallower structural level farther south where it places Lower Cretaceous strata against Neogene basin fill (Dickinson, 1998b). The shallow-level Basin and Range faults exposed at the Cascabel locality dip in excess of 70°.

Changes in fault dip from steep to shallow thus reflect either greater depth of faulting or bulk rotation of fault surfaces through time. Tilt of stratigraphic sections in the hanging walls of the normal faults may occur either during translation along fault surfaces with listric curvature or through domino-style tilting, but observations at individual fault outcrops cannot distinguish between the two modes of behavior. The systematic correlation of fault dip with depth of faulting suggests that the upper plate of the Catalina detachment system was cut by supradetachment faults, now unexposed beneath basin fill of the Tucson basin or removed by erosion, which dipped as steeply as Basin and Range normal faults dip today. The geometry of postdetachment faulting suggests that such upper-plate faults, dipping steeply near the middle Cenozoic land surface, may have curved downward in listric fashion to merge with the master detachment surface or may have subsequently been rotated to shallower dips during continuing extensional deformation.

Footwalls were cumulatively uplifted to higher and higher structural levels during sequential episodes of extensional deformation (Fig. 11). The amounts of footwall uplift, relative to hanging walls, are reflected by (1) contrasts among sequentially overprinted fabrics in footwall rocks and (2) the degree of contrast between structures of the hanging-wall or upper plate and the footwall or lower plate. Fault-rock indicators of greatest net displacement are observed for the detachment fault bounding the Catalina-Rincon metamorphic core complex where contrasting footwall fabrics range from ultramylonites to ultracataclasites and where contrasting structures range from mylonitic shear zones in the footwall to gouge-lined faults in the upper plate. Significant but lesser translation by a combination of brittle shearing and faulting is recorded along major Basin and Range faults, notably the Pirate fault, where contrasting footwall fabrics range from cataclastic foliation in sheared protolith to mode I tensile fractures filled with cataclasite dikes. The contrasting structural regimes in contact at the Pirate fault range from thick breccia zones in the footwall to largely unfractured strata of a juxtaposed, growth-faulted sedimentary basin in the hanging wall. Similarly along the San Manuel fault, intensely fragmented footwall granite is in contact with only moderately jointed and disrupted hanging-wall strata. Insignificant translation by faulting is reflected by fabrics and structures along minor Basin and Range faults cutting the post–middle Miocene Quiburis Formation near Cascabel, with no evidence for superposed fabrics or structures in the footwalls, nor any contrast in structural style between footwalls and hanging walls.

We conclude that close attention to styles and degrees of deformation producing fault rocks of varying nature can aid in the recognition of relative amounts of vertical displacement across normal faults of different generations within an extensional domain. Fault systems with displacements insufficient to juxtapose rocks derived from different depth levels in the crust display congruent structures in their footwalls and hanging walls, whereas faults that displace rocks from deep regimes to shallow levels display contrasting structures in their footwalls and hanging walls.

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