

Field-trip guide to the Catalina-Rincon metamorphic core complex, Tucson, Arizona

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ABSTRACT

The Santa Catalina and Rincon Mountains north and east of Tucson, Arizona, form one of the largest core complexes on Earth. Both ranges consist primarily of Eocene leucogranites that intrude Proterozoic and late Cretaceous granitoids, and two Oligocene plutons. Mylonitic fabrics are well developed on the southern flank of the Santa Catalina Mountains and the southwestern flank of the Rincon Mountains. The corrugated form of the two ranges reflects the grooved form of the ca. 15–30 Ma Catalina–San Pedro detachment fault exposed primarily at the foot of the ranges. Normal displacement on two younger high-angle normal faults is responsible for much of the substantial relief of the ranges. This field guide is focused on fault rocks and mylonitic fabrics in the footwalls of the detachment fault and the high-angle Pirate normal fault, and includes description and analysis of shear-zone kinematics and processes, U-Pb geochronology of leucogranites, and core-complex geomorphology.

OVERVIEW OF THE CORE COMPLEX GEOLOGY OF THE SANTA CATALINA AND RINCON MOUNTAINS, SOUTHEASTERN ARIZONA

The Catalina-Rincon core complex, consisting of the contiguous Santa Catalina and Rincon Mountains, is one of the largest metamorphic core complexes on Earth. Core complexes are low-angle normal-fault footwalls characterized by a suite of features indicating tectonic exhumation from temperatures sufficient for mylonitization to conditions of brittle deformation. These features include the following, in order of development at outcrop scale: (1) penetrative, distributed mylonitic shearing, typically with strong lineation development, (2) narrow mylonitic shear-zone development, commonly with ultramylonites and

moderate to extreme grain-size reduction, at high structural levels (3) penetrative brecciation and chloritic alteration near the top of the mylonite zone, (4) local and variable development of ultracataclasite and rare pseudotachylite, and (5) brittle faulting and fault-gouge genesis within a discrete detachment fault zone, commonly with iron-oxide precipitation in fractures and small faults (e.g., Davis, 1980; Davis et al., 1986). In addition, somewhat older pegmatitic leucogranites are common in detachment-fault footwalls in Cordilleran core complexes. Most likely they are unrelated to younger extensional exhumation but reflect melting in overthickened crust during a period of low-angle subduction and lower crustal hydration (e.g., Keith, 1986; Fornash et al., 2013).

The Catalina detachment fault at the southern foot of the Santa Catalina Mountains continues southeastward along the

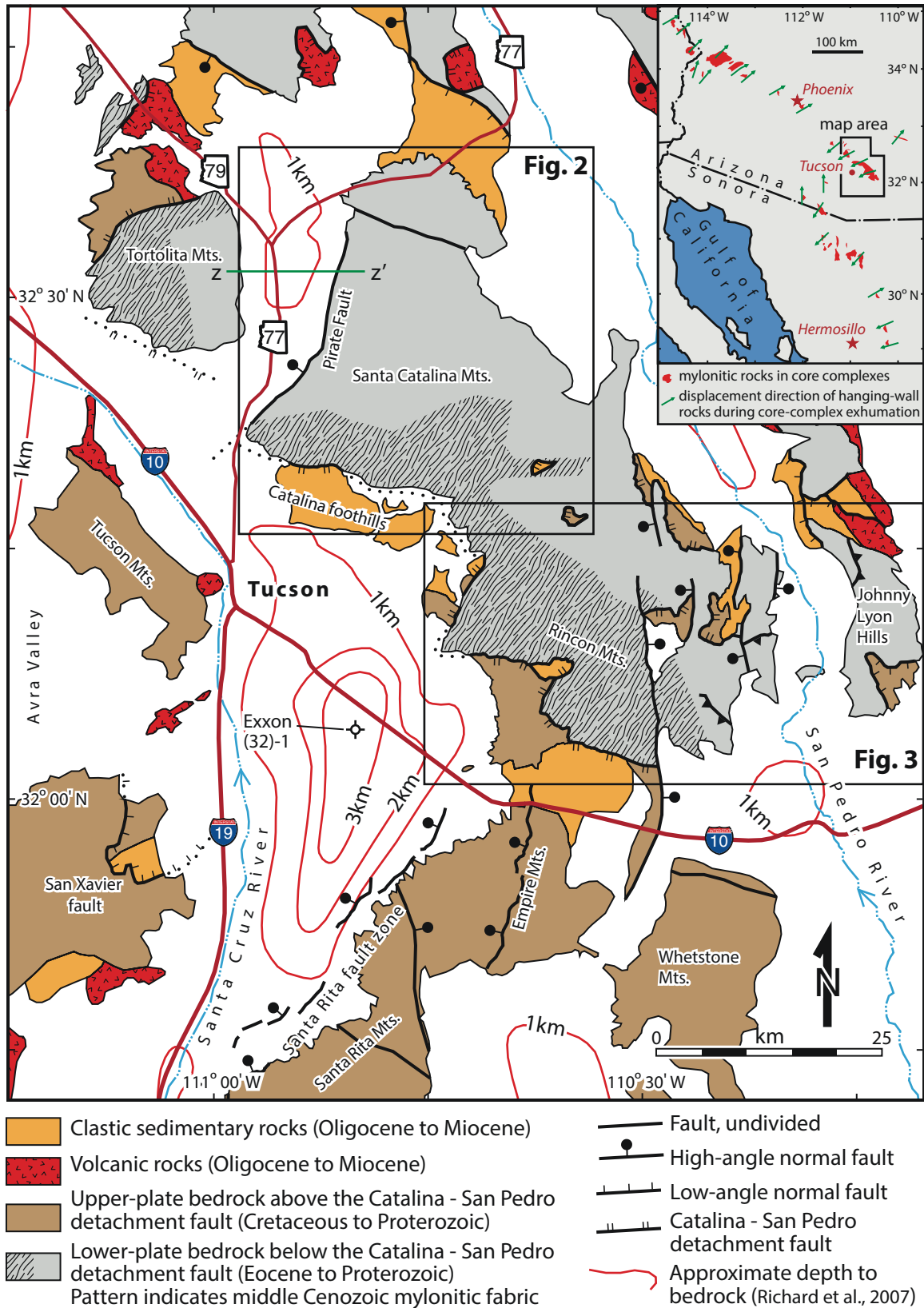


Figure 1. Simplified geologic map of the Catalina-Rincon core complex and surrounding regions. The Guild Wash fault in the northern Tortolita Mountains and nearby detachment faults are shown as segments of the Catalina-San Pedro detachment fault, but details of correlation are not well constrained. Modified from Richard et al. (2000).

western foot of the Rincon Mountains. It has been correlated with the San Pedro detachment fault in the eastern Rincon Mountains (Lingrey, 1982) as both form the upper bounding surface to core-complex rocks and structures (Dickinson, 1991). The two faults are considered correlative and the combined fault is referred to here as the “Catalina–San Pedro detachment fault” although it is still commonly referred to as the “Catalina fault” in the areas visited during this field trip (Fig. 1). The exceptional exposures of core-complex rocks in the Santa Catalina and Rincon Mountains are partly the result of younger high-angle normal faulting that uplifted the complex (Davis et al., 2004). Many core-complex features will be viewed and discussed in the course of this field trip, which is concerned primarily with rocks in the footwall of the Catalina–San Pedro detachment fault (see Table 1 for coordinates of field stops).

Historical Background

By the 1970s, a long history of studies of gneissic and high-grade metamorphic rocks in orogenic belts had generally concluded that such rocks were displaced from middle to lower crustal depths by thrust faulting and folding. Beginning in the 1970s, many field and geochronologic investigations recognized a recurring and previously undocumented set of geologic features that led to the interpretation that metamorphic core complexes contain rocks that were exhumed during severe extension (Crittenden et al., 1980). The term “metamorphic core complex,” originally coined by University of Arizona Professor Peter Coney to apply to metamorphic complexes in the core of the Cordilleran orogen, morphed into a term representing a characteristic suite of rocks and structures at the scale of individual mountain ranges that were interpreted as extensional in origin. Trip leader George

Davis, along with Peter Coney and Max Crittenden, were the conveners of the Geological Society of America Penrose Conference “Cordilleran metamorphic core complexes,” held in 1977 in Tucson (Crittenden et al., 1980). The term “metamorphic core complex” entered the geologist’s lexicon at this time, albeit with much controversy surrounding associated interpretations. By the mid-1980s, the geologic community was converging on a consensus that core complexes originated by tectonic exhumation (Davis, 2008). Shear-sense determinations from mylonitic rocks, including those in the Tucson area, played a significant role in bringing about this consensus view, as did geochronologic investigations that revealed youthful cooling histories and mylonitized middle Cenozoic igneous rocks. Since then, core complexes have been identified in many parts of Europe and Asia, the southwestern Pacific Rim, in the deep ocean where they are associated with plate divergence at moderate to slow rates, and probably on Venus. The Catalina core complex played an important role in the recognition of what have turned out to be widespread tectonic features.

Santa Catalina Mountains

In their most general form, the Santa Catalina Mountains consist of a single northeast-tilted fault block, with gneissic middle crust exposed on their southern flank. Mesoproterozoic to Cretaceous strata tilted northeastward on the northeast side of the range rest on ca. 1.4 Ga Oracle Granite and ca. 1.7 Ga Pinal Schist (Fig. 2). Two Laramide intrusions (ca. 70 Ma) and the 25.8 Ma Catalina granite intrude these units (Banks, 1976; Force, 1997; Bykerk-Kauffman, 2008; Fornash et al., 2013). Abundant Eocene pegmatitic leucogranites (ca. 45–57 Ma), many forming northeastward-dipping sills and lenses, also intrude Laramide and older rocks south of the range crest. Eocene leucogranites,

TABLE 1. COORDINATES OF FIELD STOPS

Stop	Feature	Latitude	Longitude
Stop 1	Dead Hawk Gulch	32.554240°	–110.847033°
Stop 2A	Tanque Verde Falls—parking lot	32.254364°	–110.664795°
Stop 2B	Tanque Verde Falls—subdetachment fault view	32.252278°	–110.662689°
Stop 2C	Tanque Verde Falls—subdetachment fault up close	32.251984°	–110.662793°
Stop 2D	Tanque Verde Falls—shear-sense indicators	32.251541°	–110.664517°
Stop 3	Babad Do’ag	32.309488°	–110.721114°
Stop 4	Toll booth	32.333053°	–110.695029°
Stop 5	Prison camp	32.336808°	–110.719432°
Stop 6	General Hitchcock campground	32.376872°	–110.686428°
Stop 7	Windy Point	32.368520°	–110.716837°
Stop 8	Geology Vista	32.370604°	–110.711268°
Stop 9	Cactus Forest, Saguaro National Park	32.183653°	–110.708488°
Stop 10	Javelina picnic area, Saguaro National Park	32.165774°	–110.723616°
Stop 11	Visitor Center, Saguaro National Park	32.180163°	–110.736265°
Stop 12	Cataclasite, Saguaro National Park	32.151204°	–110.733137°
Stop 13	Overturned Jurassic conglomerate, Saguaro National Park	32.135244°	–110.685061°
Stop 14	Natural history, Saguaro National Park	32.134460°	–110.685933°

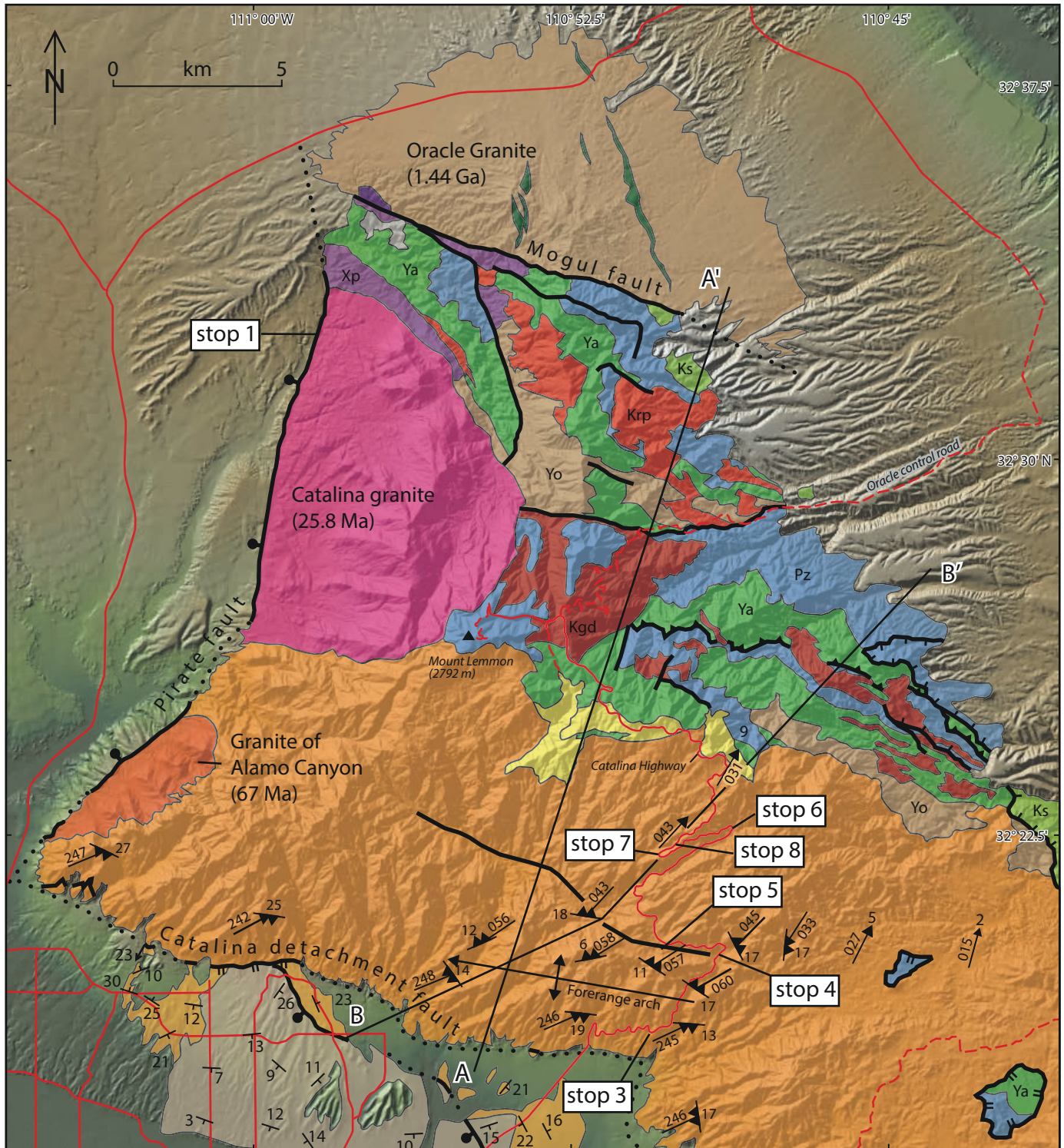


Figure 2. Simplified geologic map and cross sections of the Santa Catalina Mountains, southeastern Arizona. Data sources include Banks (1976), Creasey and Theodore (1975), Force (1997), Dickinson (1999), Spencer et al., (2000); Spencer and Pearthree (2004), Spencer (2006), Bykerk-Kauffman (2008), and Fornash et al. (2013). (Continued on facing page.)

Geologic map and cross sections of the Santa Catalina Mountains, southeastern Arizona

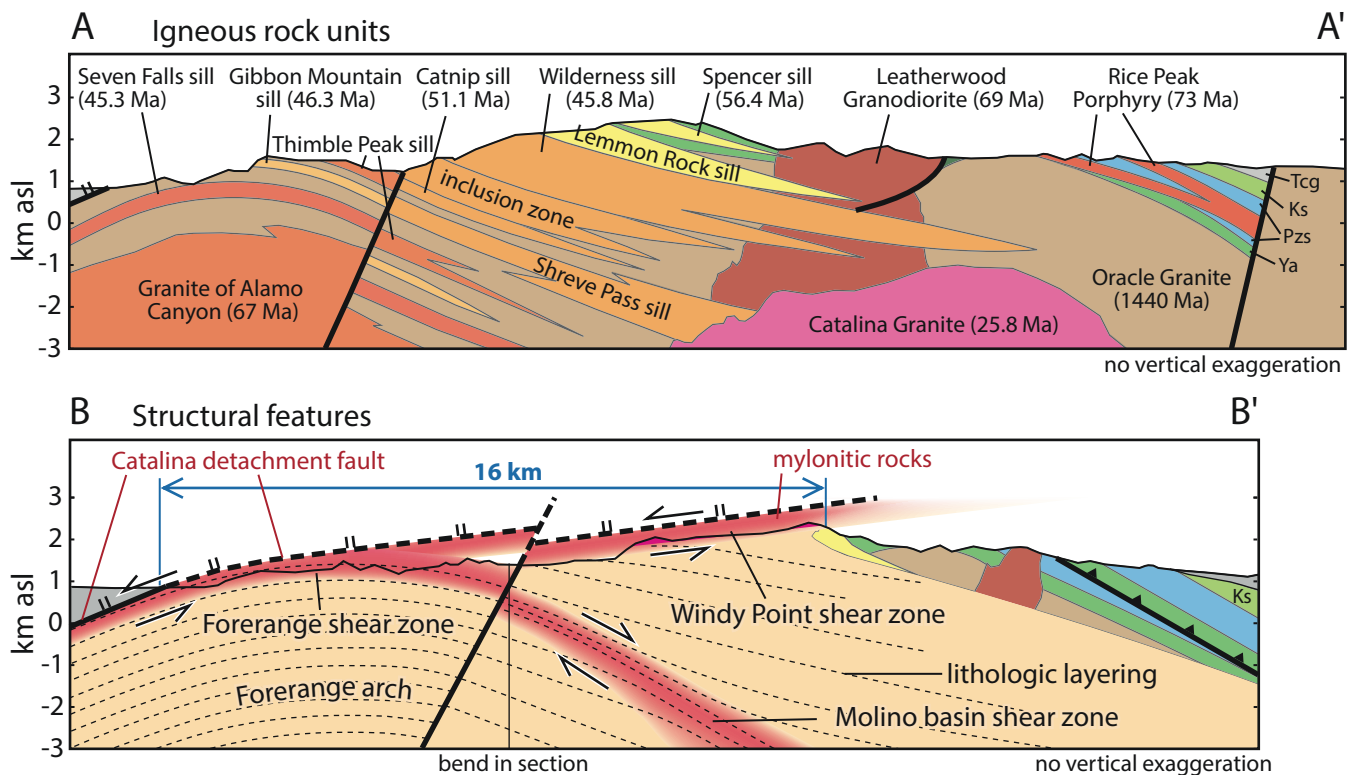
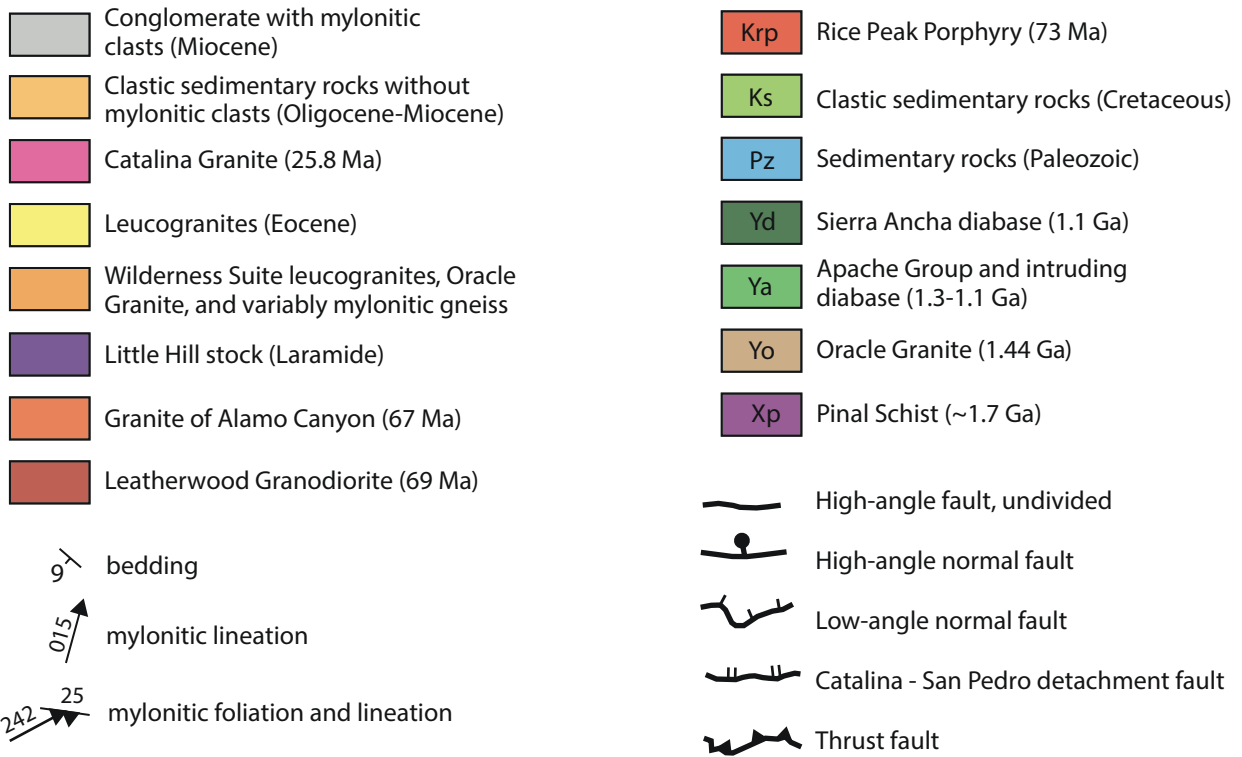


Figure 2 (continued).

along with abundant screens of Oracle Granite between leucogranite intrusions, form almost all the southern half of the range (Banks, 1980; Keith et al., 1980; Force, 1997). Neodymium and hafnium isotope analyses indicate that Eocene peraluminous granites were derived almost entirely from Oracle Granite and its possibly more mafic, deeper equivalents (Fornash et al., 2013).

Well-developed mylonitic foliation on the south flank of the range dips southward and is characterized by pervasive, southwest-plunging lineation and top-southwest shear-sense indicators. Mylonitic fabrics form the 280°-trending, forerange arch (Fig. 2), with common top-northeast shear-sense indicators on the north limb of the arch (Naruk and Bykerk-Kauffman, 1990; Spencer, 2006). This relationship is interpreted to indicate that the arch represents two normal-sense shear zones in which the north-dipping shear zone was truncated and, at high structural levels, transposed southwestward into parallelism with the south-dipping shear zone (Spencer, 2006). The Catalina detachment fault at the south foot of the range, exposed only locally on private property, displaces reddish sandstone and conglomerate of the Oligocene to lower Miocene Pantano Formation and overlying tan conglomerate containing mylonitic debris (Dickinson, 1999). Lack of mylonitic clasts in the Pantano Formation is interpreted to indicate that mylonitic rocks had not yet been exhumed at the time of deposition (Dickinson, 1999). Late Cenozoic normal displacement on the Pirate fault at the western foot of the range (Fig. 2) elevated the western Santa Catalina Mountains and down-dropped Oro Valley. Approximately 4 km of vertical offset was determined from gravity data and the modern elevation of the range crest (Davis et al., 2004).

Rincon Mountains

The geomorphology of the Rincon Mountains is dominated by the corrugated form of the slightly to moderately eroded footwall of the Catalina–San Pedro detachment fault (Pain, 1985). The highest point in the range, Mica Mountain, is on the crest of one of the largest core-complex antiformal corrugations on Earth (Fig. 3). Furthermore, the antiform itself is arched about a perpendicular axis so that corrugation axes plunge outward and the range forms a corrugated dome. Footwall rocks consist primarily of Proterozoic granitoids, Pinal Schist, and abundant Eocene pegmatitic leucogranite (e.g., Drewes, 1974, 1977). A ca. 27 Ma granitoid forms part of the footwall in the southeastern part of the range. Footwall mylonitic foliation parallels the corrugated form of the detachment fault footwall and lineation parallels the corrugation axes. Lineation trends more southerly with increasing westward distance, suggesting a slightly curved displacement path (Spencer et al., 2019). A suite of rocks indicating deformation and hydrothermal alteration under progressively cooler conditions is well exposed around the western foot of the Rincon Mountains (Davis, 1987, 2013).

Rocks above the Catalina–San Pedro detachment fault are diverse. In Rincon Valley on the west side of the range these include the 1.65 Ga Johnny Lyon granodiorite thrust over over-

turned strata of the Upper Jurassic to middle Cretaceous Bisbee Group (Fig. 3). These rocks are essentially identical to similarly juxtaposed rocks in the footwall of the detachment fault in the northwestern Johnny Lyon Hills, 40 km to the east (Figs. 1, 3). This relationship is interpreted to indicate 35–40 km of top-west detachment-fault displacement, consistent with mylonitic lineations and shear sense (Spencer et al., 2019).

Extension began before deposition of a 26.4 Ma tuff near the base of the extensional Cienega basin at the south foot of the Rincon Mountains (Fig. 3; Peters et al., 2003). Illite from fault gouge and adjacent cataclasite from the Catalina–San Pedro detachment-fault zone in the western Rincon Mountains yielded conventional K-Ar dates from four samples that are all ca. 21 Ma (Damon and Shafiqullah, 2006), suggesting that detachment faulting and cooling during exhumation were under way at this time. Detachment faulting likely ended in the middle Miocene and was followed by displacement on younger high-angle normal faults that contributed significantly to uplift of the modern ranges (Davis et al., 2004).

FIELD STOPS

Coordinates for all stops are in Table 1.

Stop 1. Pirate Fault

Stop 1. Geologic Setting

The focus of Stop 1 is the Pirate fault, a west-dipping Basin and Range normal fault that defines the western flank of the Santa Catalina Mountains (see Fig. 2) (Davis et al., 2004). Offset along the Pirate fault is largely responsible for spectacular scarp-like topographic expression (Fig. 4) of the western Catalinas as viewed from the west. Greatest topographic relief of the steep west face is ~2000 m, as measured from the Mt. Lemmon summit (2800 m) to the Canada del Oro drainage (800 m). The Pirate fault juxtaposes crystalline bedrock on the east with syntectonic Neogene basin-fill strata on the west. Crystalline bedrock in the footwall includes Paleoproterozoic Pinal Schist, Cretaceous Granite of Alamo Canyon, Paleogene peraluminous granite (ca. 45–50 Ma), and Oligocene Catalina Granite (ca. 26 Ma) (Keith et al., 1980; Dickinson, 1994; Spencer and Pearthree, 2004; Hoxie, 2012). The Miocene-Pliocene basin-fill strata are composed of debris derived from the relatively upthrown (footwall) block. Dickinson (1994) concluded that the syntectonic basin-fill sediments were deposited primarily between 12 and 6 Ma. These strata occupy the Oro Valley half graben, which lies between the Tortolita Mountains on the west and the Catalina Mountains on the east (see Fig. 1). From 6 Ma into the Pleistocene, coalescing alluvial fans developed along the lower west flank of the Catalinas, creating the upper gently dipping aggradational surface that can be seen today. This geomorphic surface, the Cordones surface, is Pleistocene (McFadden, 1981). The Cordones surface and braidfan deposits beneath are dissected by the Cañada del Oro drainage system (Spencer et al., 2000). Exposure of the

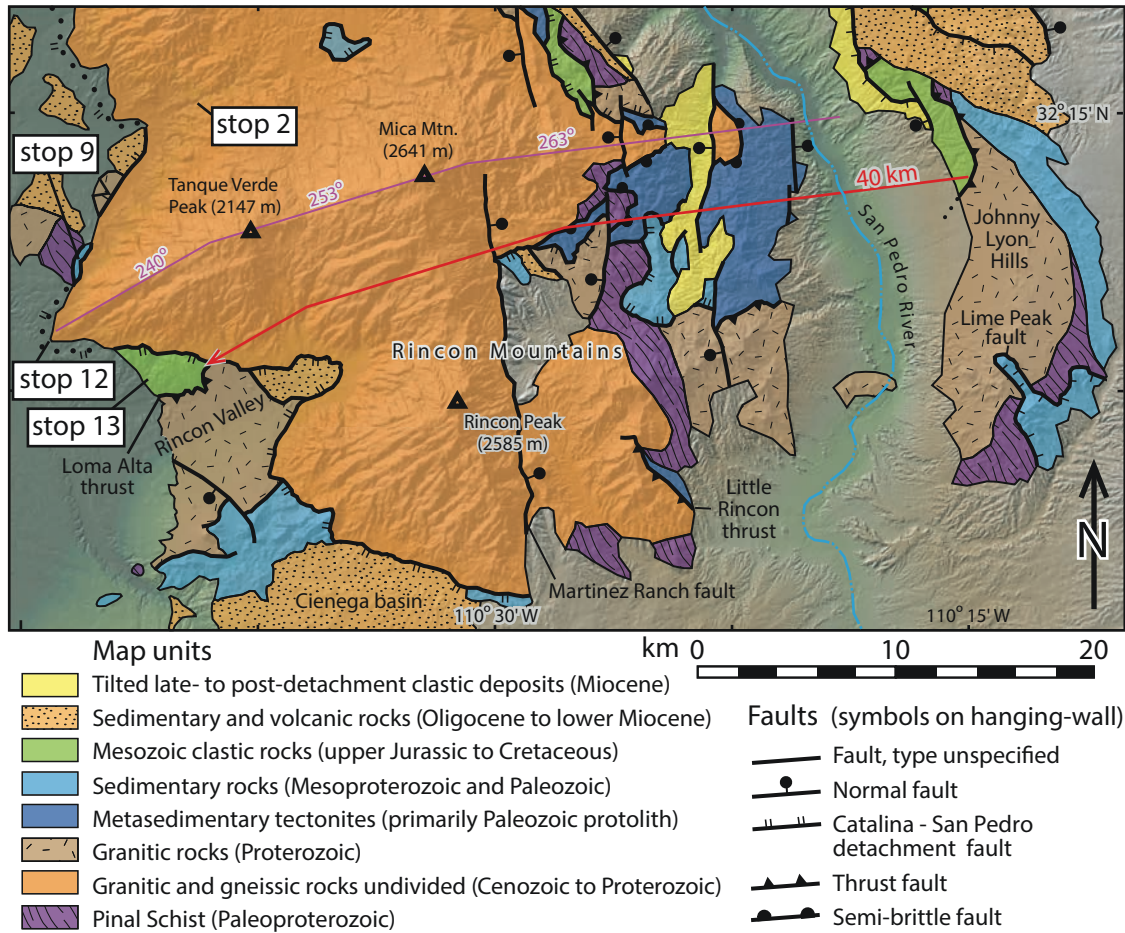


Figure 3. Simplified geologic map of the Rincon Mountains and Johnny Lyon Hills. Sources of map data include Cooper and Silver (1964), Drewes (1974, 1977), Richard et al. (2005), Spencer et al. (2009a, 2009b, 2011). See Figure 25 for locations of Stops 9–14.



Figure 4. South-southwest-directed oblique photograph of the western flank of the southern Catalina Mountains. Dissected Neogene alluvial fan deposits are on far right. (Photograph courtesy of Peter Kresan.)

Pirate fault along the Cañada del Oro is due to incision of the Cañada del Oro, which removed sufficient Neogene basin fill and Pleistocene fan deposits to expose the fault surface and its impressive footwall damage. The Dead Hawk Gulch locality, our Stop 1 destination, is one of the very few deep exposures of Basin and Range faulting in southeastern Arizona.

Stop 1A. Access

The SaddleBrooke Active Adult Community extended permission to access Stop 1. From the junction of State Highways 77 and 79 (Oracle Junction; see Fig. 1 overview map), take Arizona Route 77 south-southeastward, passing between the Tortolita Mountains on the west and the Catalina Mountains on the east. To access exposures of the Pirate fault, take SaddleBrooke Boulevard east toward the SaddleBrooke community, and drive upgrade through the syntectonic Neogene basin fill, which is replete with granitic detritus. At the crest of the dissected plateau, look north and south to appreciate the elevation and character of the Cordones surface. From this crest, descend toward the heart of the community, but before reaching it turn north and circle the perimeter clockwise, eventually parking on a bluff above the Cañada del Oro.

Stop 1A. Parking Area on Bluff above Cañada del Oro

From the parking area on the bluff, look down (eastward) into the Cañada del Oro. The Pirate fault is evident on the east side of the Cañada del Oro, expressed as a resistant, dissected fault-line scarp composed of highly cohesive fault breccia (Fig. 5). The height of the fault-line scarp ranges up to 17 m. The cohesive breccia is rose colored, tinged with abundant yellow lichen. The landscape to the east beyond the scarp is a pediment surface

that has been cut into the 26 Ma Catalina Granite. Far to the east, the approximate position of the eastern edge of the pediment surface is located where the Catalina Mountains rise abruptly from that position.

The mouth of Dead Hawk Wash can be seen from our vantage. Dead Hawk Wash cuts transversely through the scarp exposing the cohesive-breccia damage zone as well as the non-cohesive breccia zone that extends fully 300 m from the fault-line scarp. We can appreciate the breadth of the full footwall-damage zone by spotting where the tor-like granitic terrain, which is underlain by undamaged Catalina Granite, is weathered in a way to produce large rounded granite “boulders.”

Before heading down into Dead Hawk Wash, it is useful to examine Figure 6, a geological map of the area (Davis et al., 2004). Note the map location of Dead Hawk Wash in relation to the Cordones surface, the Cañada del Oro, and the fuller length of the trace of the Pirate fault in this subregion. The overall north-south trace of the Pirate fault is consistent with the east-west-oriented Basin and Range extension that prevailed in southern Arizona during the life of this fault when it was active. (This contrasts with the 60°/240° Oligocene to early Miocene extension direction). From north to south (see Fig. 6), the Pirate fault cuts Mesoproterozoic Apache Group, Paleoproterozoic Pinal Schist, Oligocene Catalina Granite, Paleogene Wilderness Suite granite, Cretaceous Granite of Alamo Canyon, and more Wilderness Suite granite (Spencer et al., 2000; Spencer and Pearthree, 2004). It dips westward from 50° to 68°.

Stop 1B. Dead Hawk Wash

The Pirate fault surface exposed at the Dead Hawk Wash locality dips 50°–54°W and separates damaged Catalina Granite



Figure 5. East-directed view into the Cañada del Oro and the distinctive fault-line scarp supported by the cohesive breccia sheet in the immediate footwall of the Pirate fault. (Photograph by George H. Davis.)

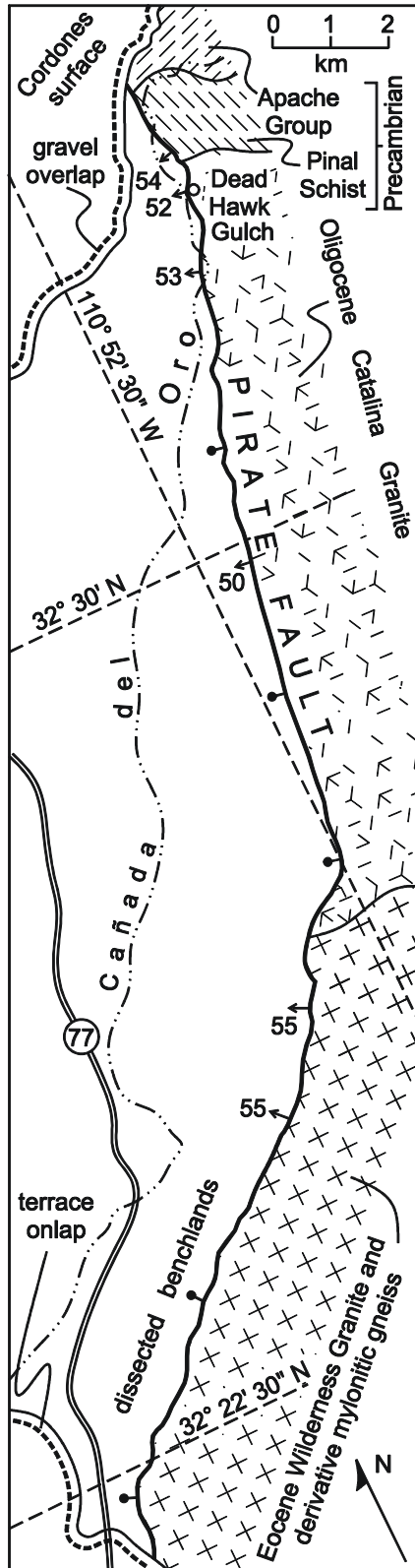


Figure 6. Geologic map of the Pirate fault. Based on Dickinson (1994). (From Davis et al., 2004, fig. 3, p. 132). Stop 1 is at Dead Hawk Gulch.

in the footwall and Neogene basin fill in the hanging wall (Fig. 7A) (Davis et al., 2004). Hanging-wall Neogene basin fill is very poorly exposed and will not be part of our inquiry. The fault surface proper is marked by fault polish and slickenlines, and the surface is mullioned as well (Fig. 7B) (Davis et al., 2004). Slickenlines (and mullions) are for the most part dip-slip in orientation, though in places there is clear expression of oblique-slip motion. Slickenlines on the fault surface occur in splotchy patches, and it appears as if most of the slickenlines occur on Riedel (R) surfaces that dip more steeply than the fault surface itself. In places there are clear fault-surface expressions of originally brecciated but now cataclastically rounded “clasts” of granite embedded in reddish fine-grained crushed and comminuted matrix rich in quartz and hematite (Fig. 7C). Cut slabs of the cohesive breccia reveals gradations of recognizable Catalina Granite cut by faults and fractures, to highly sheared quartz-feldspar-hematite crush rock (Fig. 7D). At microscopic scale, some of the finest-grained cohesive breccias are seen to be foliated, though there is no evidence of crystal-plastic deformation of feldspar or quartz. We think of this fabric and foliation as produced by semi-brittle deformation mechanisms (Fig. 7E) (Davis et al., 2004).

The maximum overall thickness of the cohesive breccia is ~15 m, but the damage zone persists for an additional ~285 m eastward (see Fig. 7A). For half of that damage breadth, the Catalina Granite is pervasively damaged by cataclasite-filled fractures as well as some semi-brittle shear foliation. Farther eastward (see Fig. 7A) the cataclasite-filled fracture systems are more moderately developed, and near the contact of the damage zone with pristine Catalina Granite there is a simple fracture gridwork of the type described by Stewart and Hancock (1994). These are essentially meter-spaced orthogonal mode-1 joints with cataclasite fracture filling. The two joint sets are parallel and perpendicular to the trace of the Pirate fault.

Davis et al. (1998) interpreted the creation of the overall damage zone as the result of upward migration of the tip line of the Pirate fault, above and beyond which there was a leading-edge process zone that caused in situ, closely spaced fracturing of the host granite. The development of the fracture system was enhanced by elevated fluid pressure. This is evident in ubiquitous, pervasive veins of quartz-hematite-rich cataclastic fracture fillings (Fig. 8). Process-zone fracturing set the stage for pervasive brecciation as the fault tip passed into and through the earlier-formed fracture zone. Over time, the zone of damage narrowed such that late stages of Pirate fault semi-brittle to brittle shearing became concentrated in what is now the “compact breccia sheet” (see Fig. 7A). Fluid pressure continued to enhance faulting and brecciation, with syn-faulting precipitation of the hematite and quartz, which is responsible for the elevated resistance to erosion of the fault-line scarp zone.

Return to Stop 1A

Davis et al. (2004) reached the conclusion that total throw accommodated by the Pirate fault zone was ~4.5 km. This estimate is based on a Bouguer gravity profile across the Neogene

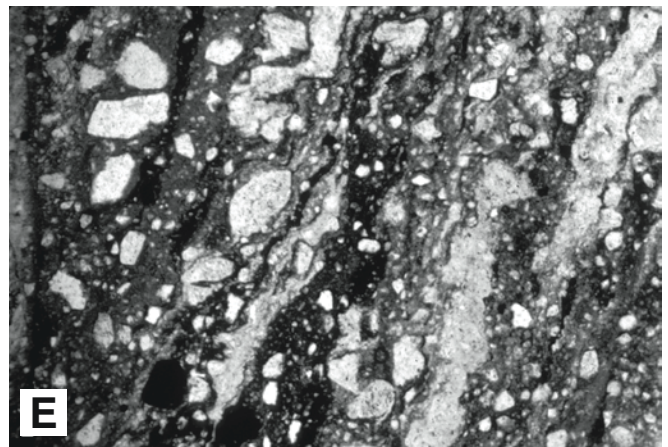
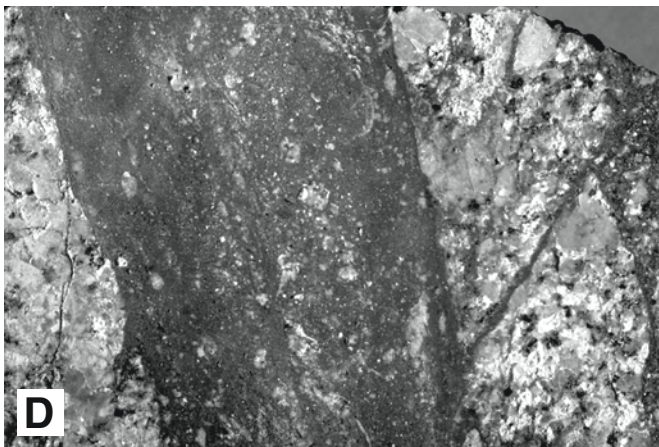
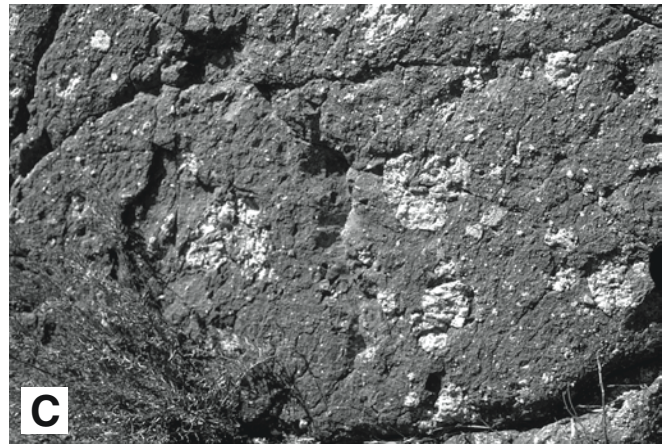
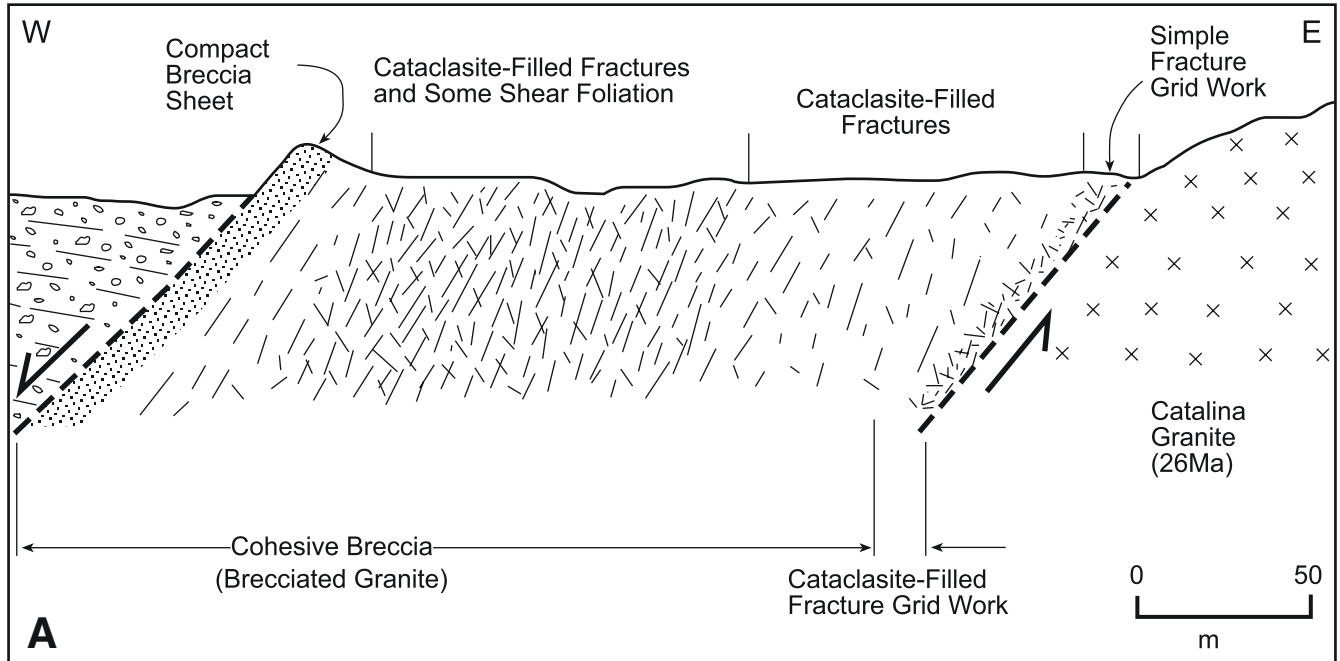


Figure 7. Pirate fault zone at Dead Hawk Gulch. (A) Line drawing of fault-zone features exposed in stream transect normal to fault trace. (B) Mullioned fault surface. (C) Close-up of fault surface showing cataclasite with light-colored clasts of Catalina Granite 5–10 cm across that forms a compact breccia sheet. Field of view is ~0.5 m wide. (D) Close-up of cut slab showing cataclasite dike intruding fractured granite of cohesive breccia zone. Field of view ~5 cm wide. (E) Photomicrograph of foliated cataclastic fabric in sheared granite (comminuted white fragments). Field of view ~5 mm wide. (From Davis et al., 2004, fig. 4, p. 133).



Figure 8. Outcrop photograph of cataclasite-filled fractures in the damage zone of the Pirate fault. (Photograph by George H. Davis.)

Oro Valley half-graben separating the Pirate fault from the Tortolita Mountains to the west (Budden, 1975; see Fig. 1). Davis et al. (2004) reevaluated the fault-throw implications of these data by applying a revised estimate for the density of basin-fill sediments and a Pirate fault dip as measured at Dead Hawk Wash (Fig. 9). Revision of the density values was informed by subsurface densities based on well logs. The Bouguer anomaly associated with the Oro Valley half graben was determined to be ~ 14 mgal. Davis et al. (2004) concluded that the Pirate fault is listric, decreasing in dip from $\sim 55^\circ$ at the Dead Hawk Wash location to a dip of $\sim 25^\circ$ at a depth of 2500 km below the ground. The dip-slip displacement was determined to be 4.4 km, including ~ 1.25 km of flexural footwall isostatic uplift as the footwall became unloaded. In fact, within the pristine Catalina Granite to the east of the Pirate

fault damage zone there is evidence of load relief in the form of exfoliation jointing.

Stop 1. Conclusion

The throw magnitude for the Pirate fault aids in understanding how mylonites formed at burial depths of 8–12 km in Oligocene–Miocene time would be exposed at the surface today. Part of the path to exhumation was 6–8 km of uplift from 28 to 20 Ma, inferred by Spencer and Reynolds (1989) based on isotopic and fission-track dating. Based on arguments presented in Davis et al. (2004), the surface elevation of southern Arizona before extension was ~ 2.5 km. Following extensional stretching, there was some gradual reduction of elevation of the ground surface, but uplift and exposure of Catalina core complex mylonites was augmented by displacement on the Pirate fault.

Stop 2. Tanque Verde Falls

Stop 2A. Access

Lower Tanque Verde Falls can be reached by driving east on East Tanque Verde Road to North Wentworth Road, where East Tanque Verde Road becomes Redington Road, eventually passing between the Catalina Mountains (to the north) and the Rincon Mountains (to the south). The Tanque Verde Falls trailhead lies less than 1 km east of where East Redington Pass Road crosses into the Coronado National Forest. There is a parking area on the north side of the road, opposite the trailhead proper (Fig. 10). Below in the wash are exquisite exposures of lower-plate mylonites, cataclasites, and mini-detachment faults. Note that flash floods are possible in the canyon and in fact have caused multiple fatalities, including 8 from a single event in July 1981. Part of the danger results from the fact that thunderstorms can quickly deliver a lot of water to upstream areas without any

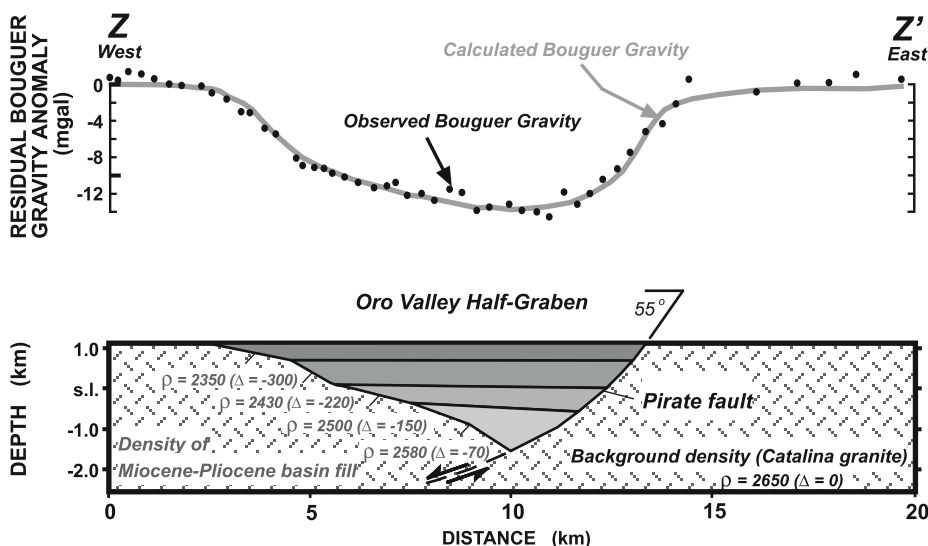


Figure 9. Interpretation of Pirate fault geometry and displacement based on gravity modeling of Oro Valley basin fill. Shadings in Oro Valley basin fill denote different model densities (ρ) and density contrasts (Δ) between basin fill and bedrock. Location of profile (z – z') is shown on Figure 1. (From Davis et al., 2004, fig. 5, p. 134.)

precipitation at Tanque Verde Falls, leaving people unaware of approaching floodwaters.

Stop 2A. Tanque Verde Falls Trailhead

We are positioned between the Catalina Mountains to the north-northwest and the Rincon Mountains to the south-southeast (see Fig. 3). The summits of the Catalina Mountains and the Rincon Mountains are Mt. Lemmon and Mica Mountain, respectively. The structural position is in lower-plate mylonites beneath the Catalina detachment fault. The structural form of the mylonite layering and the Catalina fault here is broadly synformal. The trough of the synform is expressed topographically as Redington Pass. The hinge line of this macro-synform plunges less than 15° southwest (240°), parallel to the plunge of Tanque Verde antiform, which is the adjacent macro-structure in the Rincon Mountains (see Figs. 1 and 3).

The typical outcrop character of crystalline rocks over much of the Catalina and Rincon Mountains reveals profound crystal-plastic deformation in the form of low-dipping mylonitic and ultramylonitic fabrics, penetrative shallow-plunging mineral lineation in the “plane” of foliation, and compositional banding marked by leucogranite layers. Steeply dipping jointing is

always present and tends to be organized into two dominant sets, one subperpendicular and one subparallel to lineation. However, where mylonites crop out in relatively close proximity (typically up to ~ 0.5 km) to the Catalina detachment fault, such as here at Stop 2, cataclastic fabrics overprint the mylonite, either pervasively over volumes that may be thicker than 100 m, or along more localized semi-brittle shear zones. Also, there are mini-subdetachment faults marked by observed trace lengths of tens of meters and distinguished commonly by fissure-like subhorizontal weathered reentrants. The mini-subdetachment faults are typically very low-dipping extensional faults subparallel to the mylonite fabric(s), but where they listrically curve upward, they are seen to truncate mylonitic layering discordantly, displaying normal offsets. It is this interplay among mini-subdetachment faulting, mylonitic fabrics, and cataclastic fabrics that makes the Tanque Verde Falls area such a valuable natural laboratory.

The mylonite that crops out in the Tanque Verde Falls area is largely derived from a Mesoproterozoic (ca. 1.4 Ga) protolith, namely Oracle Granite, a porphyritic quartz monzonite originally containing large feldspar phenocrysts (up to 8 cm). The bedrock at Stop 2 also contains leucocratic sill-like compositional layers, which are also mylonitic. These leucocratic layers are thought

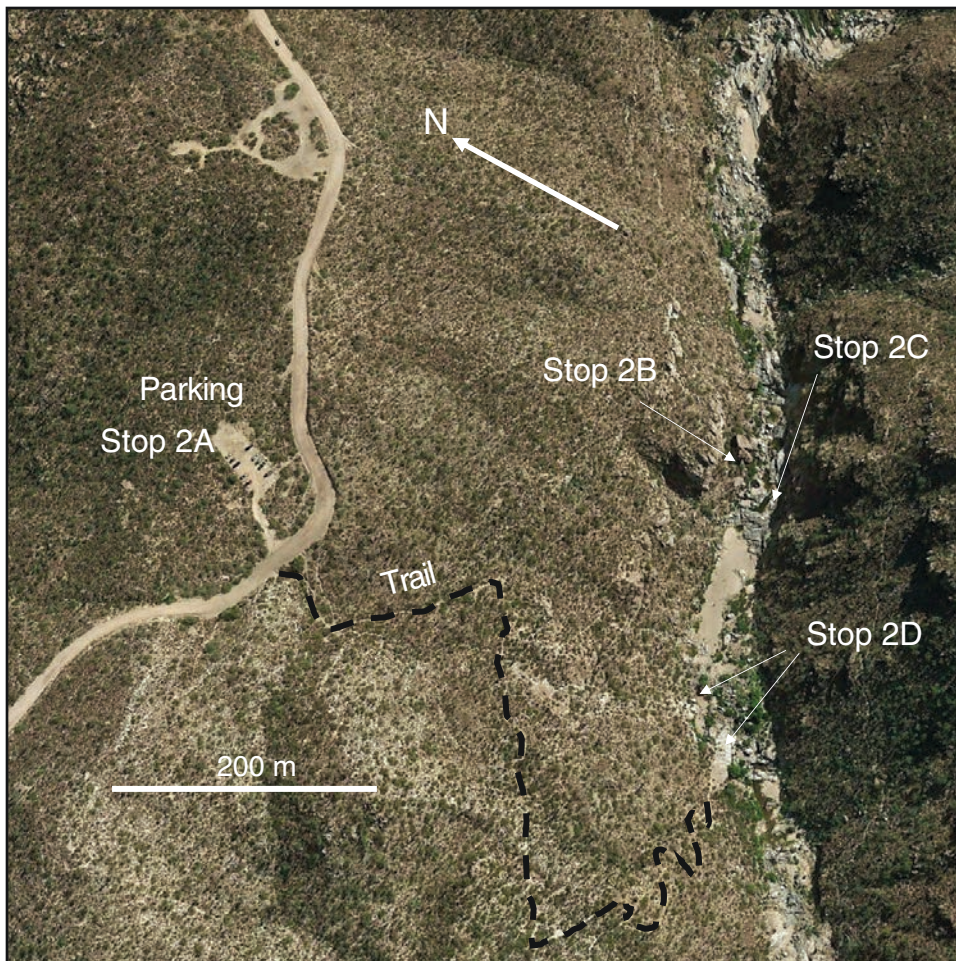


Figure 10. Aerial image of the Stop 2 area, from Google Earth Pro. The dirt road is Redington Road. The canyon wash is Tanque Verde Wash at the Tanque Verde Falls locality. The trail provides access to excellent exposures.



Figure 11. South-directed panoramic image of lower part of north-facing canyon wall adjacent to Tanque Verde Wash. The exposures comprise the Stop 2C locale. (Photograph by G.H. Davis.)

to be derived from a Paleogene anatectic-granite emplacement history (Fornash et al., 2013). The crystal-plastic fabrics now evident in O-mylonite and the leucocratic mylonites were developed through shearing in the late Paleogene to early Neogene. In lower-plate proximity to the Catalina detachment fault, later-stage progressive deformation from ductile to brittle shearing transformed mylonite into cataclasite and ultracataclasite.

Stop 2B. Initial Viewing Area of Subdetachment Faulting

From this location there is an excellent vantage to observe the interplay of subdetachment faulting and mylonitic foliation and compositional banding. Figure 11 is a panoramic display of the north-northwest-facing lower canyon wall, revealing a major continuous flat subdetachment fault as well as apparently lesser and more steeply inclined subdetachment faults that converge into it. We encourage participants to map faults and compositional layering as seen in the supplemental 11" × 17" version of Figure 11, a cross-sectional view of the structural associations¹. Consider capturing on this profile the traces of subdetachment faults, the apparent dips of compositional mylonitic layering, and the trace and orientation of the main subdetachment fault. Where possible, show offset along the faults, and plot sense-of-displacement. Mapping these features from the vantage of Stop 2B can serve as context for then crossing to the opposite side of the wash and examining the outcrops in closer detail.

Stop 2C. Examining the Subdetachment Faulting in Close Detail

There is much to see in the way of brittle to semi-brittle fault properties, fault offsets, and fault-slip indicators along this topographic bench, which coincides closely with the trace of the main continuous subdetachment fault. Fault offsets are obvious because of compositional layering within the O-mylonite and associated leucocratic mylonite. Slip directions on some of these faults can be determined through slickenlines. Compositional layering is generally inclined, presumably back-rotated from an

original gentle westerly dip inclination, and this inference raises the question as to whether the faults have also been back-rotated. Among the many interesting features along the main subdetachment fault is a special sense-of-shear indicator in the form of a 0.5-m-scale releasing bend.

This location also provides an opportunity to identify the presence of cataclastic and ultracataclastic fabrics, and to think about the semi-brittle processes that created them. These fault rocks are largely concentrated in the bedrock beneath the main subdetachment fault. Within this fault-rock zone of cataclasite and ultracataclasite there are also patches of pseudotachylite (Fig. 12). This is frictional melt representing "fossil earthquakes" (Sibson, 1977). The vein-like forms of the pseudotachylite underscore brief moments when tension fractures developed at significant depths below the surface.

Another opportunity at Stop 2C is assessing sense-of-shear during mylonitization, based on S-C fabrics, faulted/slipped porphyroclasts (Fig. 13), fish flash, sigma- and delta-porphyroclasts, and perhaps sheath folding. The opportunity here is to compare direction and sense-of-shear in the crystal-plastic mylonite fabrics with direction and sense-of-slip accommodated by



Figure 12. Macrophoto of pseudotachylite at Stop 2C. (Photograph by G.H. Davis.)

¹GSA Data Repository item 2019301, an 11" × 17" version of Figure 11, is available at <http://www.geosociety.org/datarepository/2019> or by request to editing@geosociety.org. © 2019 The Geological Society of America. All rights reserved. For permission to copy, contact editing@geosociety.org.



Figure 13. Macrophoto of faulted feldspar porphyroclast. Direction of view is northward. Sense of shear is top-southwest. (Photograph by G.H. Davis.)

subdetachment faulting. Some especially useful outcrops for assessing sense-of-shear in the mylonites are close to where the Tanque Verde Falls trail reaches Tanque Verde Wash (**Stop 2D**).

Stop 2. Conclusion

The structural and fabric elements exposed in bedrock at Tanque Verde Falls represent a persuasive example of how the structural evolution of metamorphic core complexes includes kinematically compatible brittle-on-ductile shearing (Davis, 1983, 1987), as the lower plate rocks ascended incrementally through the ductile/brittle transition. At Stop 9 it will be clear

that the Tanque Verde Falls locality lies beneath the area of most intense cataclasis. The geology has special value in that “these outcrops [at Tanque Verde Falls] provide a glimpse of what an early stage of detachment-zone faulting may have looked like prior to hydrothermal alteration and extreme cataclasis” (Davis, 2013, p. 246). The main subdetachment fault at this location is not chopped up the way it would be “where sustained faulting and the dynamics of hydrothermal solutions, high fluid pressure, and hydraulic pumping converged to create chlorite breccias” (Davis, 2013, p. 246).

Stop 3. Catalina Forerange and Babad Do’ag

Stop 3. Catalina Forerange

Catalina Highway, also known as Mt. Lemmon Highway, crosses the largely buried Catalina detachment fault at the foot of the Santa Catalina Mountains. As you proceed up the mountain from here, you will see the visually striking banded mylonitic gneiss that makes up much of the Catalina forerange. These rocks are informally referred to as the “forerange gneiss,” after the Catalina forerange which forms the southern Santa Catalina Mountains. The dark rocks with 1–4 cm augen are foliated Oracle Granite, which is undeformed in the northern Santa Catalina Mountains but is increasingly deformed southward toward the southern foot of the range. The Oracle Granite is a member of a suite of largely anorogenic granites that were intruded in a belt across North America at ca. 1.4 Ga. A sample of coarse, foliated dark granite from the forerange at the Molino Canyon overlook yielded a U-Pb date of 1441 ± 6 Ma (Fig. 14), consistent with correlation with the Oracle Granite farther north (Fornash et al., 2013). These granites typically have very few pegmatites and quartz veins and have been characterized

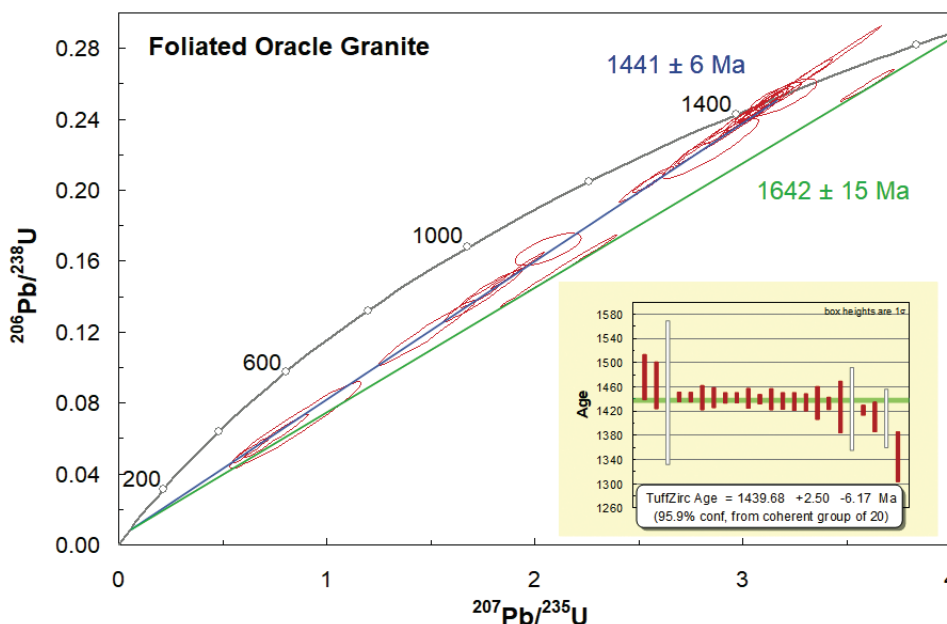


Figure 14. U-Pb Concordia diagram showing analyses of zircons from mylonitic granite interpreted as deformed Oracle Granite. Concordant analyses yield a weighted mean $^{206}\text{Pb}/^{207}\text{Pb}$ age of ca. 1439 Ma (inset). Analyses that lie along blue discordia line are of similar age but show variable degrees of Pb loss. The blue line intersects the concordia curve at 1441 ± 6 Ma. Analyses along the green discordia line, from inherited zircon cores, intersect concordia at ca. 1642 Ma. These zircon cores are from older rock units, probably including the Paleoproterozoic Pinal Schist. Data are from Fornash et al. (2013). Sample locality is from the north side of the Molino Canyon overlook parking area ~1.5 miles up the Catalina Highway from Babad Do’ag.

as “dry” (Anderson, 1989). Here the foliated granite is intruded by numerous pegmatites, quartz veinlets, and leucogranite sills up to hundreds of meters thick that have been dated at ca. 45–57 Ma (Fornash et al., 2013).

This gneiss is overprinted by a southward-dipping mylonitic fabric that is generally parallel to lithologic layering in the gneiss. Mylonitization and grain-size reduction were most effective at high structural levels on the southern side of the forerange and less effective at the lower structural levels exposed in the canyons. The mylonitic fabric is most readily identified on surfaces parallel to lithologic layering where the associated mylonitic lineation is visible. Feldspar porphyroclasts and highly sheared quartz and mica are visible on surfaces parallel to lineation and perpendicular to foliation. Shear-sense indicators are not difficult to find on these surfaces (Fig. 15).

The Babad Do’ag area is on the south side of the forerange arch, which is an east-west-trending antiform defined by gneissic layering and mylonitic foliation. Top-southwest shear-sense indicators are dominant on the south side of the arch, whereas top-northeast indicators are dominant on the north side (Fig. 16; see also Naruk and Bykerk-Kauffman, 1990; Reynolds and Lister, 1990; Force, 1997). The north-dipping zone appears to be older and transposed into parallelism with the south-dipping zone at high structural levels, with truncation of the north-dipping shear

zone by displacement on the south-dipping shear zone and the kinematically related Catalina detachment fault.

Stop 3. Babad Do’ag Overlook

Stop at the Babad Do’ag overlook parking area about two miles up the highway. (The Tohono O’odham name means “Frog Mountain.”) The rock wall on the south side of the parking lot provides a good display of the diverse granitic, gneissic, and mylonitic rocks that make up the forerange in this area. Mylonitic lineations are well displayed on the northwest edge of the parking lot on a small ridge between the parking lot and the highway. These lineations generally trend $\sim 245^\circ$ and plunge obliquely southwestward across the south-facing range front.

After looking at the rocks in the wall and the lineation on the northwest side of the parking lot, proceed to the Babad Do’ag trailhead, which is located across the highway and a few tens of meters east of the parking-lot entrance. Be careful crossing the highway at this curve as visibility is especially poor for cars and bicycles traveling down the highway. The bicyclists may travel as fast as the cars but are much quieter! Several interesting features are visible along the trail north of the highway. This field guide includes locations and descriptions of six stops along the trail, although only the first four will be viewed during the GSA 2019 field trip.

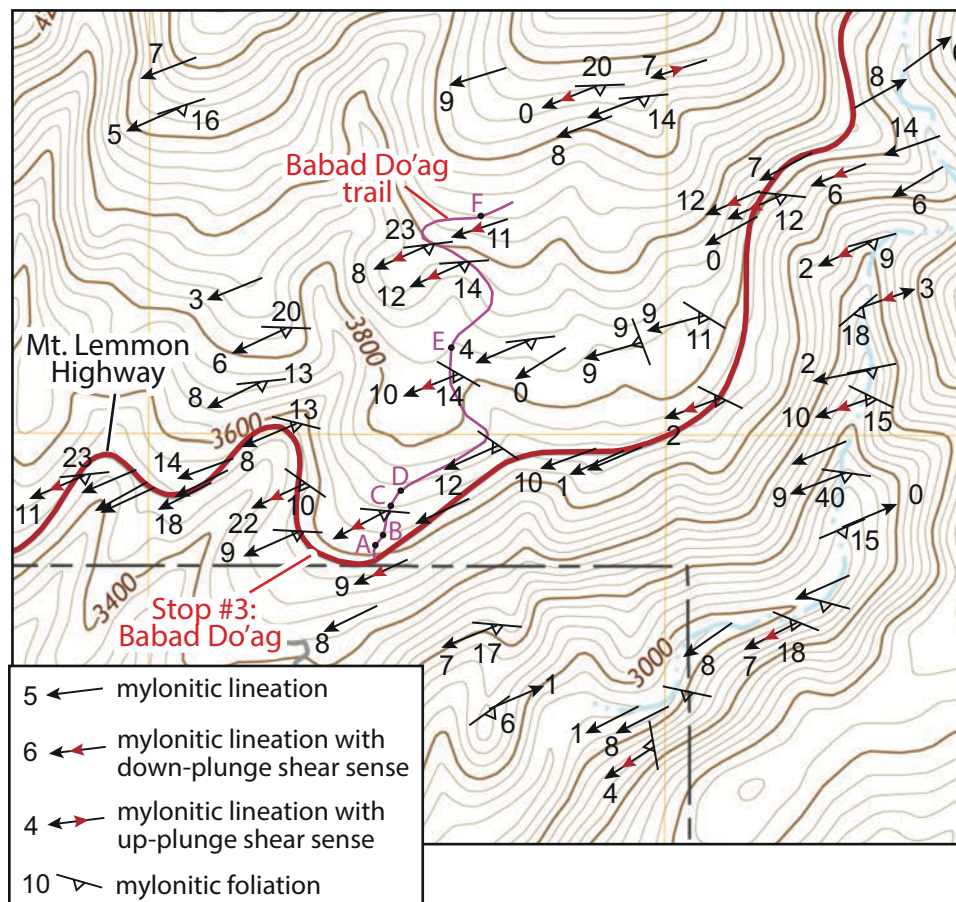


Figure 15. Map of the Babad Do’ag area showing measurements of mylonitic lineation, foliation, and shear-sense direction. Also shown are field stops along the Babad Do’ag trail.

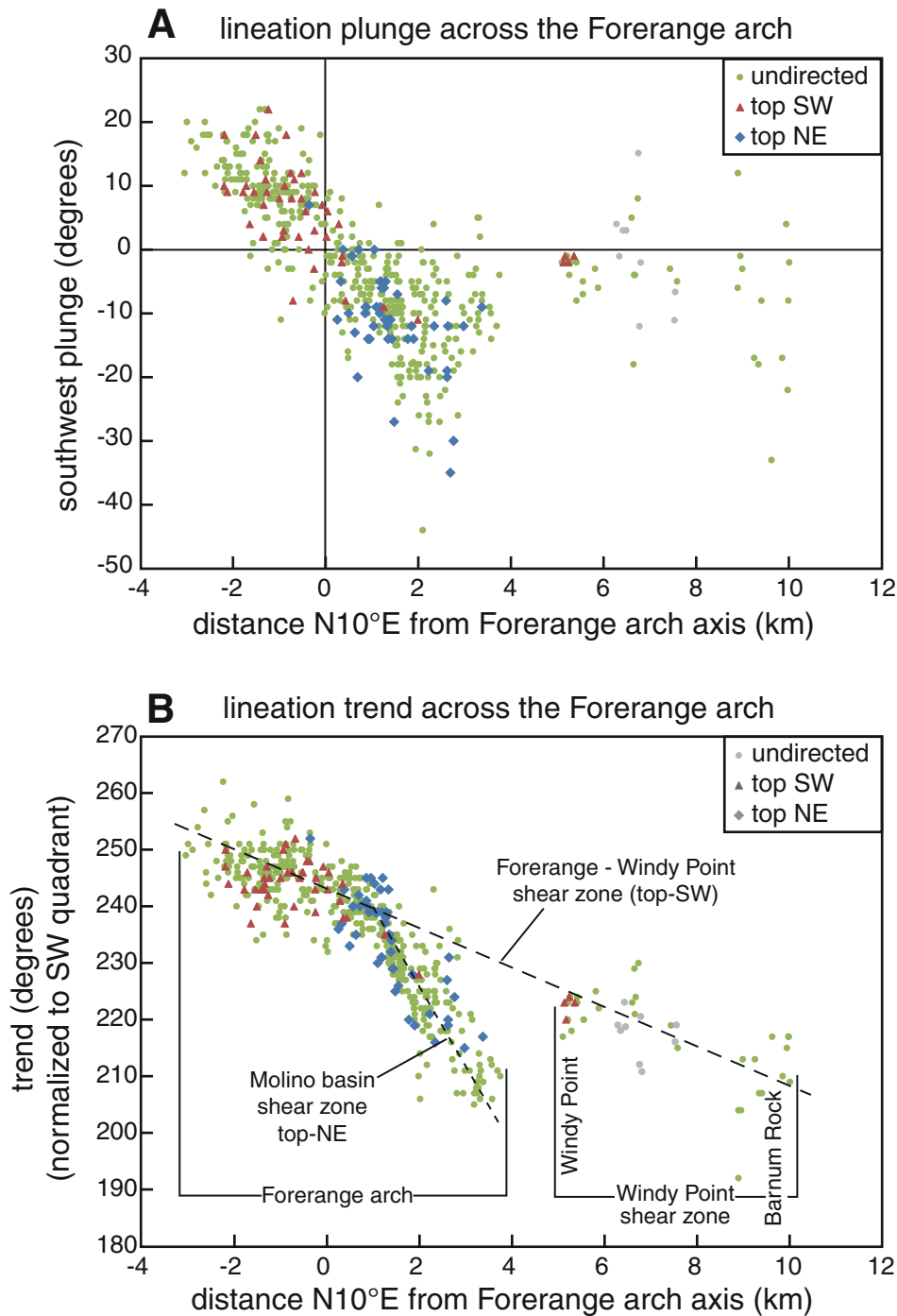


Figure 16. Plots of measurements of mylonitic lineation ($n = 548$) in a transect that includes the Catalina Highway area and Sabino, Bear and Molino Canyons. (A) Mylonitic lineation plunge across the forerange arch (left) and, farther to the right, from the Windy Point shear zone. (B) Mylonitic lineation trend that reveals the curved (in map view) trend of lineations. Correlation of the forerange and Windy Point shear zones indicates that lineations in this combined shear zone become more westerly (by $\sim 40^\circ$) over the 12–13 km distance from the range crest on the right to the foot of the range on the left. Also shown are measurements from the Molino basin shear zone that also change trend with distance from the arch crest.

Stop 3. Babad Do'ag Trail (see Figure 15)

Stop 3A. Highly sheared, dark, porphyritic granite is well exposed ~ 20 – 30 m along the trail from the Babad Do'ag trailhead. Mylonitic shearing has caused brittle rounding of K-feldspar phenocrysts to form prominent porphyroclasts. Strongly developed lineation reveals shearing direction. The protolith of foliated dark granite is almost certainly the 1.4 Ga Oracle Granite.

Stop 3B. At this stop, the trail crosses a strongly lineated quartz veinlet that is parallel to mylonitic foliation. In thin section, these highly sheared veinlets appear as 30 – 60 μm quartz subgrains that have sutured, irregular boundaries with adjacent quartz subgrains. Elongate areas contain hundreds of quartz subgrains that all have similar but slightly different orientations, with crystal-elongation direction slightly oblique to the dominant foliation such that the elongate crystals resemble flattening zones

(S surfaces) in S-C mylonites (e.g., Lister and Snoke, 1984). Grain-size reduction in these rocks was extreme. If, for example, a 4-mm-diameter quartz grain was transformed into a sutured aggregate of 40 μm quartz subgrains with similar but not identical crystallographic orientation, then this 4 mm quartz grain would have been broken into a million subgrains. Optical microscopy with crossed Nichols and a 1 λ quartz plate inserted allows determination of the approximate dominant orientation of the c-axes of the quartz subgrains. With thin sections cut parallel to lineation and perpendicular to foliation, dominant c-axis orientation was found to be tilted $\sim 10^\circ$ forward in the direction shearing from an otherwise perpendicular orientation to C-surfaces as defined by highly sheared mica (Spencer, 2006).

Similar petrofabrics in mylonitic vein quartz were identified in the Italian Alps, where the strike-slip Tonale fault zone was heated by intrusion of an adjacent pluton (Stipp et al., 2002). Metamorphic isograds in intruded sediments allow determination of approximate maximum temperatures during mylonitic shearing. Mylonitic vein quartz with similar aligned and imbricate quartz subgrains were produced at $\sim 490^\circ\text{C}$ (figs. 7e and 7f in Stipp et al., 2002). In such rocks, all grains are recrystallized with no relicts of the original vein-quartz crystals. Dominant recrystallization was by subgrain rotation in a regime of lattice-defect propagation and grain-boundary diffusion (e.g., Hirth and Tullis, 1992).

Stop 3C. Here the trail crosses a typical mix of foliated, dark, porphyritic granite and medium- to fine-grained leucogranite, both mylonitized and lineated. On a ledge on the uphill side of the trail is a top-southwest shear-sense indicator in S-C mylonite (see annotated photo in Spencer, 2006).

Stop 3D. Here the trail crosses a mylonitic shear surface that has irregularities in it that perhaps resemble incipient folds developed during shearing. The rocks above and below the irregularities must have flowed along nonlinear paths, which suggests that the rock was sufficiently soft during mylonitization that it could flow around such irregularities. Alternatively, the irregularities developed at the end of the period of mylonitization just before initiation of entirely brittle deformation such that rocks never flowed along curved paths.

Stop 3E. Slightly to the east of the trail, a highly sheared quartz vein forms part of an exposed surface that is parallel to mylonitic foliation. Irregularities in the surface suggest, as at Stop 3D, that rocks were sufficiently soft that they could flow over bumps in the shear zone during mylonitization or that the bumps are slightly younger than quartz-vein mylonitization.

Stop 3F. A very well-displayed, top-southwest, S-C shear-sense indicator is exposed along the side of the trail. An ~ 100 m length of trail here has very well-developed lineation in dark, porphyroclastic granite and fine-grained leucogranite.

Stop 4 (Optional). Laramide Granite

Proceed up Catalina Highway from Babad Do'ag and enter Molino Canyon. As you drive up Molino Canyon, you will cross the crest of the forerange arch and enter the Molino basin area

where foliation and lithologic layering dip northward rather than southward and form the Molino basin shear zone. At the abandoned toll booth is a roadcut and outcrop of a dark plutonic rock that was correlated with the Laramide Leatherwood granodiorite near the summit of Mt. Lemmon (Force, 1997). The granodiorite here forms an intrusive sheet 50–100 m thick in Oracle Granite that is in turn intruded by pegmatites and leucogranites and mylonitized (Force, 1997). This stop is included because it is the only Laramide granitoid that will be seen on this field trip.

Stop 5. Lunch Stop at Gordon Hirabayashi Campground (Modified from Spencer, 2006)

A Coronado National Forest web page stated the following about the federal prison camp located at this site from 1937 until the camp was torn down in the 1970s. All the prisoners at the honor camp had been convicted of federal crimes, ranging from immigration-law violations to tax evasion to bank robbery. During World War II, many of the prisoners at the honor camp were conscientious objectors, including Jehovah's Witnesses and Hopi Indians whose religions prohibited them from serving in the military. Some of the prisoners were Japanese-Americans protesting forced relocation during World War II. The "honor camp" designation reflects the lack of fences, walls, or armed guards. The prison camp was built here so that prisoners could do most of the labor to build the Catalina Highway.

In 1942, Gordon Hirabayashi was a senior at the University of Washington in Seattle. Instead of reporting for relocation, as mandated by the federal government in 1942 for citizens of Japanese descent, Hirabayashi turned himself in to the FBI. He challenged the constitutionality of internment based solely on race or ancestry and openly refused to comply with the relocation order. His case went all the way to the Supreme Court, but Hirabayashi was convicted. In a landmark decision in American judicial history, the court ruled that racial discrimination by the government was constitutional in a wartime emergency. Because the federal attorney involved in the case would not provide transportation, Hirabayashi hitchhiked alone from Spokane, Washington, to Tucson to serve his sentence at the federal honor camp in the Santa Catalina Mountains. In 1999, the Coronado National Forest named this site after its most famous inmate, Dr. Gordon Hirabayashi, who participated in the dedication ceremony.

Stop 6. Wilderness Granite at General Hitchcock Campground

This stop provides an opportunity to examine undeformed Wilderness granite intruded by younger but presumably related pegmatites. The Wilderness granite forms the largest leucocratic granite sill in the Eocene Wilderness suite (Force, 1997). In the study by Ruf et al. (1988), this site was used to characterize the orientation of dikes and the paleomagnetic properties of Wilderness granite below the Windy Point

mylonite zone and detachment-fault system. Stations between here and our next stop at Windy Point were used to document the upward increase in mylonitic fabric development, reorientation of pegmatitic dikes, and reorientation of anisotropic magnetic susceptibility.

Ruf et al. (1988; p. 245) concluded that:

Thin sections from the Santa Catalina Mountains indicate that magnetite occurs primarily as uniformly distributed, randomly oriented elongate inclusions within mica grains in the undeformed granite. In the deformed state the long axes become increasingly aligned parallel to the mylonitic lineation direction (X) and are rotated into the mylonitic foliation plane (XY-plane) as mica cleavage planes are rotated into the foliation with increasing strain. As a result of these rotations, a well-defined magnetic fabric develops parallel to the megascopic fabric. However, alignment of principal susceptibilities with X, Y, and Z does not continue to increase markedly in moderately to highly strained samples.

Stop 7. Windy Point Shear Zone and Wilderness Sill

Stop 7. View from Windy Point

Tucson basin to the south and southwest of the Santa Catalina Mountain consists of up to almost 4 km of Cenozoic clastic strata with minor volcanic units (Houser et al., 2005). The Tucson Mountains on the west side of the basin consist of a gently to moderately northeast tilted sequence of upper Paleozoic, Mesozoic, and Cenozoic sedimentary and volcanic rocks (Lipman, 1993). Restoration of ~30 km of slip on the Catalina fault would place the Santa Catalina Mountains beneath the Tucson Mountains, with northeast-dipping strata in the Tucson Mountains projecting downdip into the northeast-dipping strata of similar units on the northeast flank of the Santa Catalina Mountains (Bykerk-Kauffman, 2008). To a first-order approximation, the Tucson basin appears to be a half graben above the southwest dipping Catalina–San Pedro detachment fault.

Also visible to the southwest are the Sierrita Mountains and the voluminous mine dumps and tailings derived from the three large Laramide porphyry copper deposits in the range (Stavast et al., 2008). The Santa Rita Mountain range to the south is bounded at its western foot by a 20° west-dipping normal fault (Johnson and Loy, 1992). Along with the Tucson Mountains, these ranges are structurally above the Catalina–San Pedro detachment fault, and each range is separated from the others by normal faults with substantial displacement. In addition, the Molino basin mylonitic normal-shear zone separates the main mass of the Santa Catalina Mountains from the Rincon Mountains. It thus appears that all five ranges around the Tucson Basin diverged from all the others during Oligocene-Miocene tectonic extension, perhaps not unlike an ice sheet breaking up into multiple fragments and drifting apart while, in this case, floating on deep quartz-rich material that behaved as a fluid at tectonic scales (e.g., Wernicke, 1992).

Stop 7. Wilderness Granite Sill

The Wilderness granite sill, which is spectacularly exposed here at Windy Point, is the largest of the seven sill-like intrusions that form a stacked sequence of leucogranites in the central Santa Catalina Mountains (Keith et al., 1980; Force, 1997). Cathodoluminescence (CL) images of zircon phenocrysts from the Wilderness sill reveal inherited cores and zoned rims. U-Pb isotopic analysis (laser ablation–inductively coupled plasma–mass spectrometry analysis at Arizona LaserChron Center at the University of Arizona) indicates that cores are mostly ca. 1.44 Ga, whereas rims are mainly ca. 46 Ma (Figs. 17–19). U/Th values of zircons of both ages are consistently <10, suggesting that all zircons are igneous in origin rather than metamorphic.

Other sills belonging to the Wilderness Suite show a more complicated history for zircon growth. CL images show the complexity of zircon textures in three crystals from the Seven Falls sill (Fig. 20), which is the lowest of the sills in the Catalina Mountains. Each of these grains has been studied in detail with many laser-ablation analyses. This results in maps of age and U/Th, which can be combined with textural relations seen in CL images to reconstruct the history of zircon growth (Fig. 21). Combining the results of analyses of these three grains yields a surprisingly long and complicated history for the Seven Falls sill. The main phases of growth are interpreted to include:

- Ca. 145 Ma: growth of igneous zircon
- 64–60 Ma: growth of igneous zircon
- 60–52 Ma: growth of metamorphic zircon
- 52–48 Ma: growth of a second phase of metamorphic zircon
- 48–40 Ma: growth of igneous zircon
- 40–34 Ma: growth of metamorphic zircon

These relations suggest that at least some sills of the Wilderness Suite have a long and complicated growth history.

Hafnium (Hf) isotope analyses clarify the origin of magmas that crystallized to form the plutonic rocks of the Santa Catalina Mountains (Fig. 22). On Figure 22, black xs are measured values for zircons in our sample of Oracle Granite. These values overlap in age and Hf isotope signature with known values for the Oracle Granite, as measured from a whole-rock sample by Barovich (1991). Inherited zircon cores with ages of ca. 1.44 Ga in younger plutons have similar Hf isotopic values, supporting the interpretation that they were inherited from the Oracle Granite. The inherited cores of ca. 1.6–1.8 Ga are likely derived from the Pinal Schist. Zircons in younger igneous suites lie along the Hf isotopic evolution trajectory from these older rocks (gray dashed line), suggesting that the magmas were generated entirely from melting of Oracle Granite (and possibly Pinal Schist). There is no sign of any juvenile contribution to these magmas.

Stop 7. Windy Point Shear Zone

Top-southwest mylonitic shearing that affected the Wilderness granite here generally dies out downward over tens of meters of structural thickness. Mylonitic deformation in the Windy Point shear zone also affected the tops of peaks and ridges to the north (Fig. 23) and may form a synformal zone

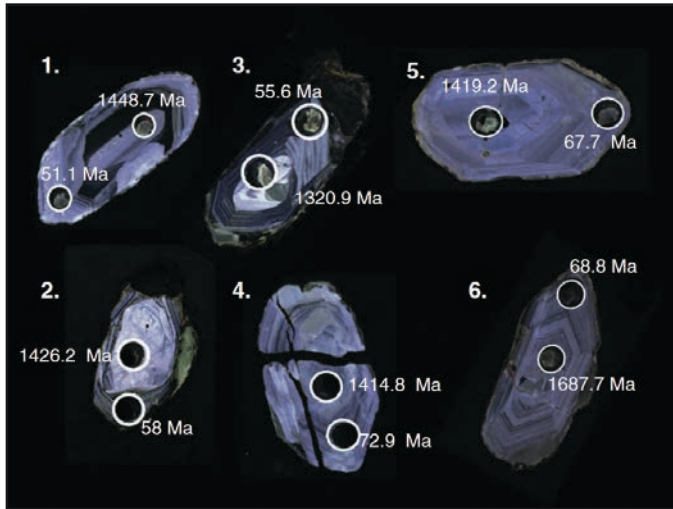


Figure 17. Cathodoluminescence images of complex zircons from Laramide and Wilderness Suite intrusive bodies. Zircons 1 through 5 show Proterozoic cores enclosed in rims from Wilderness granite or Laramide intrusions. Zircon 6 shows a core from Pinal Schist enclosed in a rim from Laramide-age Leatherwood Granodiorite.

with an axis approximately parallel to lineation (see plate 1B in Force, 1997). Lineation plunge and trend cluster around 4° toward 038° with more northerly lineation trends in more northern exposures revealing a slightly curved trend pattern in map view (Figs. 16, 23). The shear zone projects into the air to the south across the low elevation area between the high Catalinas and the Catalina forerange. Where its projection meets the crest of the forerange arch, changing lineation trend matches that of the forerange mylonitic lineation and trends more westerly with more southerly locations (Fig. 16). Correlation of the two shear zones implies 40° of clockwise curvature in shearing direction from $\sim 210^\circ$ ($\sim 030^\circ$) at the top of the range to $\sim 250^\circ$ at the southern foot of the range.

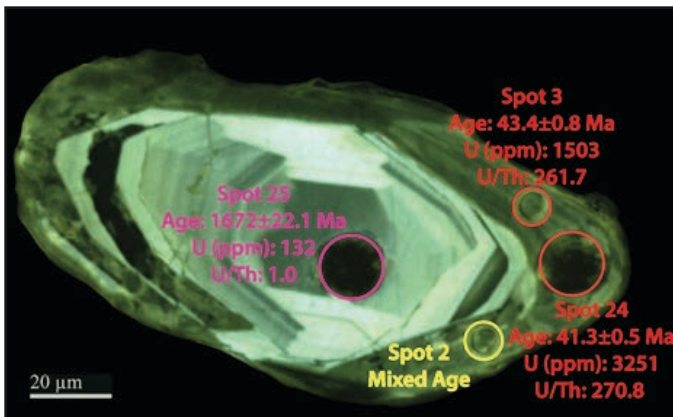


Figure 18. Cathodoluminescence image, ages, and U and Th data from a zircon grain from mylonitic rocks of the Wilderness Suite granites.

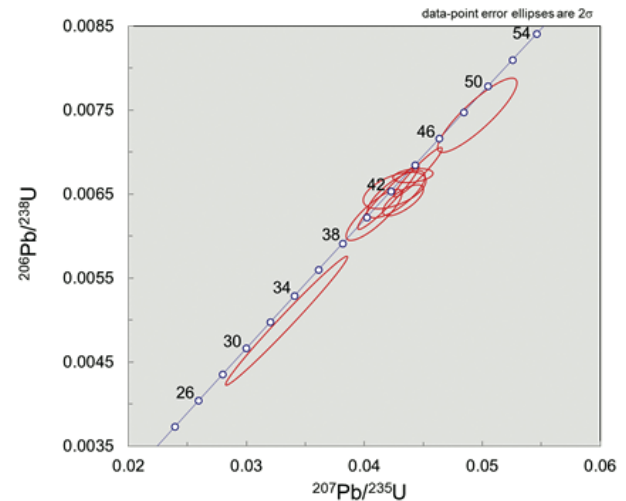
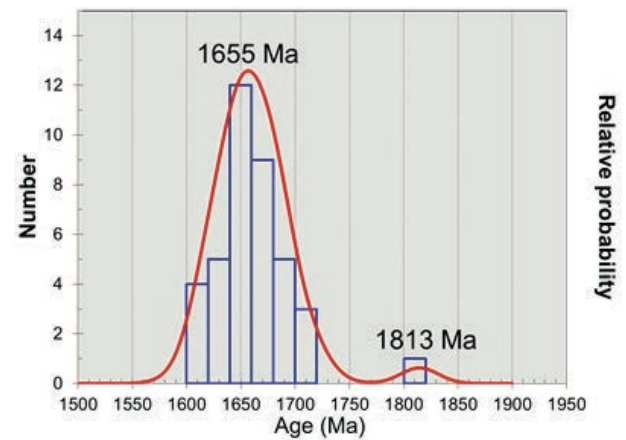
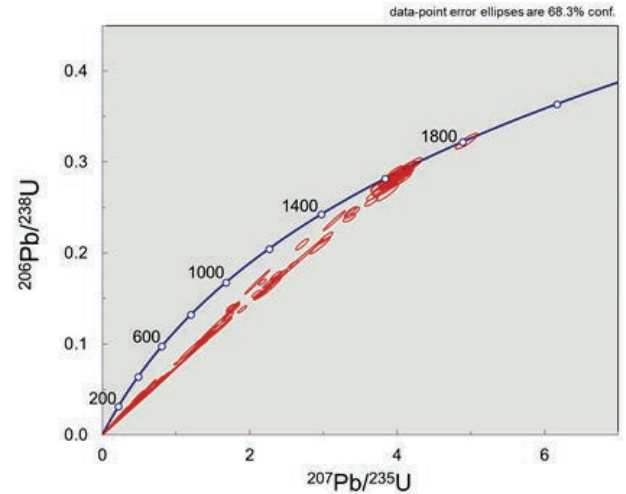


Figure 19. (A) Concordia plot of ages from Wilderness Suite zircons. Older analyses (upper right) are interpreted to represent inherited grains mainly from Pinal Schist, with a minor proportion from the Oracle Granite. Younger analyses (lower left) represent crystallization of Wilderness Suite granite at ca. 42 Ma. Intermediate analyses reflect mixing of older and younger components. (B) Age distribution of inherited cores in Wilderness Suite zircons. (C) Ages of Wilderness Suite zircons and zircon rims.

A

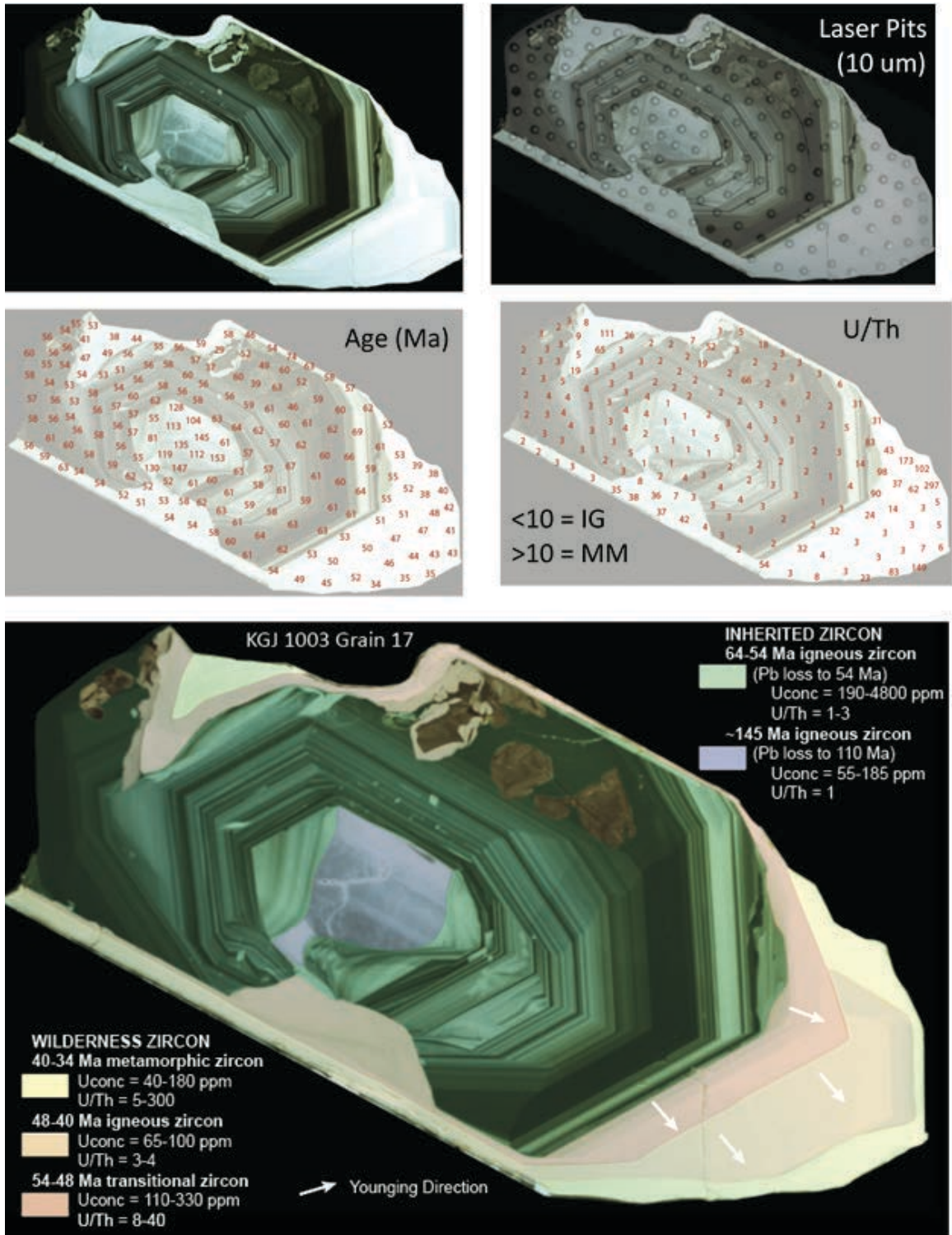


Figure 20. (A–C) Cathodoluminescence (CL) images of complex zircon textures in three crystals from the Seven Falls sill, which is the lowest of the seven sills in the Catalina Mountains. Each of these grains has been studied in detail with many laser-ablation analyses. This results in maps of age and U/Th, which can be combined with textural relations seen in CL images to reconstruct the history of zircon growth. (*Continued on facing page.*)

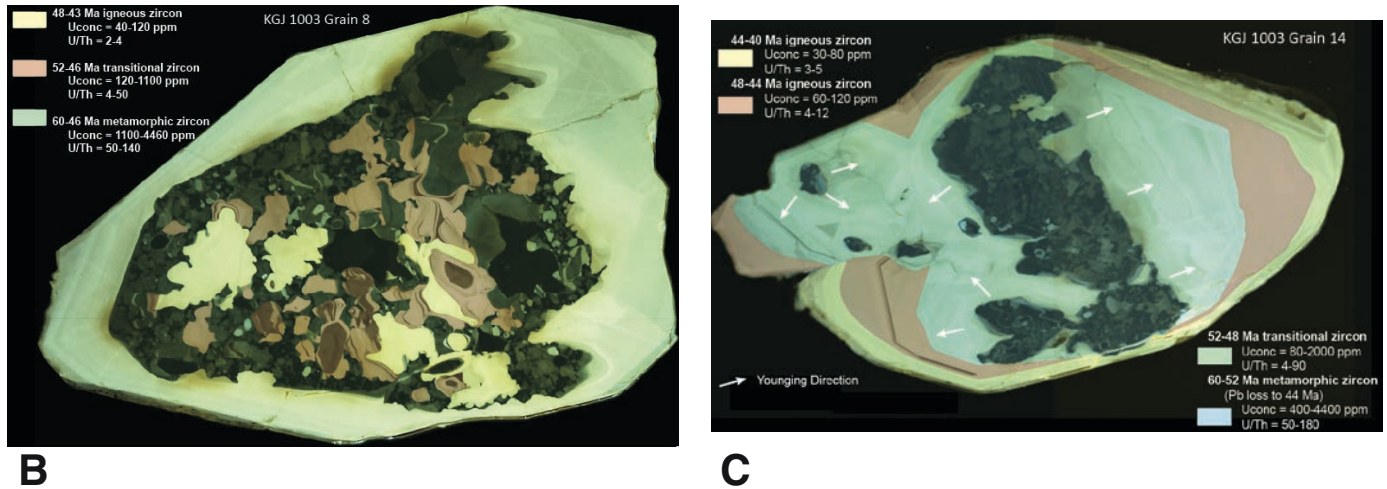


Figure 20 (continued).

Stop 8. Geology Vista

Stop 8. Regional Form of the Catalina–San Pedro Detachment-Fault Footwall

From the Geology Vista parking area, we can see the north side of Tanque Verde Ridge, which is one of the largest core-complex antiformal ridges on Earth and makes up a large part of the Rincon Mountains. Between here and Tanque Verde Ridge is the low synformal groove occupied by Redington Pass and two klippen above the Catalina–San Pedro detachment fault. At the western foot of the Rincon Mountains is the trace of the Catalina–San Pedro detachment fault.

Stop 8. Lineation-Parallel Drainages

Geology Vista provides an excellent view into upper Bear Canyon, which has a remarkably linear course ($\sim 241^\circ$) over 10 km before it bends southward within the Catalina forerange to follow the trace of a high-angle fault (Force, 1997). This straight segment is oriented parallel to mylonitic lineations on the south side of the Catalina forerange (240° – 250°) and is oblique (by 40° – 60°) to the regional southward slope of the south side of the Santa Catalina Mountains. Other drainages in the southern Santa Catalina Mountains and western Rincon Mountains are similarly oblique to the regional slope but subparallel to mylonitic lineation, including Pontotoc and Pima Canyons (Fig. 24).

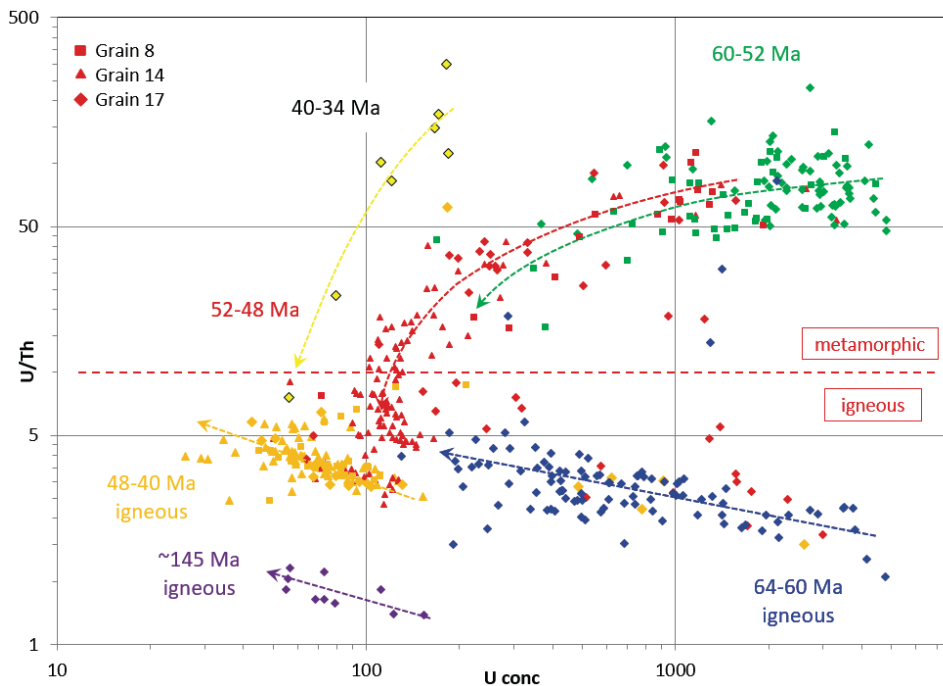


Figure 21. Combined results of laser-spot analyses from the three zircon crystals shown in Figure 20 from the Seven Falls sill. Squares = grain 8; triangles = grain 14; diamonds = grain 17.

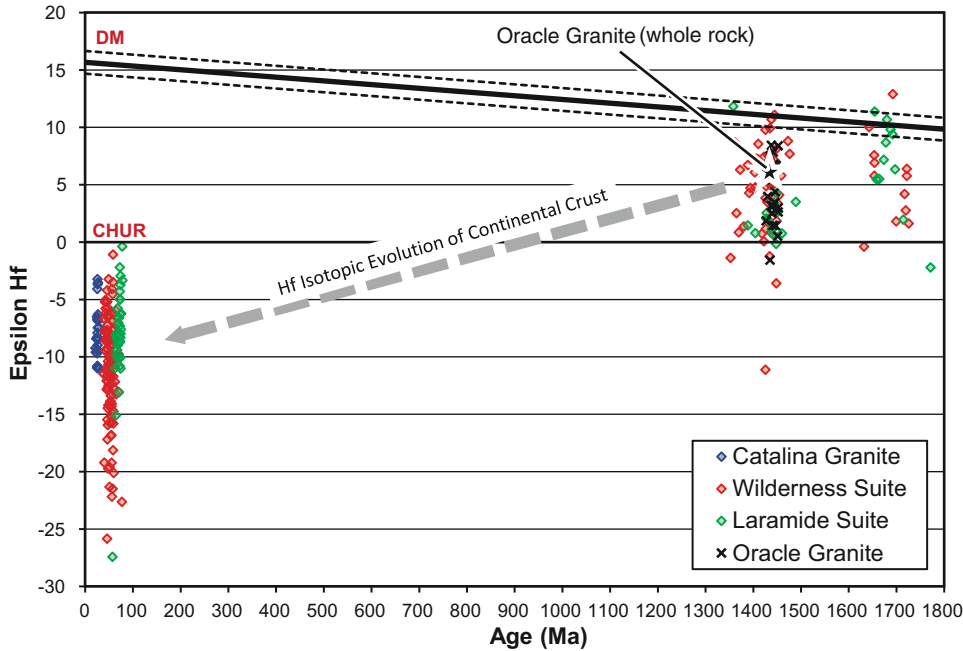


Figure 22. Hafnium-isotope measurements of zircon rims and cores from various igneous rock units in the Santa Catalina Mountains. DM—depleted mantle; CHUR—chondritic uniform reservoir.

Lineation-parallel drainages are common in Arizona's metamorphic core complexes (Spencer, 2000). They were first identified by Australian geomorphologist Colin Pain, who proposed that the drainages were initially incised into the footwalls of detachment faults as the footwalls were tectonically uncovered, and that within a core complex, the youthful drainages flowed down slope on an inclined, freshly exhumed fault plane. Then, following initial drainage incision, the footwalls were folded about lineation-parallel fold axes so that drainages no longer flowed down the steepest course but rather somewhat sideways on the flanks of gently plunging antiformal arches (Pain, 1985).

This interpretation requires that the crystalline rocks that make up metamorphic core complexes were folded into some very large folds following exhumation. Tanque Verde Ridge, which makes up most of the visible Rincon Mountains as seen from Geology Vista, would be a large, young antiformal fold if this theory is correct. Lithologic layering in lower-plate rocks roughly conforms to the corrugated form of detachment faults, perhaps reflecting deep-crustal processes (Spencer, 1999). However, much detailed mapping in and around Arizona core complexes has failed to identify any structures that could be interpreted as indicating that detachment-fault corrugations are folds produced during a tectonic regime of horizontal shortening perpendicular to fold axes and following footwall exhumation. In contrast, post-detachment reverse faults in crystalline rocks and folds in sedimentary rocks have been identified with trends at high angles to corrugations, not parallel to them (e.g., Spencer et al., 2016). It thus seems more likely that the corrugations of detachment-fault footwalls are giant fault grooves rather than folds produced after footwall exhumation as, for example, with Quaternary deep-sea core complexes (e.g., MacLeod et al., 2009).

An alternative is that small grooves in the fault footwall, where uncovered by detachment faulting, localized drainages into linear forms (Spencer, 2000). These grooves are no longer apparent in the Santa Catalina Mountains but are represented by detachment fault irregularities where the faults are exposed in other ranges such as the Rincon Mountains (e.g., figure 13 in Davis and Hardy, 1981). The slight topographic embayment at the foot of the range at the mouth of Sabino Canyon (see Fig. 2) suggests that the buried trace of the detachment fault is similarly embayed and forms a synformal groove in the detachment fault. Projected up plunge parallel to mylonitic lineation, this embayment is aligned with upper Bear Canyon, and thus is consistent with a causative relationship between an ~km-wide fault groove and a linear drainage.

Another alternative is that linear drainages were incised during exhumation because canyons in the hanging-wall block maintained hydraulic connection with their lengthening upstream reaches in the footwall block and so guided the drainages down the freshly exhumed fault footwall as it was uncovered (Spencer, 2000). This would be effective only if there is a canyon in the hanging-wall block to guide the lengthening stream. Exposures of hanging-wall rocks at the south foot of the Santa Catalina Mountains in the Catalina Foothills consist of mid-Tertiary clastic rocks (primarily fanglomerates), some of which contain mylonitic debris and would not obviously have contained canyons to guide lengthening drainages. This mechanism might have been effective in the Rincon Mountains, however, where bedrock forms the hanging-wall block and a footwall drainage is aligned with a canyon in the hanging-wall block (Spencer, 2000).

Modern drainage courses may be influenced by fractures, which may have exerted influence on stream courses in the Santa Catalina Mountains since initial footwall exhumation (Pelletier

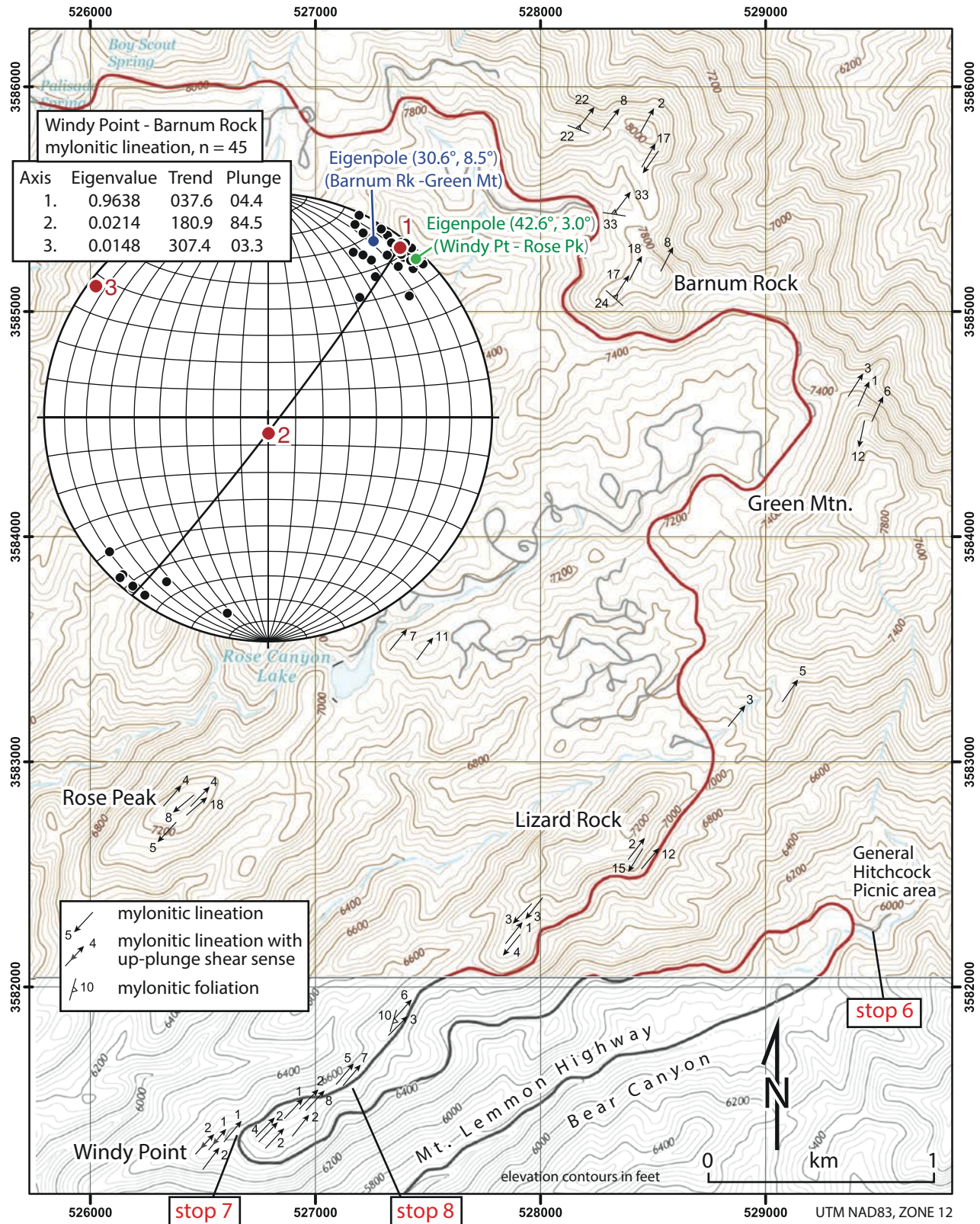


Figure 23. Map of the Windy Point shear zone showing lineation orientations. Primary eigenpoles are also shown for subsets of lineation data for Barnum Rock–Green Mountain and Windy Point–Rose Mountain. Note the ~12° clockwise rotation of lineations with more southerly position. Stereonet and eigenvalues were produced with Stereonet 10.0 software (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013).

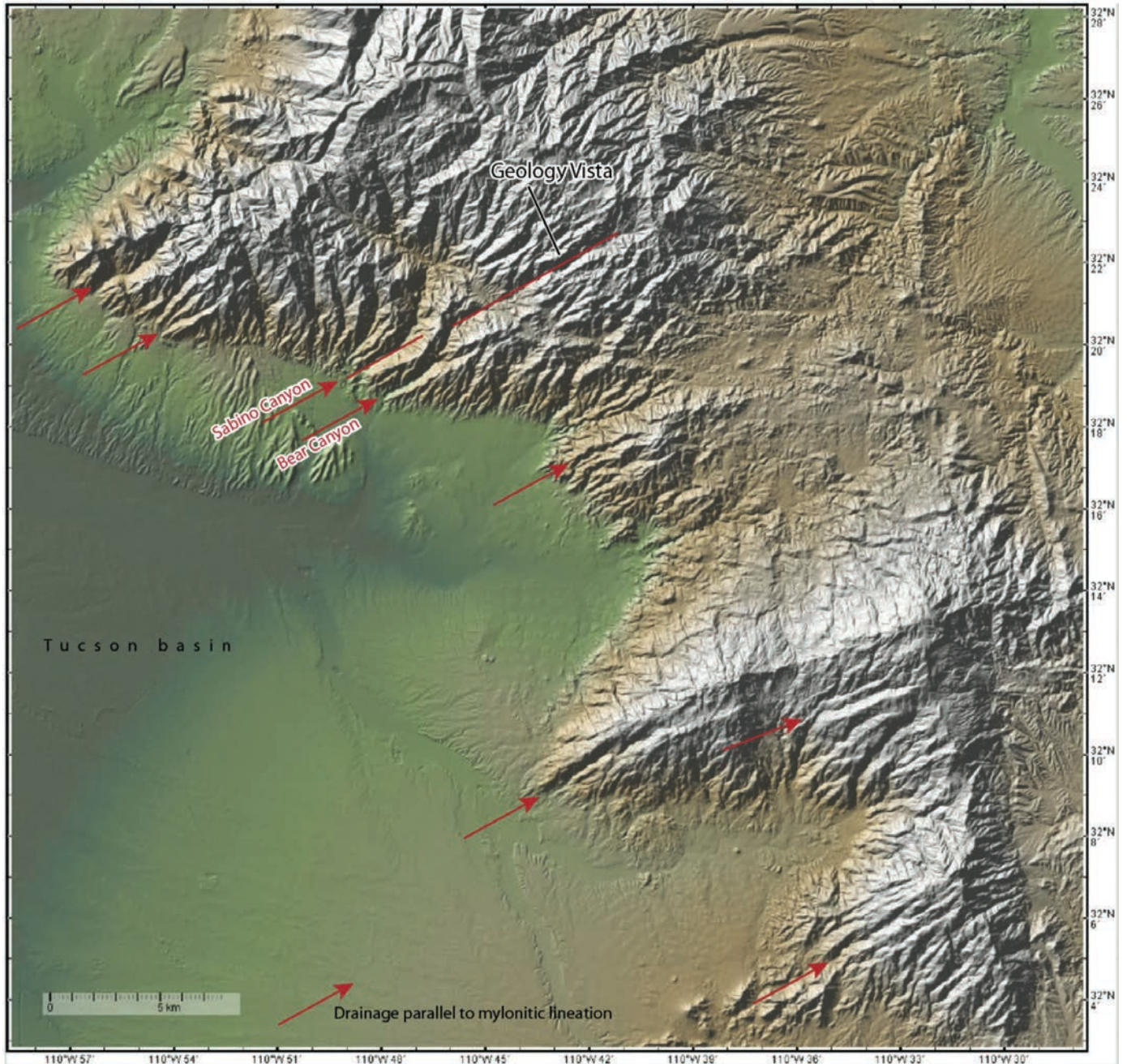


Figure 24. Shaded relief map of the Catalina-Rincon core complex showing linear drainages with southwesterly trend.

et al., 2009). This possibility has not been fully evaluated with fracture-orientation data sets. However, the South Mountain core complex south of Phoenix is much lower relief and much less incised than the Catalina-Rincon complex, with remarkably linear drainages along the long axis of the range. Mineralized and chloritic fractures measured by Reynolds (1985) are all approximately perpendicular to these linear drainages, suggesting an anti-correlation between fractures and drainages, at least in this weakly incised complex.

Stop 9. Cactus Forest Study Area, Saguaro National Park

Stop 9. Access

Stop 9 is located on the northwest flank of Tanque Verde Mountain within Saguaro National Park (SNP), Rincon Mountain District (RMD) (see Fig. 3). From Tucson, approach SNP (RMD) on Old Spanish Trail (Fig. 25), turning left into the parking lot and Visitor Center. After proceeding through the entrance station turn left (north) onto Cactus Forest Loop Drive, which

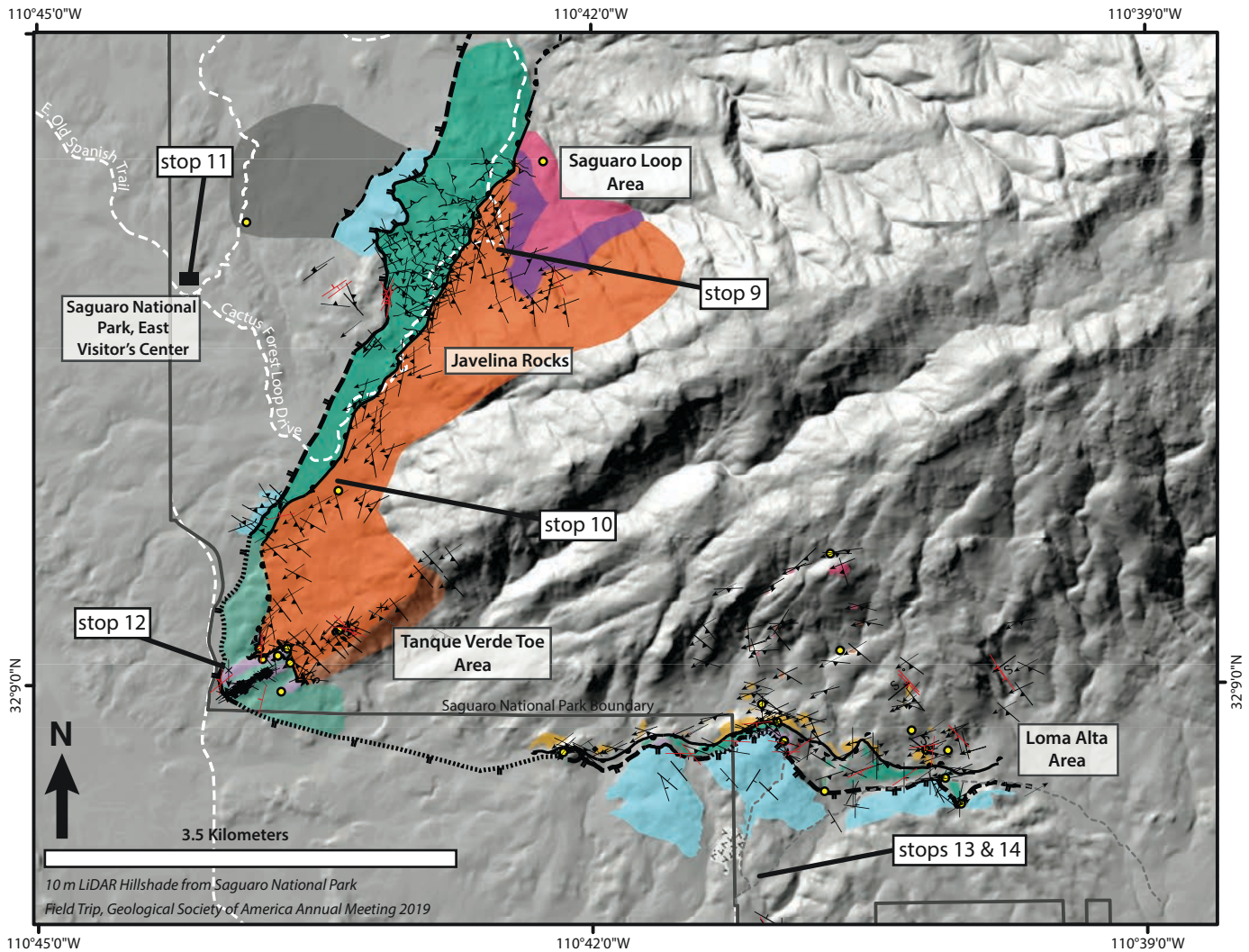


Figure 25. Geologic map of the Tanque Verde Mountain region, showing stop locations in relation to mylonites, cataclasites, the Javelina subdetachment fault, and the Catalina detachment fault. (See Fig. 26 for map explanation, and see Acknowledgments for attribution of mapping. ArcMap GIS compilation of map data by Katherine Guns.)

is one-way (see Fig. 25). Stop 9 is located approximately half-way around Cactus Forest Drive. This site has history, for it is where Davis (1977) led a field trip during the 1977 GSA Penrose Conference, “Tectonic Significance of Cordilleran Metamorphic Core Complexes” (Crittenden et al., 1978, 1980). The purpose of the 1977 field trip to this location was to introduce the salient structural characteristics of metamorphic core complexes. Later, Davis (1987) contributed a write-up of the geology of this location to GSA’s Centennial Field Guide project. What makes this location special is that during a short walk, one can traverse through lower plate mylonites and ultramylonites, the Javelina subdetachment fault, cataclastically overprinted mylonites, the Catalina detachment fault, and into upper plate non-mylonitic country rocks. Crust was lengthened and thinned as upper-plate rocks were sheared downward while lower-plate rocks were sheared upward. Mylonites and cataclasites at Stop 9 are thought

to be rocks originally located ~25–40 km to the west relative to hanging-wall rocks and at a depth of ~12 km in Oligocene time, but then raised and translated eastward during extension. Upper plate rocks were simultaneously displaced relative to footwall rocks toward 240° (Davis, 2013).

It is fortunate that SNP (RMD) occupies a metamorphic core complex. The ease of access creates a platform for interpreting geology and tectonics to the broader public. Visitors are drawn here to see exemplary Sonoran Desert flora and fauna, but the bonus is incredible geology and the relationship of this geology to overall ecology and natural history. Because of the opportunities to better understand and communicate the interplay of biology, ecology, hydrology, and geology, the Department of Geosciences at The University of Arizona and SNP (RMD) have been working together on “Researching and Interpreting the Geological Story of Saguario National Park, Rincon Mountains District,

Tucson, Arizona” (National Park Service Permit #SAGU-2016-SCI-0009). This has resulted in new detailed structural geological mapping and geochronological research by Professors George Davis, George Gehrels, and Pete Reiners. This work has actively engaged both graduate and undergraduate students. Don Swann, a biologist, is the lead investigator for the Park in helping to connect geological findings with the broader range of topics related to overall National Park Service mission. This importantly includes attention to displays and interpretive materials at the Visitor Center.

Stop 9. Background: The Structures and Fault-Rock Stratigraphy

Figure 26, a map explanation, and Figure 27, the structural-geologic map framework for Stops 9–12, help prepare us for examining the SNP system of structures and fault-rocks. The Catalina detachment fault frames the key relationships. The Catalina detachment fault is the low-dipping long-continuous fault surface that separates lower-plate mylonitic and cataclastic rocks

from upper-plate non-mylonitic rocks (this is a segment of the regional “Catalina–San Pedro” detachment fault or detachment-fault system). Cataclasites and mylonites are arranged within a low-dipping fault-rock stratigraphy beneath the detachment fault. A 3-m ledge of ultracataclasite forms a resistant ledge directly beneath the detachment fault. In turn, the ultracataclasite is sharply underlain by cataclasites derived from faulting, shearing, rigid-body rotation, and comminution of mylonites. The cataclasites are commonly referred to as “chloritic breccias” in Cordilleran core complexes because of intense chlorite-epidote-iron alteration (Crittenden et al., 1980). The base of the crudely tabular zone of cataclasis is a subdetachment fault, which on the flanks of Tanque Verde Mountain is the Javelina subdetachment fault (Davis, 1987, 2013). Beneath the subdetachment fault are mylonites derived from several different granitic protoliths. On the northwest flank of Tanque Verde Mountain, we recognize two such protoliths: O-mylonite (shown in orange), which is derived from Mesoproterozoic Oracle Granite, a porphyritic quartz monzonite; and W-mylonite, an anatectic two-mica garnet-bearing granite derived from Paleogene Wilderness Suite granite. The contact between O-mylonite and W-mylonite is marked by ultramylonite up to ~50 m thick, and thus this contact is a major shear-zone boundary. The ultramylonite was derived from both the O-mylonite and the W-mylonite. On the southeast flank of Tanque Verde Mountain (Fig. 28), a third granitic protolith has been transformed to mylonite, namely the Loma Alta mylonite of yet undetermined granitic protolith. Above the Catalina detachment fault are the non-mylonitic upper plate rocks. These range from Precambrian to Neogene in age. On the northwest flank of Tanque Verde Mountain, the upper plate rocks are dominated by Paleoproterozoic Rincon Valley Granite, Paleozoic and Jurassic-Cretaceous sedimentary formations, and Oligocene-Miocene fanglomerates (Drewes, 1977).

The outcrops in the Cactus Forest study area capture the change from quasi-plastic behavior to elastic-frictional behavior, as lower plate rocks were being simultaneously lifted (to shallower depths) and sheared (ductile to brittle) during profound extensional deformation (Davis, 2013). One of the points of emphasis is interpreting the basis for localization of the Javelina subdetachment fault, for this fault, though fashioned prior to the Catalina detachment fault, may have in turn influenced the locus and orientation of the Catalina fault.

The geology of the Rincon Mountains was first mapped comprehensively by Harald Drewes (1977). Drewes’s map has been extraordinarily valuable over the years, for it shows the full extent of the Catalina fault, identifies individual stratigraphic formations within the very complexly faulted upper plate rocks, and distinguishes broad categories of crystalline rocks in what we now call the lower plate of this metamorphic core complex. Drewes’ map of the Rincon Mountains and several U.S. Geological Survey geological maps of the Catalina Mountains were incorporated in Dickinson’s (1991) *Geologic Map of Catalina Core Complex and San Pedro Trough*. In creating this synthesis, Dickinson (1991) drew upon the advances made during the 1970s

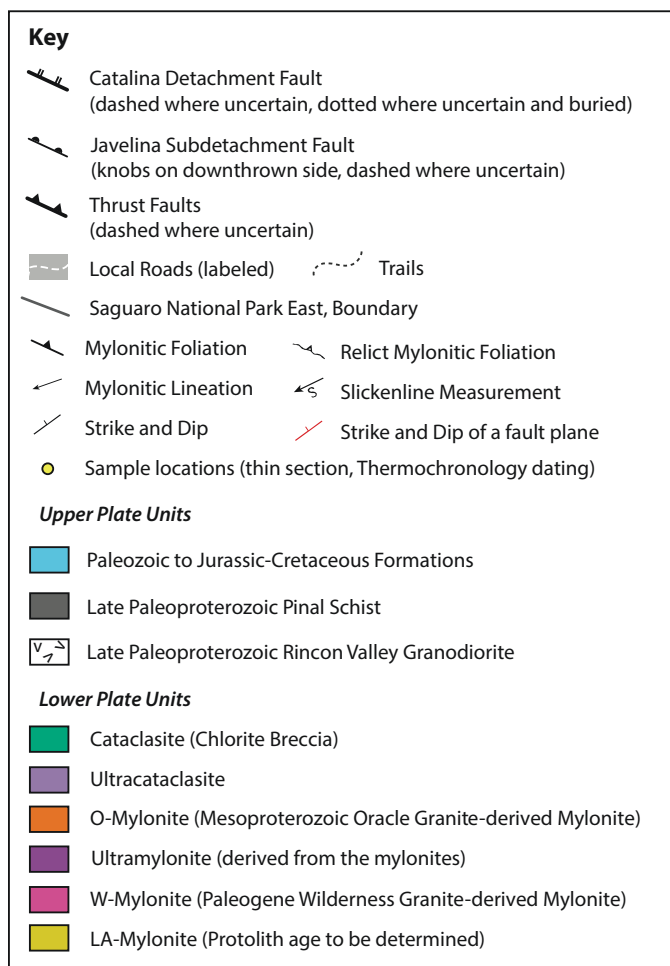


Figure 26. Map explanation for Figures 25, 27, and 28. (ArcMap GIS framing of map explanation by Katherine Guns and George Davis.)

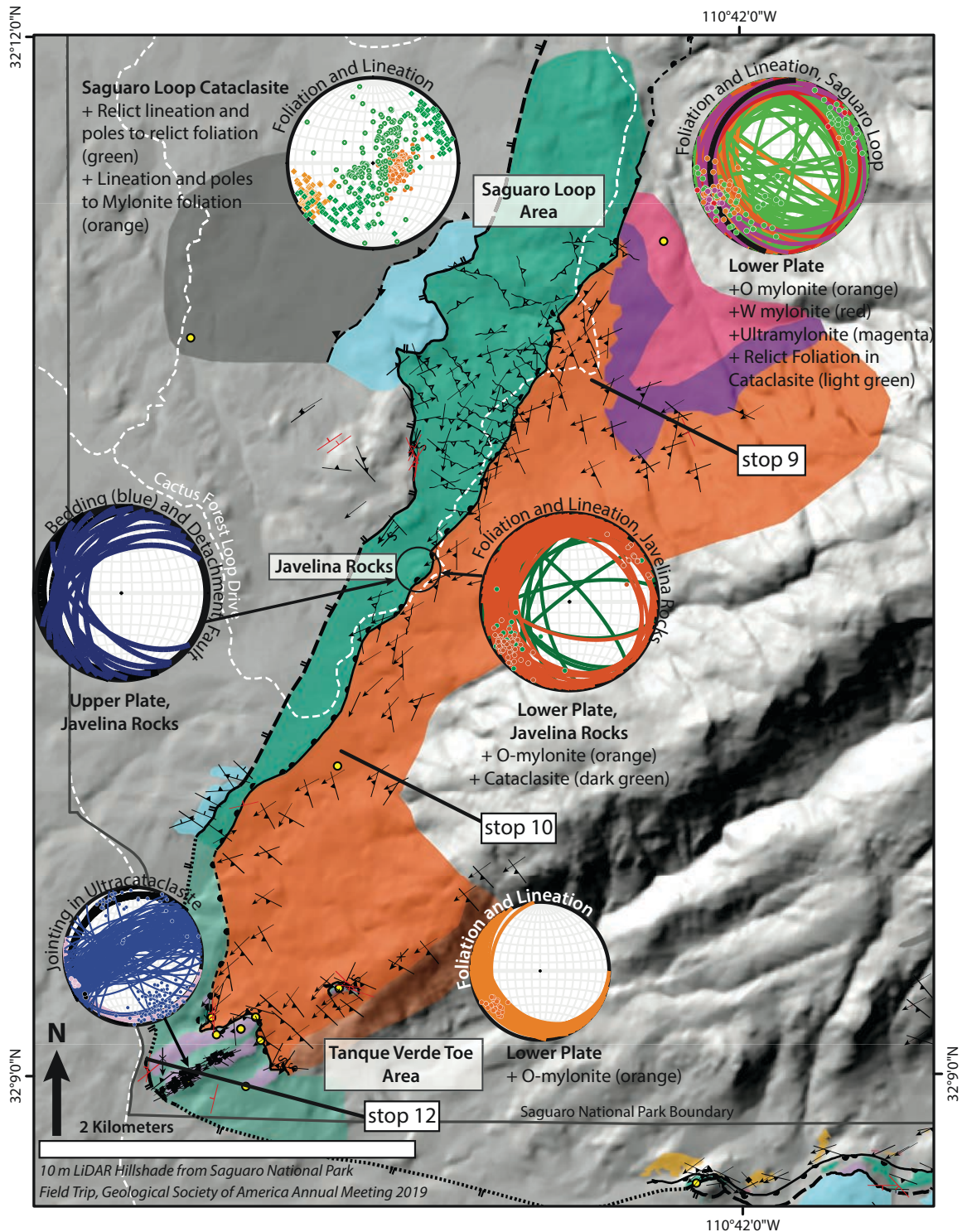


Figure 27. Geologic map of the northwest flank area of Tanque Verde Mountain. This area lies within Saguaro National Park, Rincon Mountain District, and is the most highly visited part of the park. (See Fig. 26 for map explanation, and see Acknowledgments for attribution of mapping. ArcMap GIS compilation of map data by Katherine Guns.)

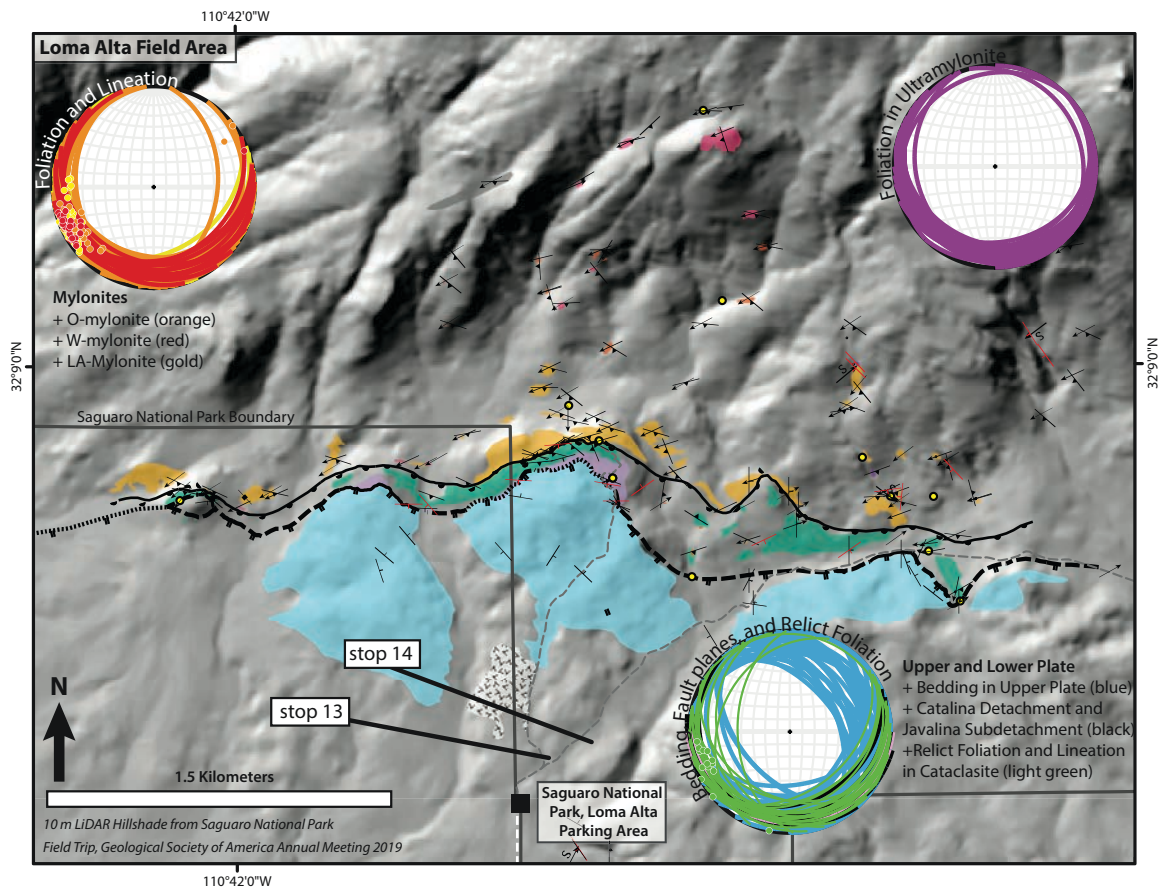


Figure 28. Geologic map of the Loma Alta area on the southeast flank of Tanque Verde Mountain. This area lies largely within Saguaro National Park, Rincon Mountain District. (See Fig. 26 for map explanation, and see Acknowledgments for attribution of mapping. ArcMap GIS compilation of map data by Katherine Guns.)

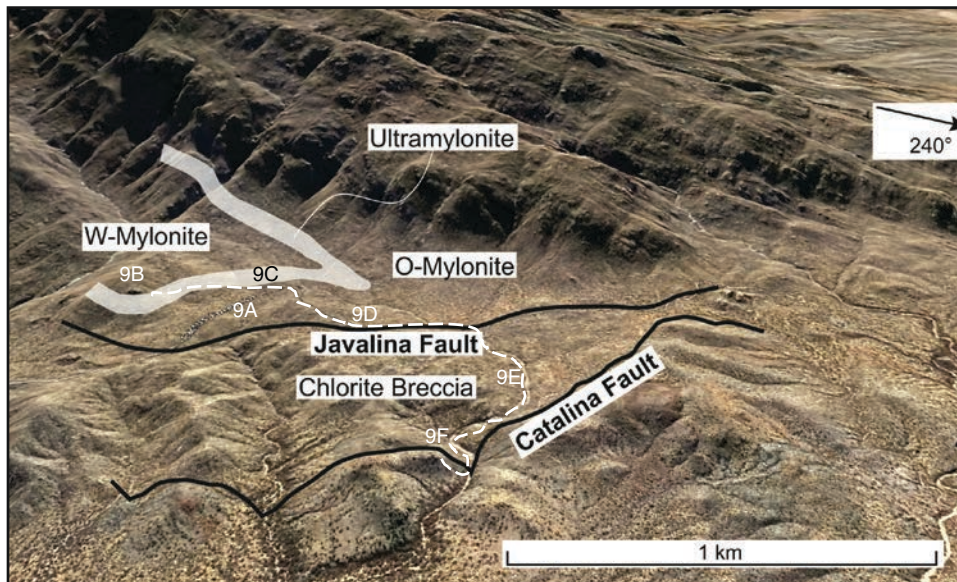


Figure 29. Oblique image of Stop 9 area, showing map pattern of fault rocks, the Javalina subdetachment fault, and the Catalina detachment fault. Also shown is the approximate path of the Stop 9 traverse. Image from Google-Earth Pro. (Modified from Davis, 2013, fig. 6A, p. 241.)

and 1980s regarding recognition and interpretation of metamorphic core complexes. One of Dickinson's important contributions in this mapping was new original work on Oligocene-Miocene extensional-basin stratigraphy.

The present structural geological mapping carried out by Davis and students (from 2012 to present; see Acknowledgments) focuses on fault-rock stratigraphy in relation to detachment and subdetachment faulting, including the interrelationships of mylonites, ultramylonites, cataclasites, and ultracataclasites. One goal of ongoing mapping is to develop an overall Rincon Mountain geological map that represents the lower plate units not as igneous rocks (see Drewes, 1977, and Dickinson, 1991), but as proper fault rocks derived (largely) from and correlated with their igneous/metamorphic protoliths. A second goal is to populate the map with fault and fabric-orientation data, communicating both tectonic transport and sense of shear.

Stop 9. Traverse

Figure 29 identifies the route for exploring the various structures and fault-rock components of the Rincon Mountain metamorphic core complex.

Stop 9A. O-Mylonite

The O-mylonite is coarse-grained porphyroclastic quartzofeldspathic mylonite (see Figs. 26, 27). It crops out in ledgey gray to dark gray outcrops, and even from 5 to 10 m away its abundant whitish porphyroclasts are evident. O-mylonite is strongly foliated and lineated, with the lineation best expressed in the fabric of quartz ribbons and preferred orientation of the long dimensions of porphyroclasts. S-C fabrics and sigmoid tails on porphyroclasts convey a top-to-southwest sense of shear (Fig. 30A). The differential brittle behavior of the feldspar porphyroclasts and the crystal-plastic behavior of quartz are strikingly evident in thin section (Fig. 30B). Feldspar porphyroclasts are subangular to rounded, ranging from 0.1 to 4 cm, and are arranged in a fine-grained matrix of ribbon-quartz layers and laminae (DiTullio, 1983). O-mylonite foliation in this subarea strikes ~N-S and dips ~10°–20° W; lineation averages 240° in trend (see Fig. 27).

George Gehrels, Clay Kelty, and George Davis collected a representative sample of O-mylonite at the Javelina Picnic area (Stop 10) for U-Pb geochronological dating in the Department of Geosciences LaserChron Laboratory (University of Arizona). Average age of the zircons examined proved to be ca. 1.45 Ga, consistent with the larger O-mylonite and Oracle Granite data set for the region.

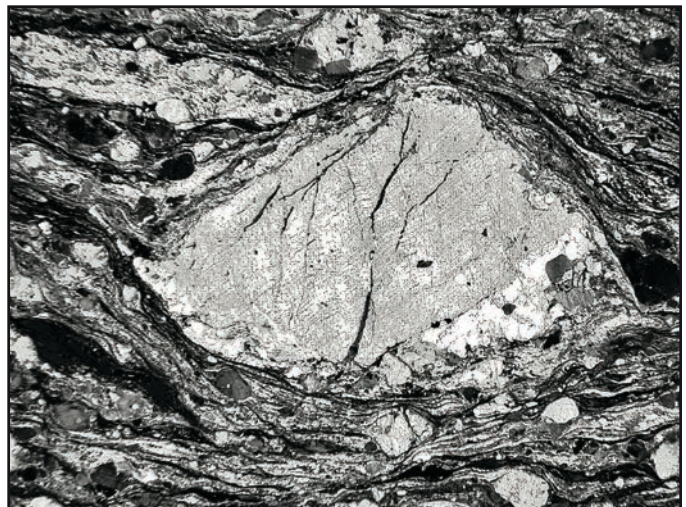


Figure 30. (A) Photograph of outcrop of O-mylonite. Note that the lineation is expressed in ribbon-quartz fabric and alignment of feldspar porphyroclasts. Porphyroclasts fractured orthogonal to lineation. Trend of lineation is NE/SW. (Photograph by G.H. Davis.) (B) Photomicrograph of porphyroclast of feldspar (1.5 cm long) enveloped in mylonitic fabric in O-mylonite.

Stop 9B. W-Mylonite

The W-mylonite is a medium- to fine-grained equigranular two-mica garnet-bearing quartzo-feldspathic mylonite. Porphyroclasts are small, ~2–4 mm. Ribbon quartz envelops the porphyroclasts, and within the ribbons there are tiny micas, 0.5–1 mm (DiTullio, 1983) (see Figs. 26 and 27). W-mylonite is finer grained, smoother, and lighter in outcrop appearance than O-mylonite, and the presence of tiny garnets is a clincher for identification. Lineation in W-mylonite is pervasive, but more delicate than in O-mylonite. S-C mylonitic fabrics are locally excellently developed in W-mylonite and reveal a top-to-southwest sense of shear in this part of Rincon Mountain. Foliation and lineation orientation in W-mylonite and O-mylonite are subparallel to one another (see Fig. 27).

Gehrels, Kelty, and Davis collected a representative sample of W-mylonite in the vicinity of Stop 9C. It was determined that the zircons from this W-mylonite sample contain ca. 1.66 Ga inherited cores and ca. 43 Ma metamorphic rims. Their elevated U/Th values and U concentrations are common features of zircons forming in fluid-rich metamorphic conditions. The inherited cores may be from Pinal Schist, which is a Paleoproterozoic formation found throughout most of southeastern Arizona. Pinal Schist occurs in the upper plate of the Catalina detachment fault in the Cactus Forest Drive area of SNP. Gehrels, Kelty, and Davis collected a sample of the Pinal Schist there and found that it is dominated by ca. 1.70 Ga zircons. This and the nature of certain other lesser populations of zircons in the sample are consistent with published and unpublished Pinal Schist detrital-zircon geochronologic data from the region.

Stop 9C. Ultramylonite

This dark-weathering, platy to schistose rock lies beneath the O-mylonite in the Cactus Forest Drive area (see Figs. 26, 27). Drewes (1977) mapped it throughout the Rincon Mountains as Pinal Schist. His mapping revealed that his Pinal Schist almost always occurred at the contact between the two major granitic bodies he mapped: Continental Granodiorite (which is O-mylonite), and Wrong Mountain Quartz Monzonite (which is mainly W-mylonite). Davis concluded in the 1970s that this unit was not Pinal Schist, but mylonitic schist and ultramylonite (Davis, 1980). In both the Catalina and Rincon Mountains it indeed tends to separate W- and O-mylonite, which suggests that these two major rock units were brought into juxtaposition through shear-zone deformation. The ultramylonite unit proved essential to determining sense-of-shear within the mylonites of the Rincons. Davis (1980) exploited the abundant asymmetrical folds within the ultramylonite to determine top-to-the-southwest shear.

The ultramylonite is silver gray to dark gray, weathering to a platy/schistose character (Fig. 31). Lineation is typically quite penetrative. Tiny white porphyroclasts of feldspar are embedded in a very fine-grained matrix, and these are visible in outcrop. In thin section (Fig. 31B), the porphyroclasts are quite obvious, and commonly there are abundant “mica fish”

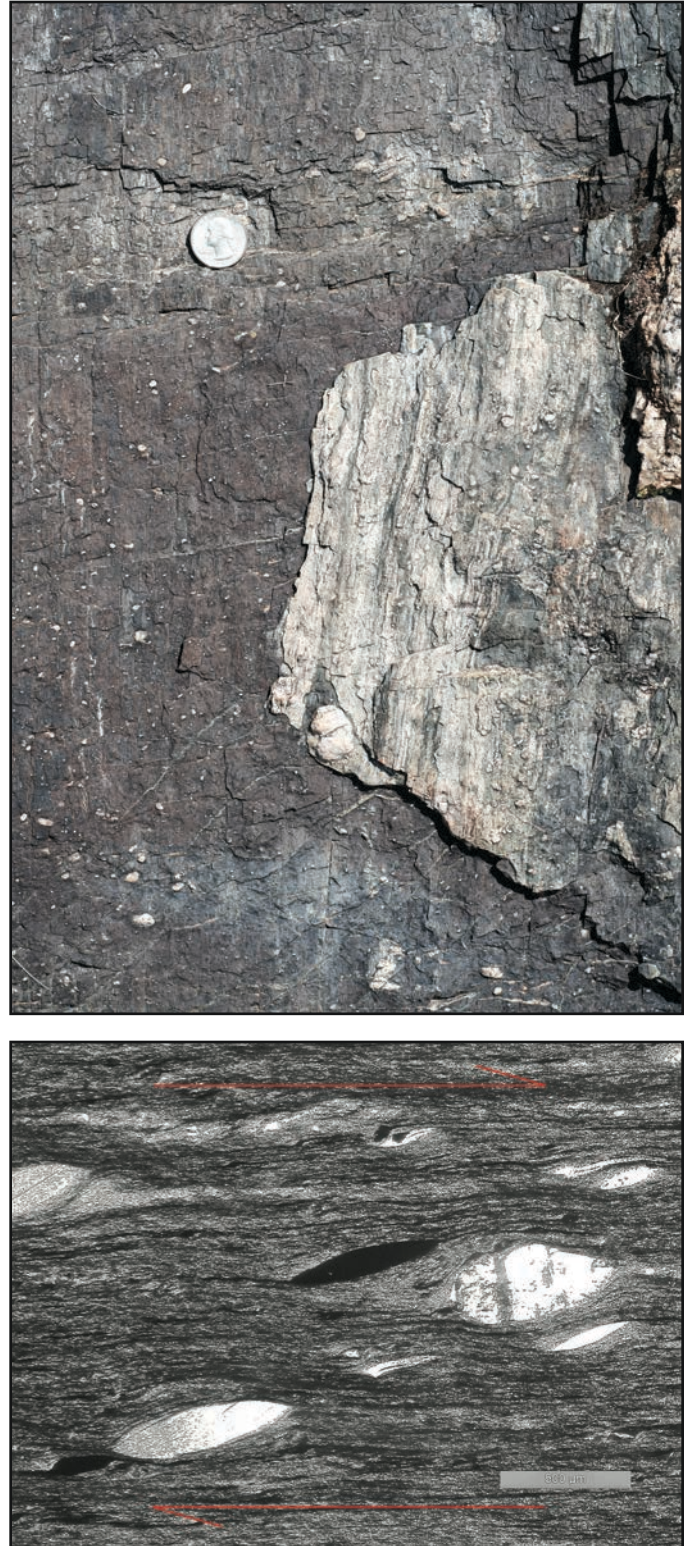


Figure 31. (A) Macro-view of part of outcrop of ultramylonite (purple-gray, left), and the O-mylonite (right) from which it was derived at this location. Lineations in these two fault rocks are slightly discordant in trend. (Photograph by G.H. Davis.) (B) Photomicrograph of ultramylonite, showing mica fish and tiny feldspar porphyroclasts. Sense of shear is top to the right (SW).

that convey sense-of-shear. The sense of shear is consistent with what can be determined through analysis of asymmetric folding in the ultramylonite.

Stop 9D. Javelina Subdetachment Fault

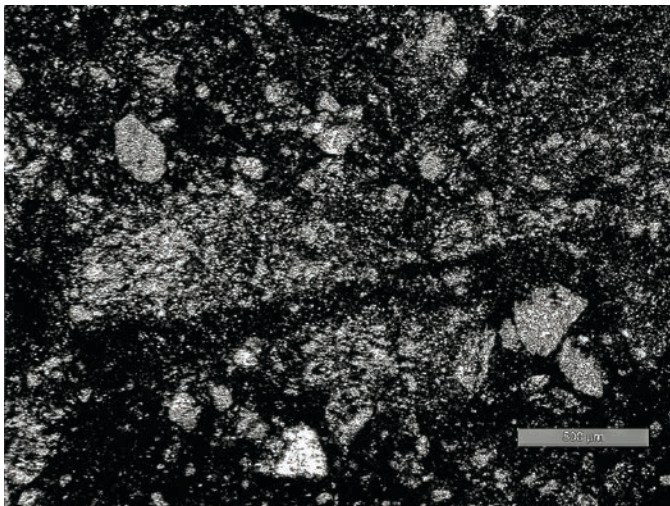
This location displays one of very few physical manifestations of the Javelina subdetachment fault on the northwest flank of Tanque Verde Mountain (see Figs. 26 and 27). It expresses itself as a very gently dipping planar surface marked by abundant close-space fracturing and strong hydrothermal alteration (hematite, manganese, limonite, chlorite). Its attitude is $160^{\circ}/10^{\circ}$. Directly above is cataclasite; directly below is mylonite. This sharp fault-induced juxtaposition permits this subdetachment fault to be followed throughout the area, even though it almost always lacks true physical expression.

Stop 9E. Cataclasite

The Cactus Forest study area contains one of the best exposures of chloritic-breccia cataclasite in the world (see Figs. 26 and 27). Outcrops are expansive and readily accessible (Fig. 32A). Damage from sustained faulting and comminution under conditions of elevated hydrothermal-fluid pressure is evident in the intense fracturing/shattering and alteration. The rocks are marked by random-fabric comminution (Fig. 32B), with original O-mylonite porphyroclasts reduced to average lengths of ~ 0.15 – 25 mm, though in places down to 0.1 mm (DiTullio, 1983). The bedrock is blue to blue-green on fresh surfaces, revealing the presence of chlorite and epidote, but the cataclasite weathers to tan, beige, and chocolate brown (see Fig. 32A). Alteration mineralogy, beyond chlorite and epidote, includes abundant manganese and iron oxides. Reynolds and Rehrig (1980) emphasized



Figure 32. (A) Photograph of brown-weathered cataclasite derived from O-mylonite. Note leucocratic layers subparallel to relict foliation. This outcrop displays a typical example of the very low dipping mini-detachment fracture fissures. (Photograph by G.H. Davis.) (B) Photomicrograph of cataclasite showing tiny comminuted quartz-feldspar clasts in ultrafine-grained matrix.



that the chlorite-epidote alteration now seen in the chloritic breccias required voluminous fluid flow. Perhaps the Javelina subdetachment fault, and comparable structures, provided major pathways for overpressured fluids that simultaneously hydraulically fractured and altered the original mylonite protolith. Reynolds and Lister (1987) concluded that this fracturing and retrograde metamorphism began near the brittle/ductile transition.

The outcrop breadth of chloritic-breccia cataclasite within this area is ~500 m, though because it is low-dipping its thickness ranges up to just 50–75 m. Pre-cataclasis mylonitic fabrics are still recognizable in the chloritic breccia (Davis, 1980), but orientations of “relict” mylonitic foliation and lineation depart (in some places quite significantly) from attitudes of the mylonite fabric elements beneath the Javelina subdetachment. Davis (1980, 2013) ascribed the now-misoriented relict mylonitic fabric elements to sustained pervasive faulting that cut and rotated, over and over, the original mylonitic layering. The rotated fabrics conform to a progressive back-rotation during down-to-the-southwest semi-brittle shear (see Fig. 27). Some “mini-detachment fault surfaces” (coined by Axen and Selverstone, 1994), which formed late and were not subjected to fault truncation and offset, are quite obvious. They occur as very gently dipping sub-planar fissure-like fracture partings that “run” for tens of meters (see Fig. 32A). The fissure-like partings are used as habitat niches by critters such as rattlesnakes, pack rats, and desert tortoises.

Stop 9F. Ultracataclasite and the Catalina Detachment Fault

The Catalina fault in the Cactus Forest study area strikes ~N25°E and dips ~10° WNW (see Figs. 26 and 27). What is uncanny is that this fault can be traced continuously from the western end of the Catalina Mountains to the southeastern end of the Rincon Mountains without segmentation (see Fig. 1). This alone distinguishes detachment faults from large conventional normal-fault systems. In contrast, the subdetachment faulting, expressed by faults such as the Javelina fault, appears to comprise a segmented system.

Directly beneath the Catalina detachment fault is a 4-m-thick cataclasite/ultracataclasite ledge aligned parallel to the detachment fault. Visible angular to rounded feldspar and quartz fragments make up 20%–25% of this rock. Comminuted porphyroclasts are set in a very fine-grained groundmass (DiTullio, 1983). Directly above the Catalina detachment fault are upper plate rocks (see Figs. 28 and 30) that at this locality consist of Paleozoic limestones (Davis, 1975; Drewes, 1977). Dominantly limestones, the fabrics are semi-brittle in the form of flexural folds and pressure-dissolution features (including abundant calcite veining).

Stop 9. Discussion

One of the important remaining questions regarding the origin of metamorphic core complexes is explaining the low-angle dip of major detachment faults. Numerous journal articles have addressed this question, and parts of tectonic workshops and conferences have wrestled with possible interpretations. The range of interpretations invoke reactivation of thrust faults, domino rotation

of originally more steeply inclined normal faults, rolling hinge models, exploitation of anomalously high fluid pressures, and strain localization due to grain-size reduction and generation of abundant phyllosilicates. Davis (2013) pointed out the irony that the historic emphasis on reactivation of low-angle thrust faults as a plausible explanation does not have a counterpart that considers strain and displacement localization along a structure that formed earlier and deeper in *the same* extensional tectonic regime.

Davis (2013) carefully mapped the trace of the Catalina detachment fault, the Javelina subdetachment fault, and the ultramylonite zone, recording waypoints in terms of latitude, longitude, and elevation. Waypoints for each of the three structures were best-fit to surfaces, carried out by Phillip McFarland (Davis, 2013, appendix A therein, p. 251–252). The parallelism of major elements is striking: the Catalina fault is oriented 213°/07°; the Javelina subdetachment fault is oriented 215°/08°, and ultramylonite shear zone 210°/05°. The Javelina fault thus occupies the same orientation as the ultramylonite shear zone, and both are parallel to the Catalina detachment fault (Fig. 33). Moreover, at some locations, the top of the ultramylonite shear zone inserts itself into the Javelina fault (Davis, 2013). One extensional klippe of cataclasite, floored by the Javelina subdetachment fault, rests directly on ultramylonite. Cataclastically overprinted ultramylonite occurs *within* the chloritic breccia, and there are in places ghost-like relic asymmetric folds of a type that only occur within ultramylonite.

Davis (2013, p. 250–251) reached the conclusion that:

The mechanically soft nature of the ultramylonite was responsible for creating a favorable detachment zone for normal faulting. Minidetachments, faults, and fracture surfaces now evident within the chlorite breccia damage zone may well represent the remains of a progressive faulting and coalescence of lower reaches of normal faults, localized near the top of and/or within the ultramylonite shear zone.... Strain softening contributed by the ultramylonite was due in part to its very fine grain size and the relative high percentage of phyllosilicates. Grain-size reduction...is an integral part of ultramylonitization, and this in itself favored strain softening, for deformation mechanisms are most efficient in fine-grained rocks.

Indeed, if the subdetachment fault is controlled in this way, and the Catalina detachment fault is parallel and nearly co-spatial, then could this not be a productive way to think about why the Catalina detachment fault is oriented at such a low angle?

Stop 10. Javelina Picnic Area

This picnic spot is situated on O-mylonite bedrock. Some of the rock is a protomylonite with a relatively light mylonitic overprint. As a result, the protolith character of porphyritic quartz monzonite (Oracle Granite) is obvious even in outcrop. This is the site where Gehrels, Kelty, and Davis collected the O-mylonite sample that (properly) yielded an age date of ca. 1.45 Ma.

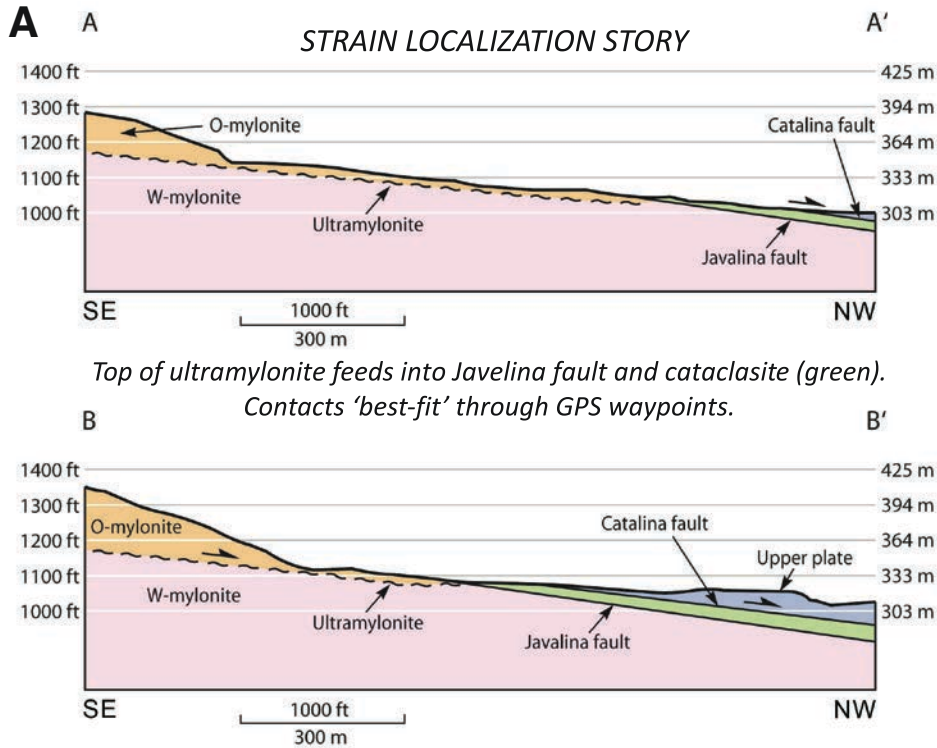
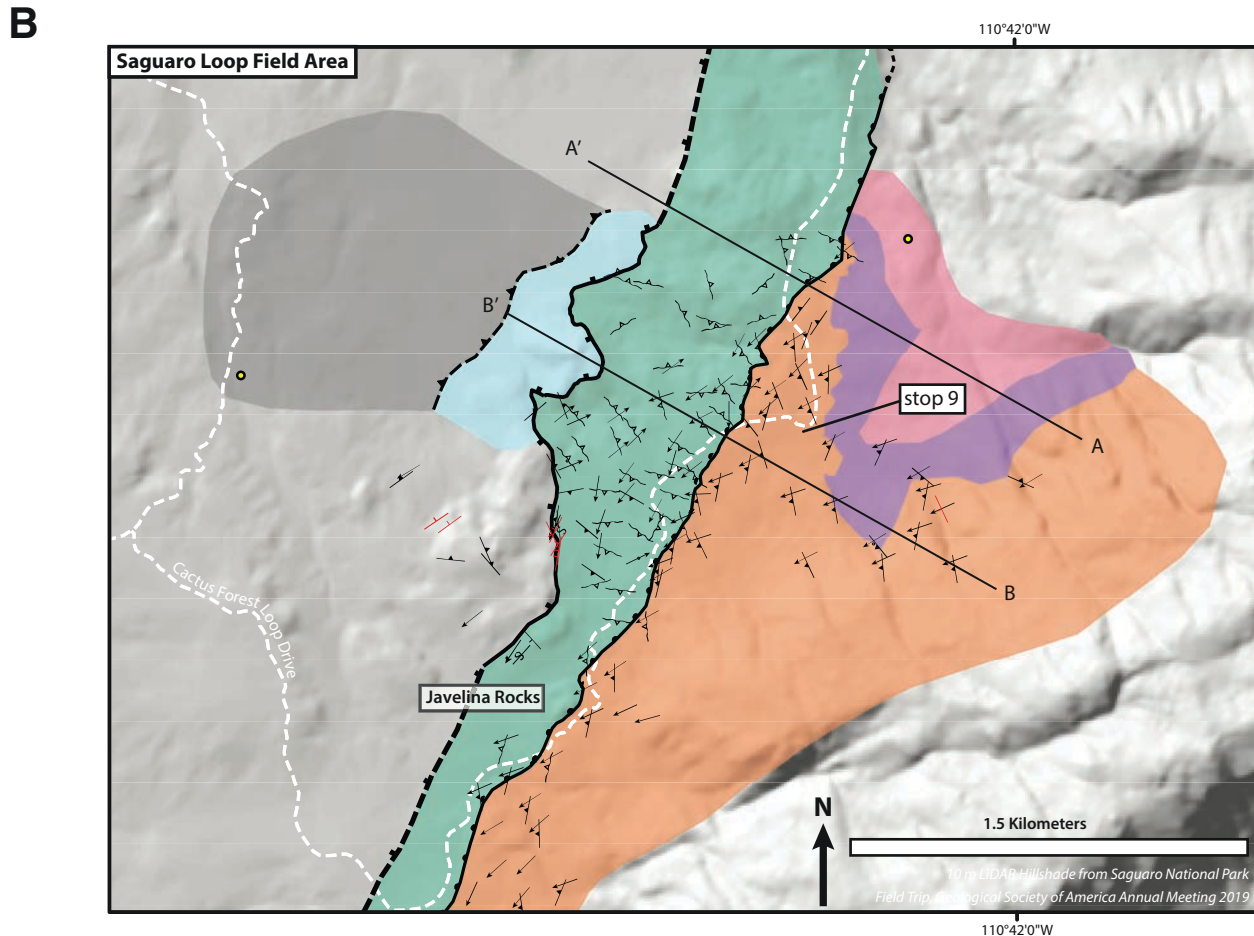


Figure 33. (A) Geologic cross sections (A–A' and B–B') showing the structural arrangement of fault-rock stratigraphy, the Javelina subdetachment fault, and the Catalina detachment fault within the Cactus Forest Study area. (See Fig. 26 for map explanation. From Davis, 2013, fig. 19, p. 248.) (B) Geologic map showing distribution of fault rocks and faults and approximately locations of endpoints of NW-SE cross-sections A–A' and B–B', above. (See Fig. 26 for map explanation.)



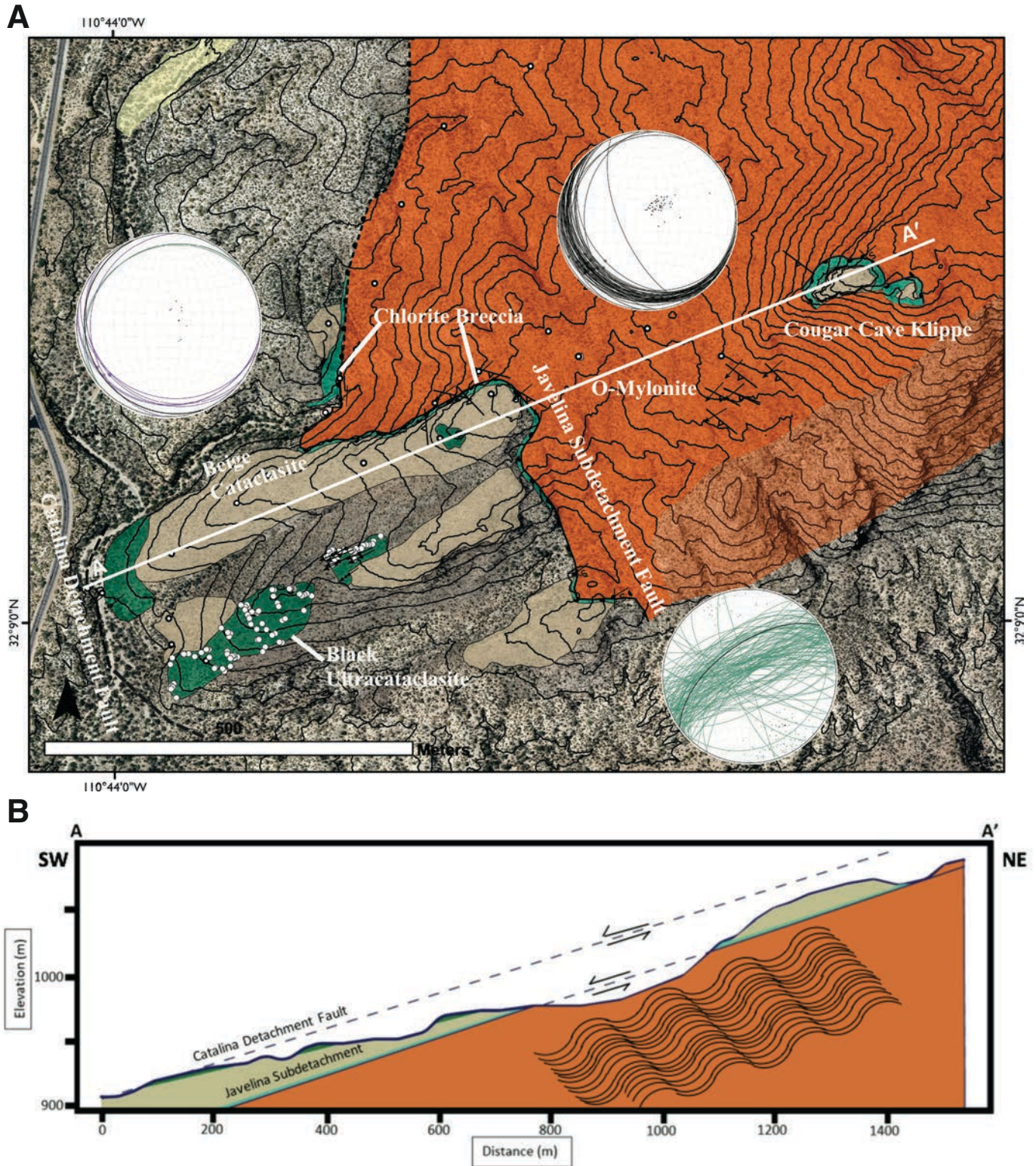


Figure 34. (A) Structural geologic map of Tanque Verde Toe area, with stereographic projections of mylonitic foliation in the O-mylonite (black), layering in the ultracataclasite (purple), and jointing in ultracataclasite (green). A–A' is line of cross section. (B) Geological cross-section showing the strain localization of mylonite (orange), chloritic breccia (light green), ultracataclasite (dark green), the Javelina subdetachment fault, and the Catalina detachment fault. (From Alke et al., 2019. ArcMap GIS compilation of map data by Katherine Guns.)

Stop 11. Visitors Center

In 2018–2019, SNP (RMD) obtained Geologist-in-Park (GIP) funding for three student interns to support research-based interpretation. The GIP program is run by the Geological Society of America, the National Park Service, and other partners. One of these focused on designing interpretive materials that would help visitors understand the nature and origin of metamorphic core complexes. Biologist Don Swann, SNP (RMD), supported by George Davis, advised these projects. Interpreting the nature and significance of “metamorphic core complexes” has always been a “tall order.” In many National Parks, the main geologic-based interpretive challenges commonly relate to conveying paleolandscapes and seascapes, especially the timing of “transgression” and “regression” of shallow seas; the weathering, erosion, deposition of sediments; the faulting and folding; or the rise of magma and volcanic eruption at the surface. All these interpretive challenges are made somewhat easier because basic terminology and/or process are more familiar and easier visualized. This is decidedly not the case for explaining core complexes, which requires answering the question of how to deal with terminology impediments such as *shear-zone deformation*, *partial melting*, *mylonitization*, *cataclasis*, *detachment faulting*, *extensional mountain building*, *protolith*, *U-Pb geochronology*, and the biggest of them all, *metamorphic core complexes*. The challenges are in circumventing these taxonomic and conceptual impediments, telling the story in a new way, and doing so without completely “dumbing things down.” Our stop at the Visitor Center will allow us to feature some of the results of the first attempts.

Stop 12. Toe of Tanque Verde Ridge

This brief stop permits a viewing of “world-class” ultracataclasites situated directly on the crest of Tanque Verde antiform (see Fig. 27). Figure 34 shows the detailed map relationships as well as a cross section of the fault rock stratigraphy (ultracataclasite, chloritic breccia, mylonite), the Catalina detachment fault, and the Javelina subdetachment fault (Alke et al., 2019). O-mylonite is by far the dominant mylonite, although there is minor W-mylonite that is too sparse to represent in Figure 34A. In places the O-mylonite reveals ultramylonitic fabrics, and at one of these locations the lineation is profoundly expressed (Fig. 35).

Ultracataclasites occur directly beneath the Catalina detachment fault. In the main wash at the west end of the map area the ultracataclasite is jet black (Fig. 36), resembling obsidian, but it is a cohesive breccia marked by comminuted quartz/feldspar fragments within an extremely fine-grained cohesive crush matrix (Fig. 37). Shiny black shear zones, up to several mm thick, lace through the ultracataclasite from place to place. Moreover, there are very light gray to white splotches and streaks within the black ultracataclasite that may represent original O-mylonite not completely destroyed by cataclasis. A second variety of the ultracataclasite is beige weathering (see Fig. 34), a hue produced by weathering of the significantly hydrothermally altered ultra-

cataclasite and the presence of iron oxides and chlorite. The beige cataclasite is seen in the background of Figure 36.

The ultracataclasite outcrops are marked by systematic close-spaced parallel fracturing, resembling the products of hydraulic fracturing. The ultracataclasites transition abruptly downward into cataclasite and chloritic breccia (with relict mylonitic fabrics) (see Figs. 34 and 35). The chloritic breccia fault-rock zone is truncated abruptly by the Javelina subdetachment fault, beneath which is O-mylonite and minor W-mylonite. Farther northeast along the crest of Tanque Verde antiform, there is an extensional klippe, the Cougar Cave klippe (see Figs. 34 and 35) that provides a second exposure of the Javelina subdetachment faulting, creating yet another control point for its shallow southwest-dipping inclination.

The only known locations of black ultracataclasite in the Catalina-Rincon metamorphic core complex are on the crest and southeast flank of the lower reaches of Tanque Verde antiform. The original discovery locality is the Tanque Verde Toe area (Davis, 1980), but geological mapping in the Loma Alta area revealed an expansive exposure of black ultracataclasite, once again directly beneath the Catalina detachment fault (see Fig. 28). The presence of this highly comminuted fault rock underscores the fact that Tanque Verde arch is at least in part a giant fault mullion, whose orientation is parallel to penetrative mineral lineation in the mylonites (and ultramylonite) and the tectonic transport direction of upper plate with respect to lower plate assemblages.

Stop 13. Overturned Jurassic Conglomerate

Drive to the Loma Alta trailhead adjacent to Saguaro National Park East. From here we will walk ~300 m east along



Figure 35. Outcrop photo of highly lineated O-mylonite. Alan Gregorski on left; Alan Alke on right. View to the northeast. (Photograph by G.H. Davis.)



Figure 36. Northeast-directed photograph of black and beige ultracataclasite. Note the mullion-like character of the outcrop. Note as well the characteristic very light gray ghost-like splotchy and streaked patterns within the jet-black ultracataclasite. Black cataclasite reflects fresh surfaces, whereas beige hues are on more weathered surfaces. (Photograph by G.H. Davis.)

the Hope Camp trail and then climb a small hill to an outcrop of uppermost Jurassic Glance Conglomerate. This conglomerate is the basal member of the Jurassic to Lower Cretaceous Bisbee Group, which was deposited in extensional basins produced by latest Jurassic rifting associated with opening of the Gulf of Mexico (Dickinson and Lawton, 2001). At this outcrop we will see an overturned channel in the Glance Conglomerate.

The overturned Bisbee Group in this area forms part of the hanging-wall block to the nearby Catalina–San Pedro detachment fault. Structurally above the overturned Bisbee Group is the Loma Alta thrust, which places 1.65 Ga Johnny Lyon granodiorite over Bisbee Group, with slivers of volcanic-lithic conglomerate along the thrust fault. All three units and their thrust juxtaposition are present 40 km to the east in the northwestern Johnny Lyon Hills (see Fig. 3), which is the inferred source area of the Loma Alta rocks before displacement above the Catalina–San Pedro detachment fault (Spencer et al., 2019).

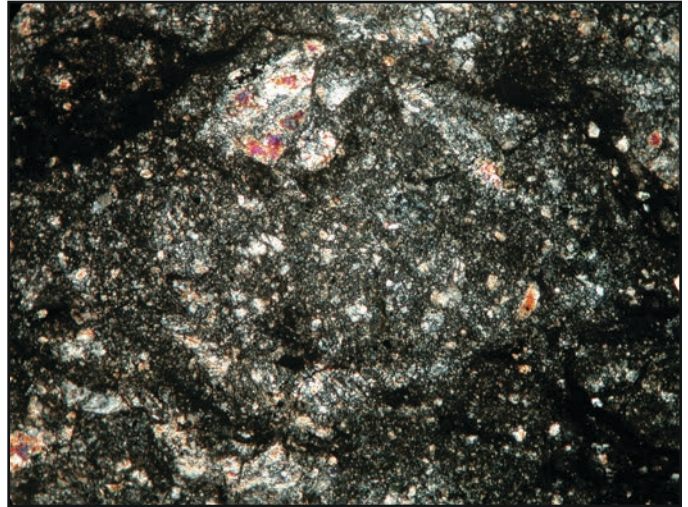


Figure 37. Photomicrograph of cataclastic fabric of the ultracataclasite. Width of field of view is 5 mm, cross-polarized light. (Photograph by Alan Alke and Alan Gregorski.)

Stop 14. Saguaro National Park and Its Natural History

Biologist Don Swann, key partner in the geological collaboration between SNP (RMD) and the Department of Geosciences, University of Arizona, focuses at this stop on the interaction of the park's geology with its ecology. Swann will direct our attention to saguaros and other desert plants and discuss how their distribution is influenced in different ways by the fault rocks of the core complex and the sedimentary rocks of the upper plate. It is an opportunity to explore the desert and its life and talk about the many ways that the geology has shaped the flora, fauna, and prehistoric cultural aspects of the Rincon Mountain District of Saguaro National Park.

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The field-trip stops within Saguaro National Park (Rincon Mountain District) are based on multiple generations of geological mapping, with the foundational work by George Davis in the mid- to late-1970s and later in 2012–2014. To this is added the results of geological mapping by Davis and students in the period 2016 to present, as part of a cooperative project with the National Park System (Permit # SAGU-2016-SCI-0009): “Researching and interpreting the geological story of Saguaro National Park, Rincon Mountains District, Tucson, Arizona.” The structural geological mapping at Loma Alta presented here (see Fig. 28) was carried out in a graduate field workshop by graduate students Hanna Brooks, Chris Clinkscales, Roy Greig, Katherine Guns, Vince Leblanc, and Simon Stickroth, and by Adjunct Professor Steve Lingrey. Undergraduate students also contributed significantly to this cooperative project, including mapping by Alex Pritika and Arthur Osakwe in the Javelina Rocks area (incorporated in Fig. 27), and by Alan Gregorski

and Alan Alke in the Tanque Verde Toe area (see Fig. 27). All of field data produced in the multiple generations of mapping were integrated with an ArcMap GIS data base by Ph.D. candidate Katherine Guns. This was not merely a compilation, but a geologically astute research rendering of the emerging state of knowledge of the fault-rock relationships. The mapping is intended to be a core contribution to Saguaro National Park and to our point research partner Don Swann, biologist for the Park.

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