Excursion to Gardner Canyon: Sedimentology and Tectonic Context of Mesozoic Strata in the Santa Rita Mountains, southeastern Arizona

by

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2003 GeoDaze Field Trip

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[entry route via Davidson Canyon – optional exit route via Box Canyon]

ENTRY ROUTE: From the UA campus, proceed south down Campbell Ave and Kino Blvd, then take the El Paso exit to I-10 eastbound. While traveling southeast along I-10, Mount Wrightson (Baldy Peak) in the Santa Rita Mountains is at 2 o'clock (eventually at 3 o'clock) on the southern skyline. To the northeast, the Rincon Mountains (rounded Tanque Verde Ridge and Mica Mountain; pointed Rincon Peak) occupy the southeast end of the Catalina core complex. Our route lies entirely within the upper plate of the detachment system.

About 20 miles down the freeway, take the State Hiway 83 exit south toward Sonoita (exit ramp is about two miles beyond the Vail Road overpass). As you approach the turnoff, the range straight ahead is the Whetstone Mountains (southwest of Benson), where the full marine Paleozoic section of southern Arizona (Creasey, 1967; Schreiber et al., 1990) overlies undeformed Precambrian basement unaffected by core-complex deformation, and is overlain unconformably by the nonmarine Bisbee Group (upper Mesozoic).

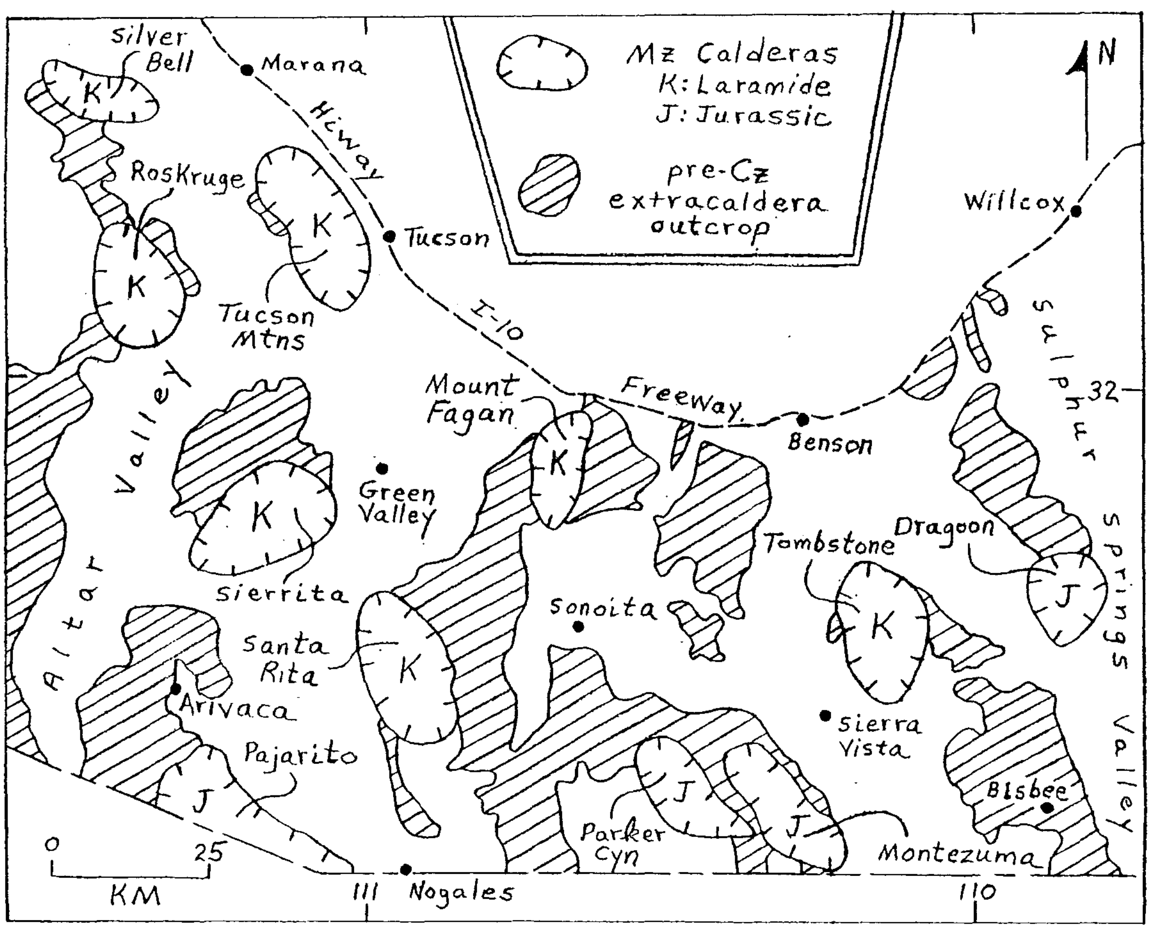
Leaving the freeway, Hiway 83 takes a straight course for about five miles across pediments (local outcrops of upper Mesozoic Bisbee Group cut by Laramide quartz porphyry) before entering Davidson Canyon. Gray Paleozoic limestone is exposed depositionally below Bisbee Group on the hill to the left at the righthand curve just before entering Davidson Canyon, which separates the Empire Mountains to the left (east) from the northern end of the Santa Rita Mountains to the right (west).

Nondescript outcrops along Davidson Canyon are mainly heterolithic intracaldera breccias (ignimbrite matrix) of the recently named rhyolite of Mount Fagan within the Upper Cretaceous Salero Formation (Ferguson et al., 2001). Outcrops near and south of the Hilton Ranch Road (about eight miles from the freeway) were referred by Schafroth (1965, 1968) to his "Hilton Ranch Conglomerate", a puzzling unit as originally described because it included conglomerate (similar to Fort Crittenden Formation seen twice later today) supposedly interbedded with volcanic rocks (uncharacteristic of Fort Crittenden Formation). With the insight provided by the recent mapping farther north, "Hilton Ranch Conglomerate" can be interpreted as intracaldera megabreccia in which slabs and rafts of Fort Crittenden Formation (older than caldera collapse) are encased in ignimbrite matrix, into which the sedimentary masses slid from the caldera rim. In the Davidson Canyon area, Fort Crittenden Formation (mapped locally by Schafroth as basal Hilton Ranch Conglomerate) is exposed resting unconformably on Bisbee Group and overlain by intracaldera breccia. Wondrous are the puzzles that nature offers the field geologist!

GATHER POINT: About 12 miles off the freeway, gather at the picnic table on the right shoulder between the sign marking the edge of Coronado National Forest and the turnoff to Rosemont Junction for a discussion of recent AzGS mapping along Davidson Canyon behind us. A rugged dip slope of Lower to Middle Jurassic Mount Wrightson Formation (volcanic & volcaniclastic) forming the core of the Santa Rita Mountains is prominently in view capping the high topographic crest to the south.

<u>Expanded Focus</u>: Mesozoic Calderas in Southeastern Arizona

In southeastern Arizona, many mountain ranges south of I-10 harbor variably modified Jurassic and Laramide calderas. A dozen major calderas have been identified (see below after Lipman and Sawyer, 1985; Riggs, 1987; Lipman and Fridrich, 1990; Riggs and Haxel, 1990; Riggs and Busby-Spera, 1991; Lipman and Hagstrum, 1992; Lipman, 1993; Moore, 1993; Ferguson et al., 2000, 2001; Richard et al., 2000). The fills, walls, and floors of the calderas occupy a significant percentage of pre-Cenozoic bedrock exposures outside Cenozoic volcanic fields and alluviated basins.



Essentially all the calderas have had some morphological features removed by deep erosion, have been tilted by later structural deformation, and are locally disrupted by younger faults. Recognition of the calderas is nevertheless vital for understanding the geologic framework of southeastern Arizona. Without appreciation of their presence, structural and sedimentological interpretations become garbled.

All the ranges were initially mapped by field geologists who lacked the volcanological insights required to appreciate the presence of calderas, and essentially all pre-1985 geologic maps are inadequate. The earlier compilation of Drewes (1980), for example, shows no Mesozoic calderas in any guise. Recognition of the calderas had to await the capability to distinguish routinely between welded tuffs and lava flows, between thick ignimbrite masses ponded within calderas and more widespread outflow tuff sheets, between intracaldera tuffs and hypabyssal intrusions, between intracaldera landslide megabreccias and other disrupted rock masses, between the onlapping depositional contacts beneath ash-flow tuff bodies that are emergent from caldera rims and more widespread unconformable contacts, between caldera-bounding structures and other kinds of faults, between caldera-rim concentric or radial dikes and other kinds of dike swarms, and between resurgent domes or intrusions of caldera interiors and plutons unrelated to calderas. Students should beware that few skills needed to map features of ancient calderas with confidence can be acquired from standard texts!

The Jurassic calderas were associated mainly with the waning phases of Jurassic arc magmatism (see *expanded focus* on Jurassic arc assemblage at Stop #1), prior to a hiatus in magmatism extending from Late Jurassic to Late Cretaceous time, and the Cretaceous calderas were associated with latest Cretaceous to earliest Paleogene magmatism and deformation (see *expanded focus* on Laramide events at Stop #3).

Davidson Canyon to Gardner Canyon

The road ahead of the gather point climbs uphill through bouldery redbeds, dipping south, of Oligocene-Miocene Pantano Formation. At the top of the first steep grade, about half a mile from the gather point, the roadcut on the left exposes a poorly dated intra-Miocene unconformity between steeply dipping Pantano Formation and gently dipping Sonoita gravels (basin fill of the Sonoita basin). The relict erosion surface on Pantano Formation just beneath the contact, which is a buttress unconformity below onlapping Sonoita gravels, is marked by boulders coated with desert varnish described by Dorn and Dickinson (1989). This is to my knowledge the only occurrence of Miocene paleovarnish ever described (nor is any comparable exposure known to me elsewhere in southern Arizona). The knobby skyline to the west is underlain largely by Paleozoic strata, with underlying Precambrian basement out of sight beyond the ridge crest and overlying Bisbee Group (upper Mesozoic) exposed in lower hills in front of the ridge.

Good roadcut outcrops of gently dipping (<5°) Sonoita gravels are exposed about one mile, two miles, and three miles up the road from the paleovarnish outcrop. Topping the crest of the hill to descend toward Sonoita, the ranges visible across Sonoita valley (left to right; east to south) are the Whetstone and then the Mustang Mountains, the Huachuca Mountains (highest crest) and the Canelo Hills (low ridge) exposing varied Paleozoic and Mesozoic strata overlying locally exposed Precambrian basement (Mule Mountains near Bisbee visible on the distant skyline to the southeast).

Note the Greaterville turnoff to the right about six miles from the Gather Point (optional return route leaves State Hiway 83 at the Greaterville turnoff this afternoon).

TURN RIGHT (west) up Gardner Canyon Road about ten miles from the Gather Point (if you reach Sonoita, you went too far!). The first mile and a half up the Gardner Canyon Road lies along valley-floor alluvium past the side road to Kentucky Camp (ignore it). Just past the sign marking the boundary of Coronado National Forest, the road climbs onto benchlands underlain by subhorizontal Sonoita gravels. About five miles from Hiway 83, ***bear right on Gardner Canyon Road, not left to Apache Springs Ranch.*** The first outcrops of complexly deformed Paleozoic and Mesozoic rocks within the Sawmill Canyon fault zone appear beside the road on the right as we pass the Apache Springs Ranch buildings to our left. Continue straight past the forest road and Arizona Trail junctions to the crossing of Cave Creek about six miles from Hiway 83.

STOP #1. Gardner Canyon Formation (***pack vehicles tightly beside the road at the ford, some behind the lead vehicle on the right and others on the shoulder to the left, leaving the center of the road clear; overflow vehicles can pull ahead up a steep short grade, to park at one of several spaces on the right shoulder, then walk back to the ford***).

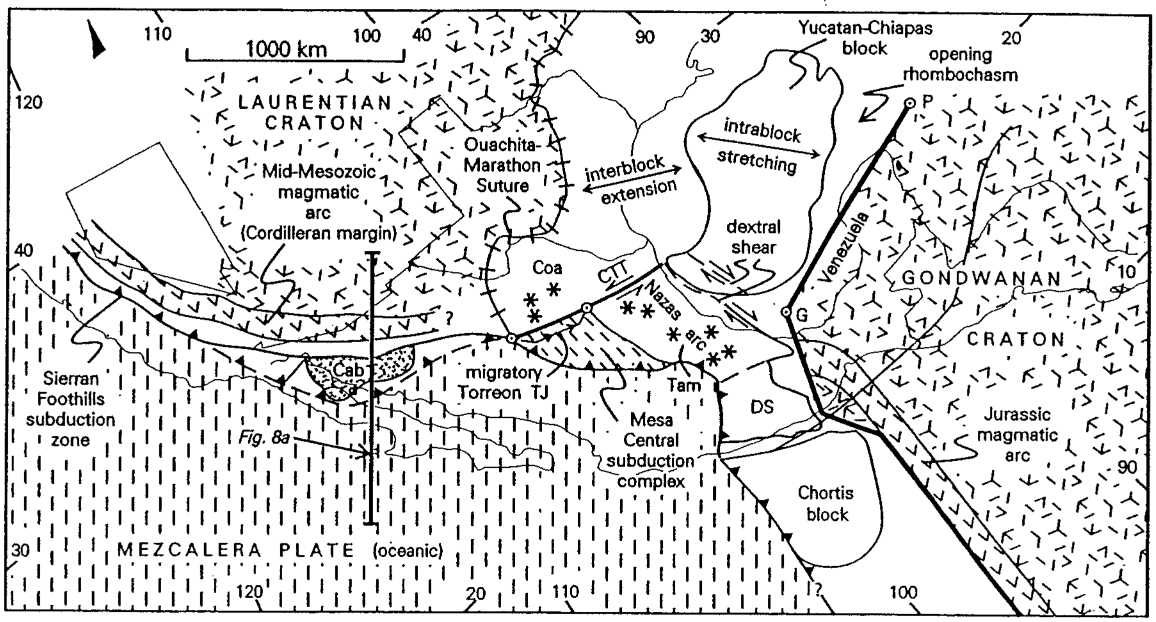
Typical lithologic constituents of the Gardner Canyon Formation, a volcaniclastic component of the Jurassic arc assemblage in southern Arizona, can be examined within the Sawmill Canyon fault zone in cutbank outcrops along Cave Creek and the tributary stream entering from the right (north):

(a) Up the side canyon, silty beds with intercalated dacite (welded tuff with eutaxitic structure) rest depositionally upon (or may be locally faulted against) Paleozoic strata (dominantly carbonate rocks) mapped as Permian Epitaph Dolomite (Drewes, 1971b).

(b) In the Cave Creek cutbank (across a minor fault mapped right along the creekbed), typical argillitic redbeds include a greenish white bed right beside the ford that may be intercalated tuff (although local diagenetic bleaching of overlying red argillite to similar pale coloration is common); interbeds of red volcaniclastic sandstone of fluvial origin can be accessed by climbing the cutbank from where the possibly pyroclastic white beds are exposed in the streambed just below the road crossing.

<u>Expanded Focus</u>: Jurassic Arc Assemblage in Southern Arizona

Jurassic igneous rocks in southern Arizona formed an integral link in a continuous chain of subduction-related arc activity that connected the mid-Mesozoic arc of the Laurentian margin along the eastern flank of the Sierra Nevada (Schweickert and Lahren, 1993) through the Mojave Desert region (Busby-Spera et al., 1990) and Arizona to the Nazas arc (asterisks in Mexico in figure below from Dickinson and Lawton, 2000), which linked in turn, prior to the opening of the Gulf of Mexico and the proto-Caribbean Sea, to the northern end of the Mesozoic Andean arc in Colombia.



Geotectonic reconstruction of Mexico from Middle Triassic (232 Ma, middle Ladinian) to Middle Jurassic (164 Ma, base of the Callovian) time. Barbs are on overriding plates of linked continental-margin arcs (position in Del Sur and Chortis domain west of Colombian Jurassic arc uncertain). Position of restored edge of Precambrian South America (see Fig. 2) at 164 Ma after Figure 3 (note unresolved mismatch of eastern tip of Del Sur block overlapped by westernmost projection of Colombian basement). Asterisks denote dated rocks of Nazas arc; trends of aligned magmatic arcs (V pattern) in California-Arizona and Colombia are schematic (see text for references). Abbreviations: Cab—Caborca block, Coa—Coahuila block, CTT—Coahuila-Tamaulipas transform, DS—Del Sur block, G—Guajira Peninsula (Colombia) (restored), P—Península de Paria (Venezuela) (restored), Tam—Tampico block, Torreon TJ—Torreon triple junction

Establishing the timing of Jurassic arc magmatism in southern Arizona has been a continuing challenge because fossils are unknown (Hayes and Drewes, 1978) and isotopic systems have been disturbed by varied processes including lead inheritance and lead loss. The most reliable single date is a concordant U-Pb age of 188 ± 2 Ma (Asmerom et al., 1990) for the Piper Gulch Monzonite (Drewes, 1971b) intruding the lower member of the Mount Wrightson Formation in the Santa Rita Mountains. This age corresponds to the Toarcian Stage (Gradstein et al., 1994), or alternatively to the preceding Pliensbachian Stage (Pálfry et al., 2000), of Early Jurassic time.

The Mount Wrightson Formation is a multivent volcanic complex of andesitic to dacitic lavas, flow breccias and volcaniclastic deposits of stratovolcanic edifices interstratified with silicic ignimbrites derived from unknown loci of eruption, and containing multiple intercalations of quartzose eolianite derived from Jurassic ergs lying to the north toward the Colorado Plateau (Riggs and Busby-Spera, 1990). The volcanogenic succession, nearly 5000 m of strata divided into three mappable members, accumulated in an arc graben depression (Busby-Spera, 1988) with its northeastern flank corresponding closely to the later position of the complexly deformed Sawmill Canyon fault zone of younger age (Laramide).

Interpretations of discordant U-Pb data initially suggested ages of ~210 Ma (Late Triassic) for the lower member (Asmerom, 1988), and of 206 ± 9 and 181 ± 9 for samples from the middle and upper members, respectively (Riggs and Busby-Spera, 1990). These inferred ages were in general accord with the preliminary age range (190 ± 10 Ma) inferred for comparably discordant U-Pb results from the apparently correlative arc succession approximately 7500 m thick exposed in the Baboquivari Mountains of the Tohono O'odham Indian Nation to the west (Tosdal et al., 1989). Further appraisal of available U-Pb data suggests, however, that the best estimates of member ages are instead as follows (key samples in each case): lower member, 184 ± 8 Ma (overlapping the age of the presumably cogenetic Piper Gulch pluton); middle member (ignimbrite sample), 183 ± 2 Ma; upper member (ignimbrite sample), 171 ± 2 Ma (Riggs et al., 1993).

Revised U-Pb ages for ignimbrites within the middle and upper members of the Mount Wrightson Formation are statistically indistinguishable from imprecise K-Ar ages of 177 ± 8 Ma and 169 ± 6 Ma (Marvin et al., 1973) for intracaldera welded ash-flow tuffs of the Canelo Hills Volcanics (Hayes et al., 1965) ponded within the Turkey Canyon and Parker Canyon calderas to the southeast (Lipman and Hagstrum, 1992). The revised age for the upper member is comparable to U-Pb ages (175-170 Ma) for ash-flow tuff erupted from the Pajarito caldera between Nogales and Arivaca to the southwest (Riggs, 1987; Riggs and Haxel, 1990; Riggs et al., 1993; Drewes, 1997). The age of 171 ± 2 Ma for the upper member is also statistically indistinguishable from an Rb-Sr isochron of 172 ± 6 Ma (May et al., 1986) for multiple ash-flow tuffs in the Corral Canyon block of the Patagonia Mountains (Simons, 1972), northeast of Nogales, where enigmatic megabreccias (Simons et al., 1966) suggest the presence of an unidentified Jurassic caldera.

A nearly concordant U-Pb age of 200 ± 5 Ma (Asmerom et al., 1993) from a dacite layer (presumably welded ash-flow tuff) within the Gardner Canyon Formation in the Sawmill Canyon fault zone (not far from our outcrop) may represent the oldest dated record of local arc volcanism shortly after the beginning of Jurassic time. Fluvial volcaniclastic strata that were perched early in the history of arc volcanism on the shoulder of the arc graben, resting unconformably on a substratum of Paleozoic rocks, may have remained unburied by the younger volcanic succession that later grew to immense thicknesses during subsidence of the adjacent arc graben. Sparse quartzose sandstone beds in the Gardner Canyon Formation (Beatty, 1987) were probably reworked from eolian sand delivered to proximal sources by the regional erg system for sediment dispersal.

Quartzose sandstones associated with redbeds that are lithologically similar (Beatty, 1987) to the Gardner Canyon Formation (and probably age-equivalent) are preserved locally in the Mustang Mountains east of Sonoita (Hayes and Raup, 1968) beneath outflow sheets of ignimbrite derived from Jurassic calderas (Turkey Canyon, Parker Canyon, Montezuma) in the Canelo Hills and Huachuca Mountains (Lipman and Hagstrum, 1992). Redbeds and overlying quartzose sandstones in the Canelo Hills that are lithologically indistinguishable (Beatty, 1987; Bilodeau et al., 1987) from the sub-ignimbrite strata of the Mustang Mountains were mapped by Kluth (1982) as "Monkey

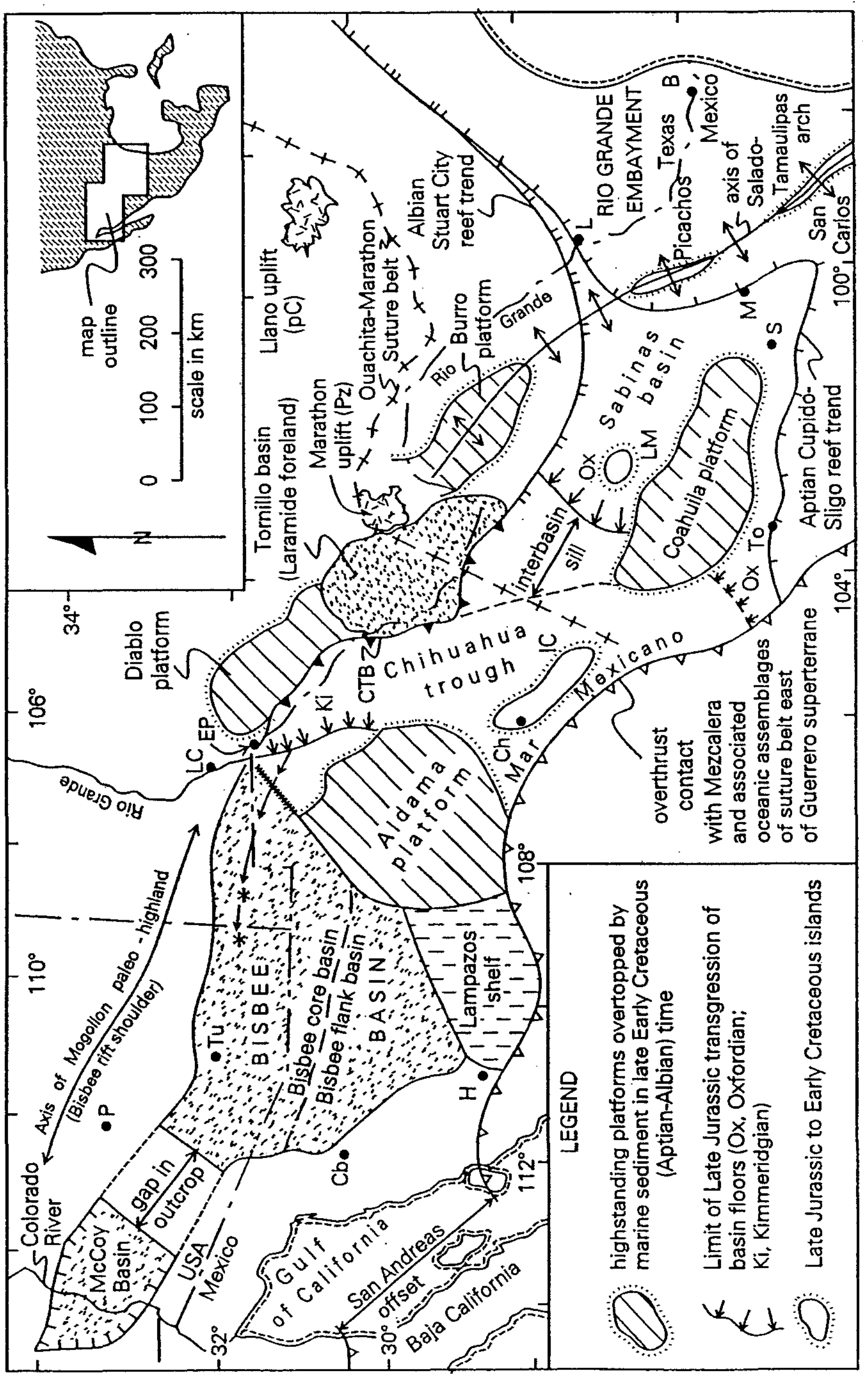
Canyon Member" and "Dark Canyon Member", respectively, of his "Mount Hughes Formation" (rocks of Mount Hughes of Kluth, 1983), and underlie welded ash-flow tuff bodies, mapped by Kluth (1982) as "Canelo Ridge Member of the Mount Hughes Formation", which probably represent outflow ignimbrite sheets of the Canelo Hills Volcanics (Krebs and Ruiz, 1987; Dickinson et al., 1987). Correlative intracaldera units of the Canelo Hills Volcanics exposed farther southeast include the "rhyolite flow member" (densely welded tuff) of the Turkey Canyon caldera and the "welded tuff member" of the superposed Parker Canyon caldera (Hayes et al., 1965; Hayes, 1970; Vedder, 1984; Lipman and Hagstrum, 1992). The "Monkey Canyon Member" redbeds and "Dark Canyon Member" sandstones are lenticular and locally intertonguing units (Beatty, 1987), with redbeds (where present) resting unconformably on Paleozoic rocks, as does the Gardner Canyon Formation, and quartzose sandstone resting unconformably on Paleozoic rocks where the redbeds are absent. The "Monkey Canyon Member" and Dark Canyon Member" of the Canelo Hills (and Mustang Mountains) can now best be regarded as local lithologic expressions of the Gardner Canyon Formation (a name which has precedence).

Stop #1 to Stop #2: The route beyond the Cave Creek ford follows stream terraces along Cave Creek and Gardner Canyon. About half a mile beyond the Cave Creek ford, turn left (just beyond a cattle guard) on Road 785 up Gardner Canyon; another half mile past the road junction, park on the left at the junction to Hog Canyon (Road 4111); then walk down Hog Canyon Road into the Gardner Canyon creekbed and traverse downstream to the left (east).

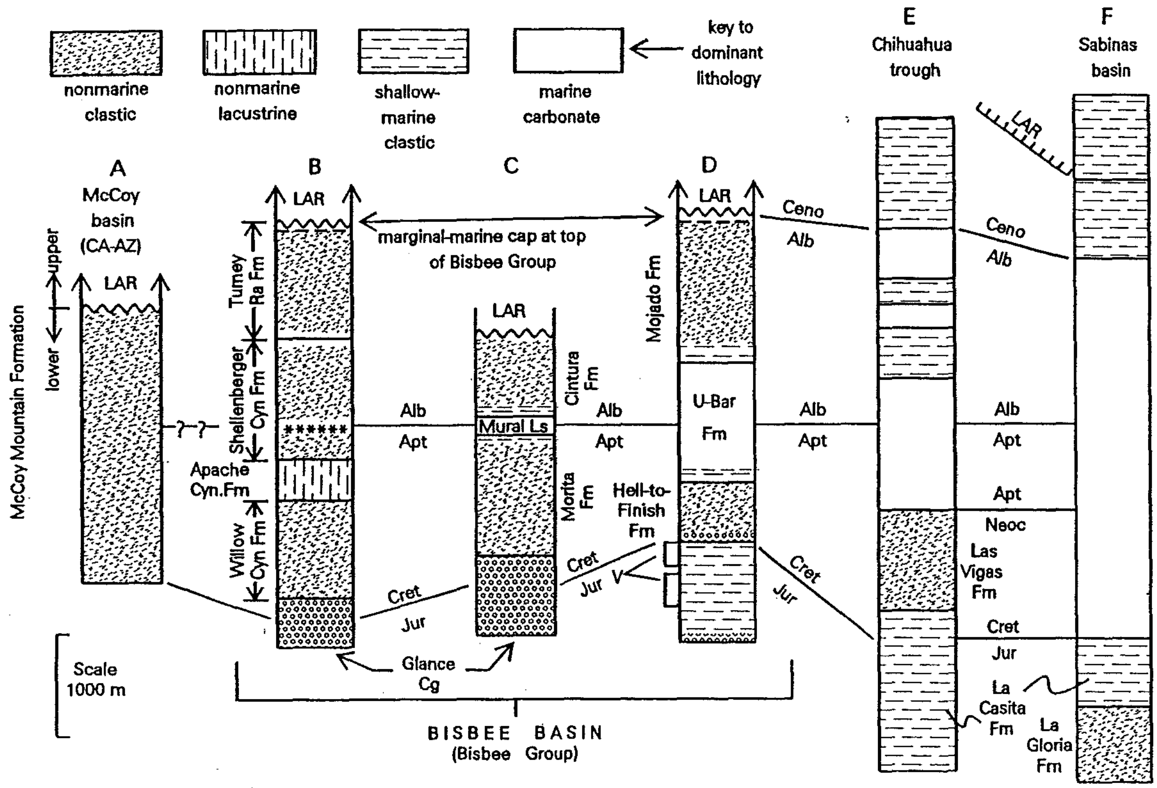
STOP #2. Upper Cretaceous Fort Crittenden Formation faulted against mid-Cretaceous Turney Ranch Formation of the Bisbee Group. The first outcrops are Fort Crittenden conglomerates, containing intercalated redbed sandstone (lithic volcaniclastic) and shale, of alluvial fan or braided fluvial facies (excellent streamswept exposures in the bend of the creek). At a narrows farther downstream, quartzose sandstone of multistory fluvial channel complexes, together with intercalated overbank red mudstone, of Turney Ranch Formation are exposed just beyond a fault at the edge of the Sawmill Canyon fault zone (fault poorly exposed in creekbed just above narrows and on vegetated sideslopes). For a quicker return to the vehicles from the outcrops at the narrows, climb the sideslope to the left (north) to the road, and retrace the road to the parking area.

***Expanded Focus:* Bisbee Basin Deposystems in USA-Mexico**

The Turney Ranch Formation is the youngest unit of the northwestern nonmarine facies belt (Klute, 1987, 1991) of the Bisbee basin, a unique Cordilleran tectonic element that was formed in late Mesozoic time as part of a rift trend (see figures on the following two pages from Dickinson and Lawton, 2001) extending into the continental block from the northwestern corner of the oceanic Gulf of Mexico as far as the inland flank of the Cordilleran magmatic arc to form a geotectonic link between Cordilleran and Caribbean realms (Dickinson et al., 1986). Incipient continental rifting in Late Jurassic time was succeeded by thermotectonic subsidence that extended into mid-Cretaceous time. In Adobe Canyon of southern Santa Rita Mountains, uppermost beds of the Turney Ranch Formation, where overlain disconformably by basal fluvial and lacustrine deposits of the Upper Cretaceous Fort Crittenden Formation, are coastal-plain deposits that include shoreface sandstone bodies recording the terminal mid-Cretaceous (latest Albian to earliest Cenomanian) marine transgression into the Bisbee basin (Inman, 1987).

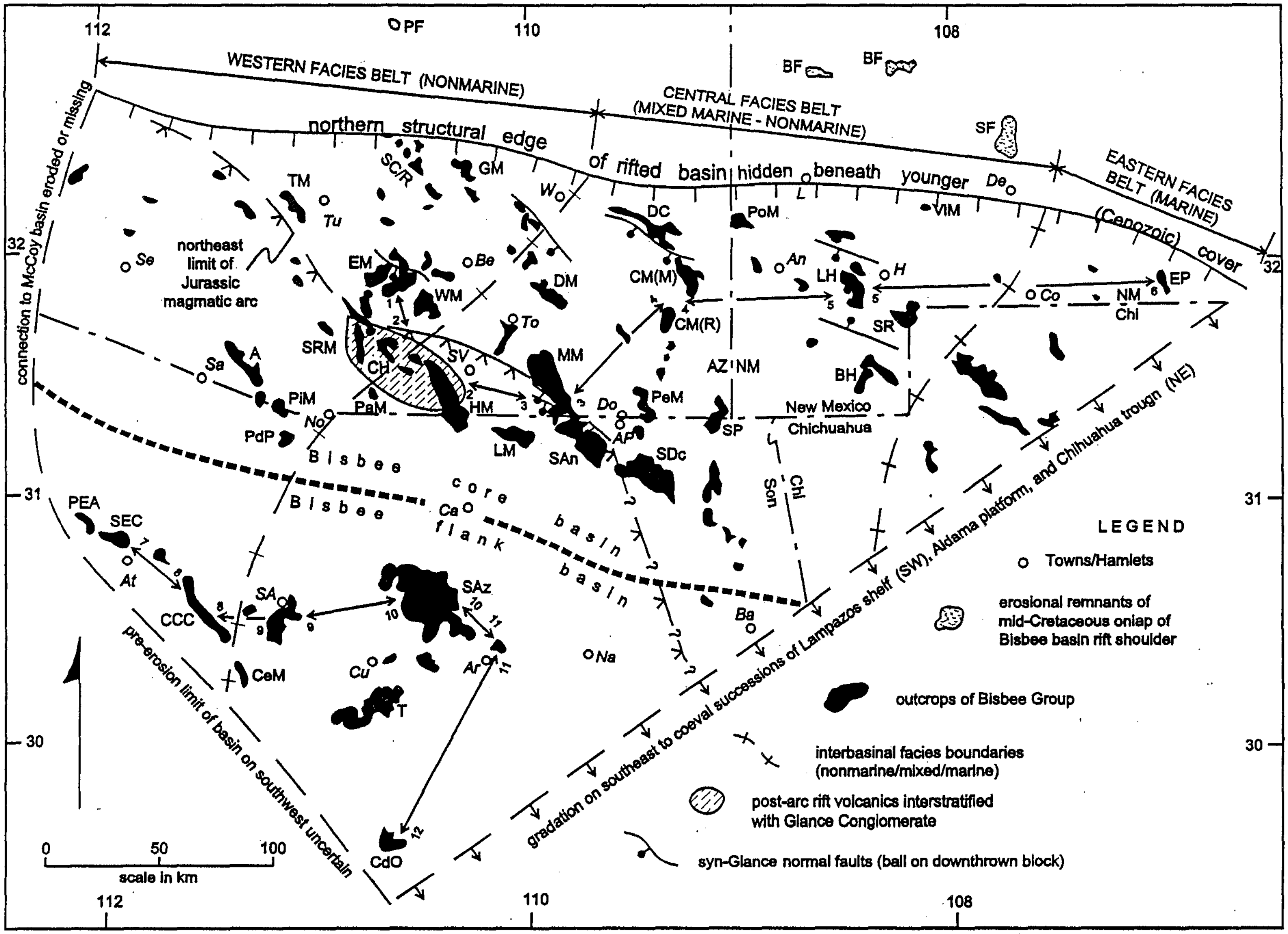


Regional tectonic setting of Bisbee and associated basins of the USA–Mexico border region. Bisbee core basin and Bisbee flank basin from Fig. 3; asterisks (*) denote exposures of Upper Jurassic marine strata along rifted keel of Bisbee basin. Extent of McCoy basin from Fig. 5. Configuration of basins and platforms in northeastern Mexico adapted after DeFord (1969), Smith (1970, 1981), Pingitore et al. (1983), Wilson et al. (1984), Cantú Chapa et al. (1985), Padilla y Sánchez (1986), Wilson (1990), Zwanziger (1992) and Wilson and Ward (1993). CTB is Chihuahua tectonic belt (Laramide) flanking deformed Chihuahua trough, and IC is Jurassic–Cretaceous Isla del Cuervo at the south end of Chihuahua trough. Jurassic islands fringing Gulf of Mexico margin after Morán-Zenteno (1994) for positions, and Götte and Michalzik (1992) for names; Late Jurassic–Early Cretaceous La Mula island (LM) of Sabinas basin after Jones et al. (1984). Aptian Cupido–Sligo and Albian Stuart City reef trends after Lehmann et al. (1999, 2000) and Wilson (1999) in Mexico, and Winker and Buffler (1988) in Texas. North edge of Bisbee basin (limit of rift trough) modified after Mack (1987a,b) and Dickinson et al. (1989). Cities: B — Brownsville; Cb — Caborca; Ch — Ciudad Chihuahua; EP — El Paso; H — Hermosillo; L — Laredo; LC — Las Cruces; M — Monterrey; P — Phoenix; S — Saltillo; To — Torreon; Tu — Tucson.

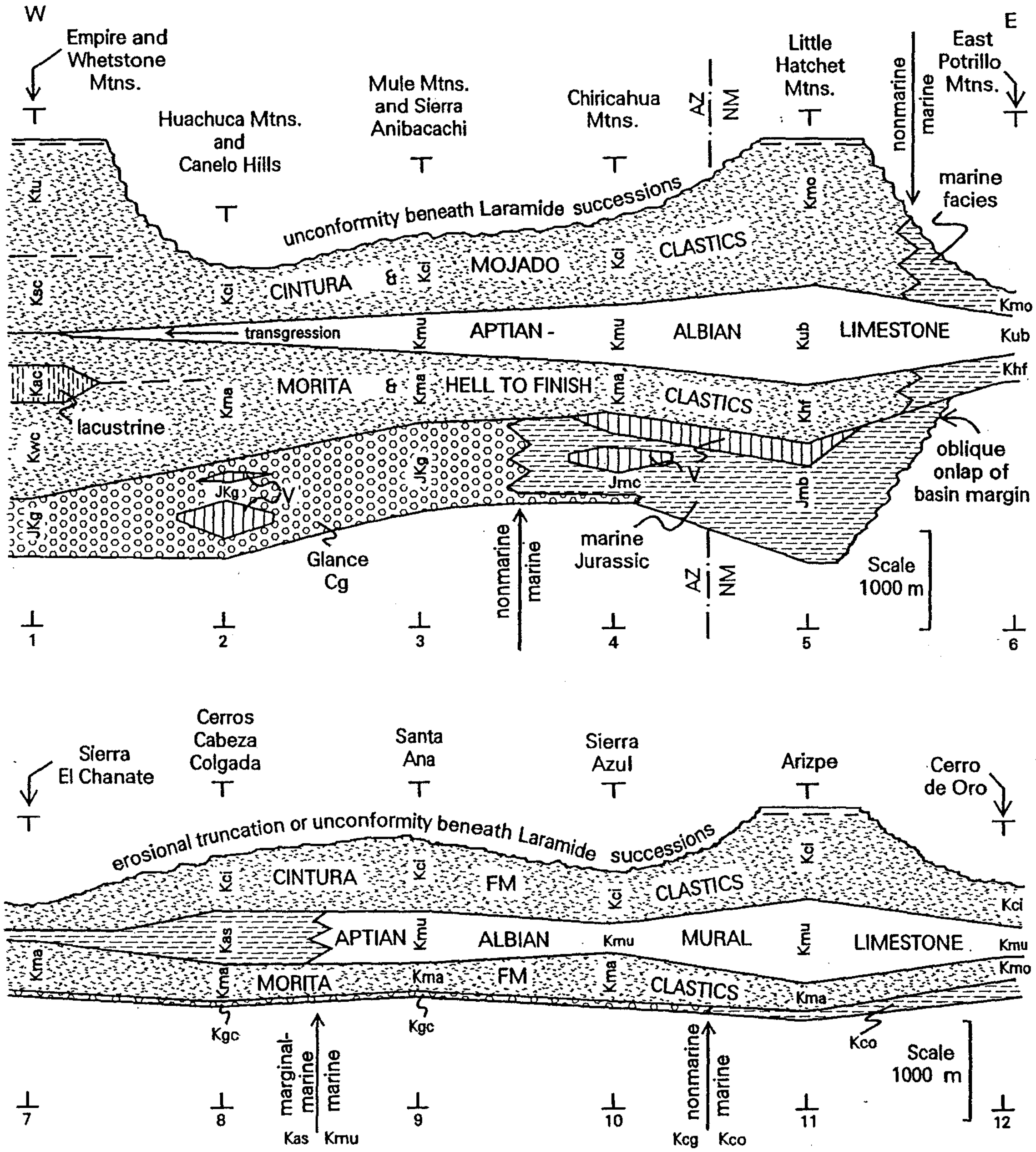


Representative stratigraphic columns (central datum at Aptian–Albian boundary) showing regional WNW–ESE lithofacies gradient within Jurassic–Cretaceous strata of the Border rift system (see Fig. 1 for geographic relations): A — McCoy basin after Harding and Coney (1985), Stone et al. (1987) and Tosdal and Stone (1994); B–C–D — Bisbee basin (see Fig. 3 for distribution of facies belts), including western (nonmarine) facies tract (B) after Dickinson et al. (1986, 1987) and central (mixed marine–nonmarine) facies tract (C–D) in southeast Arizona (C) after Dickinson et al. (1986, 1987) and lute (1991), and in southwest New Mexico (D) after Mack et al. (1986), Lawton and Harrigan (1997, 1998) and Lucas and Lawton (2000); E — Chihuahua trough after Córdoba (1969), Córdoba et al. (1970), DeFord and Haenggi (1970), Eaton et al. (1983), Araujo Mendieta and Casar González (1987), Cantú Chapa (1993), Monreal-Saavedra (1993) and Monreal and Longoria (1999); F — Sabinas basin after Cantú Chapa et al. (1985), Cuevas Leree (1985) and McFarlan and Menes (1991). Basaltic volcanic and volcaniclastic strata (denoted 'v') are interstratified with Upper Jurassic marine strata within Martyr window of Chiricahua Mountains (Fig. 4) in Arizona near New Mexico line (Lawton and Olmstead, 1995). Double-headed arrow denotes local occurrences of Albian–Cenomanian marginal-marine facies at top of Bisbee Group, and asterisks denote Aptian–Albian marginal-marine interval within otherwise nonmarine Shellenberger Canyon Formation. La Gloria and Las Vigas Formations also include marginal-marine intervals. Key biostratigraphic boundaries (inferred where dashed or queried): Cret/Jur — Cretaceous–Jurassic; Apt/Neoc — Aptian–Neocomian; Alb/Apt — Albian–Aptian; Ceno/Alb — Cenomanian–Albian (Upper–Lower Cretaceous boundary); LAR (unconformity or hachured line) — base of Laramide (Campanian–Maastrichtian) strata.

The rifted keel of the Bisbee basin extended through southern Arizona and the bootheel of New Mexico, as a rift link between the nonmarine McCoy basin to the northwest and the marine Chihuahua trough to the southeast (see the figure above from Dickinson and Lawton, 2001), with the basin flank extending southward into Sonora; facies of the Bisbee Group are nonmarine to the west, mixed marine and nonmarine within a central facies belt, and marine to the east (see figures on the following two pages from Dickinson and Lawton, 2001). The overall geometry of the Bisbee basin must be reconstructed from disconnected outcrops in multiple basin-range fault blocks, but no segment of the basin is wholly hidden from view.

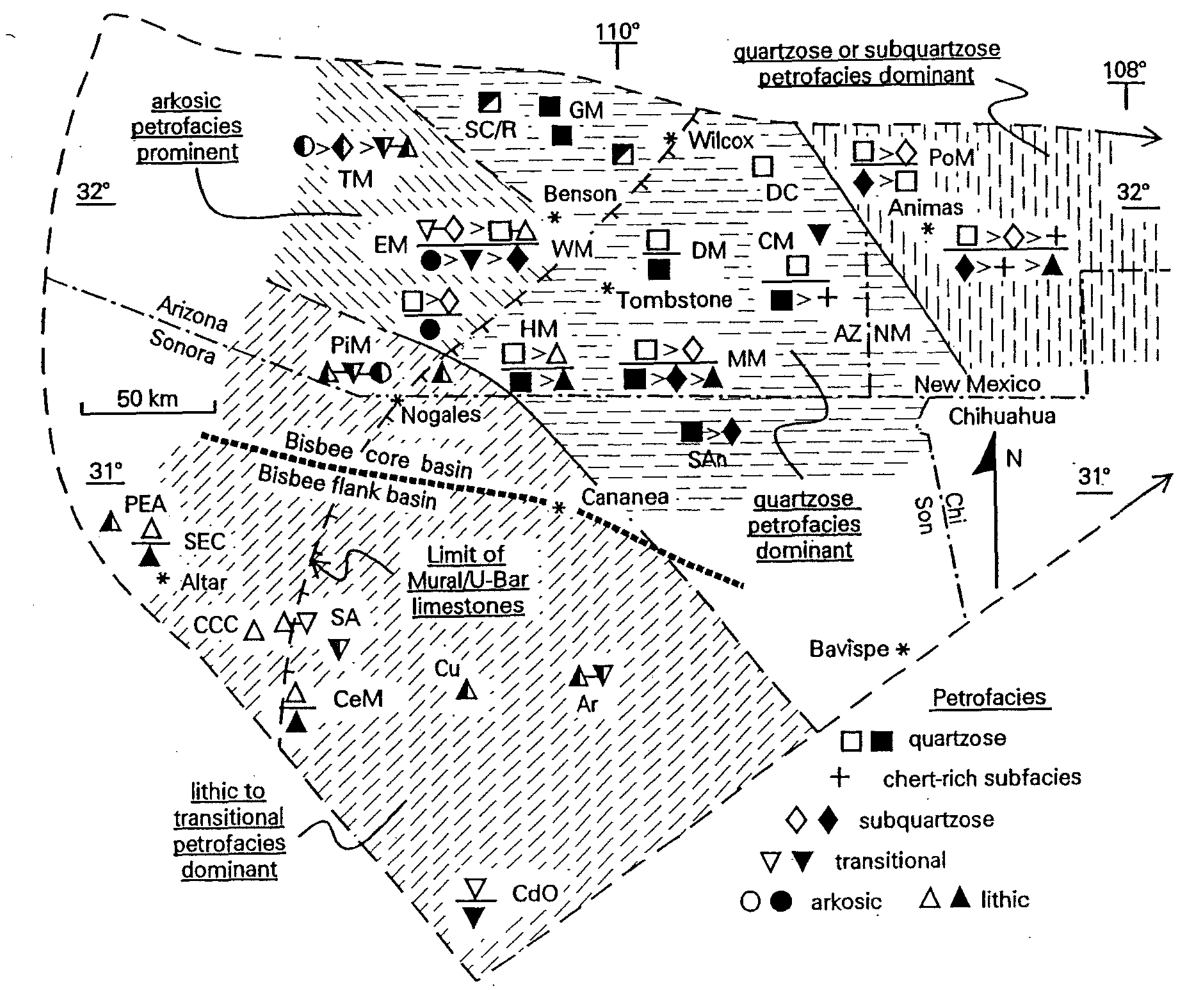


Lateral extent and internal compartments of Bisbee basin (USA–Mexico). See Fig. 1 for regional setting. Black areas denote Bisbee Group exposures (nearby outcrops grouped for clarity). Stippled areas denote mid-Cretaceous marine to marginal-marine strata (PF — Pinkard Formation; BF — Beartooth Formation; SF — Sarten Formation) onlapping Bisbee rift shoulder marked by Mogollon paleohighland (eastern extent termed Burro uplift in New Mexico). Lines with arrows show trends of panel diagrams (Fig. 4), with numbers at arrowheads indicating general locations of control columns (1–6, Fig. 4 top; 7–12,



Summary panel diagrams of stratigraphic relationships within Bisbee Group: top, Bisbee core basin in Arizona and New Mexico (AZ/NM is state line); bottom, Bisbee flank basin in Sonora. Lateral spacing of control columns (Fig. 3) not to scale. Central datum at Aptian–Albian Mural/U-Bar marine limestone interval (or equivalent). Unit designations: (a) Upper Jurassic marine strata ('v' denotes basaltic volcanic–volcaniclastic interbeds): Jmc — Crystal Cave Fm. (Chiricahua Mtns.); Jmb — Broken Jug Fm. (Little Hatchet Mtns.). (b) Jurassic–Cretaceous Glance Conglomerate and marine Cretaceous equivalents ('v' denotes mafic and silicic volcanic interbeds): JKg — Glance Cg. (Kgc where inferred to be entirely Cretaceous); Kco — Cerro de Oro Fm. (c) Pre-mid-Aptian (post-Glance but pre-Mural/U-Bar limestones) Lower Cretaceous strata: Kac — Apache Cyn. Fm. (lacustrine); Khf — Hell-to-Finish Fm. (includes Glance-equivalent conglomerate at base); Kma — Morita Fm.; Kwc — Willow Cyn. Fm. (d) Aptian–Albian marine limestone interval (and marginal-marine equivalent): Kas — Arroyo Sásabe Fm.; Kmu — Mural Ls.; Kub — U-Bar Fm. (e) Post-mid-Albian (post-Mural/U-Bar limestones) Lower Cretaceous strata (capped locally by mid-Cretaceous Albian–Cenomanian marine to marginal-marine deposits denoted by dashed line near top): Kci — Cintura Fm.; Kmo — Mojado Fm.; Ksc — Shellenberger Cañyon Fm. (basal part below Mural/U-Bar equivalent); Ktu — Turney Ranch Fm. Adapted after Mack et al. (1986), Dickinson et al. (1986, 1989), Bilodeau et al. (1987), Mack (1987a,b), González-León and Jacques-Ayala (1988), Jacques-Ayala (1989, 1992a,b, 1995), Monreal et al. (1994), Monreal (1995), González-León and Lucas (1995), Lawton and Olmstead (1995), Lawton and Harrigan (1997, 1998), Seager and Mack (1998), McKee and Anderson (1998) and Lucas and Lawton (2000).

As developed in detail by Dickinson and Lawton (2001) based on 626 modal counts by ~20 operators (largely students at UA, NMSU, UNISON), sandstone petrofacies of the Bisbee basin reflect multiple sources in several internal or nearby provenance terranes (with transitional petrofacies of mixed provenance in variable proportions locally): (a) *arkosic* petrofacies, dominant at lower stratigraphic horizons of the western nonmarine facies belt, derived from Precambrian and Jurassic granitic rocks of intrarift fault blocks; (b) *subquartzose* petrofacies, dominant at lower stratigraphic horizons in New Mexico, derived from Paleozoic strata once capping the Burro uplift (the New Mexico extension of the Mogollon highlands) along the northern rift shoulder; (c) *lithic* petrofacies (rich in volcanic rock fragments), dominant in Sonora, derived mainly from the Early Cretaceous Alisitos magmatic arc which lay immediately to the southwest of the Bisbee basin prior to Neogene opening of the Gulf of California; (d) *quartzose* petrofacies, dominant in the central mixed marine-nonmarine facies belt of southeasternmost Arizona and at upper stratigraphic horizons to both the east and the west, reworked from quartz-rich Permian and Jurassic eolianites that once capped the Mogollon highlands along the northern rift shoulder in central Arizona (see figure below from Dickinson and Lawton, 2001).



Distribution of sandstone petrofacies (Fig. 8) within Bisbee basin. Solid and open symbols for pre-mid-Aptian and post-mid-Albian strata lying respectively below and above the Aptian–Albian Mural/U-Bar limestone interval or its lateral equivalent in nonmarine strata (horizon shown as horizontal lines breaking symbol clusters). Symbols half-solid where correlation of sample sites uncertain. Tie lines connect interstratified petrofacies (>symbol where one dominant). Outline of Bisbee basin (dashed line) and limit of marine Mural/U-Bar transgression from Fig. 3.

Stratigraphic, sedimentological, and petrofacies relations of the Bisbee Group jointly exclude the hypothesis (Drewes, 1991) that the rifted Bisbee basin was instead one of an evolving family of retroarc foreland basins, related to unknown backarc thrusting, which developed sequentially from west to east between Jurassic and Paleogene time. Backarc Sevier thrusting did not extend more than ~150 km south of Las Vegas, and the Rocky Mountain retroarc foreland basin confined to the region lying north of the Mogollon highlands rift shoulder of the Bisbee basin was not onlapped from the north in central Arizona and adjacent New Mexico until Late Cretaceous (late in Cenomanian) time (Dickinson et al., 1989). Moreover, subsequent latest Cretaceous–Paleogene Laramide deformation (see *expanded focus* on Laramide events at Stop #3) was superposed on the Bisbee basin throughout its extent (Dickinson and Lawton, 2001).

Stop #2 to Stop #3: Return to the Cave Creek road (**LUNCH STOP** in a shaded grove along the way), and turn left up Cave Creek. About three-quarters of a mile up Cave Creek from the Gardner Canyon road junction, pull into a big open campsite pullout (with a rock firepit) on the right (the first such site along our route).

STOP #3. Fort Crittenden Formation. Descend on foot into the Cave Creek gorge, and also explore briefly up the small side draw beyond the main creekbed, to observe tabular-bedded sheetflood fan facies of both (a) streamflood sandstone beds including clast-supported pebble stringers, and (b) matrix-supported fine-grained debris-flow deposits (pebbly mudstone). Such overbank debris-flow deposits are not well described in the sedimentological literature, which focuses on coarse-grained debris flows within incised channel complexes, but are common in both modern and ancient settings.

<u>Expanded Focus</u>: Syntectonic Laramide Basins in AZ-NM

The Fort Crittenden Formation was deposited in one of the downflexed and downfaulted nonmarine basins contemporaneous with Late Cretaceous (Campanian) to Early Eocene (Laramide) magmatism in southeastern Arizona, southwestern New Mexico, and adjacent Sonora-Chihuahua. Syntectonic Laramide strata commonly overlie the Bisbee Group disconformably, and basement-involved reverse faults associated with the Laramide event commonly inverted normal faults that had earlier delineated depocenters of the rifted Bisbee basin (Lawton, 2000). Laramide petrofacies are highly varied, reflecting derivation from both syndepositional volcanic fields and uplifted basement blocks, as well as recycling from Bisbee Group or older strata (Dickinson and Lawton, 2001).

Except for lacustrine and overlying progradational fan-delta deposits near its base, exposed only in Adobe Canyon (Inman, 1987), the Fort Crittenden Formation of the Santa Rita Mountains (Hayes, 1986, 1987) is an alluvial fan complex built dominantly northwestward (1000-1250 m of strata derived from a combined volcanic and plutonic provenance), but also later southwestward (250-500 m of strata at its top recycled almost entirely from the Bisbee Group). In Corral Canyon at the northwestern end of the Canelo

Hills, a somewhat more proximal fan facies rests depositionally on penecontemporaneous (~75 Ma) andesitic volcanic rocks. Farther southeast, a distinctly different succession of fluvial and marginal lacustrine strata, mapped as Fort Crittenden Formation in both the Canelo Hills (Kluth, 1982) and Huachuca Mountains (Hayes and Raup, 1968), displays southeasterly directed paleocurrents, and probably represents a separate depositional system that drained into the Laramide Cabullona basin of nearby Sonora (Hayes, 1986, 1987; Lawton, 2000).

In southeastern Arizona, some have extended the name Fort Crittenden to correlative strata in multiple Laramide basins (Dickinson et al., 1989), but the standard current practice is to use a different formational name for each separate basin or discrete area of exposure: (a) American Flag Formation for associated multiple stratal successions (three intraformational members) recording complex depositional, intrusive, and deformational events along the northern edge of the Catalina Mountains (Force, 1997); (b) Cascabel Formation (~1000 m) for strata gradationally overlying the Muleshoe Volcanics (~75 Ma) along Hot Springs Canyon in the Galiuro Mountains (Goodlin and Mark, 1987); (c) Javelina (Epis, 1956) or Rucker (Mann. 19095) Formation for strata disconformably overlying Bisbee Group in Rucker Canyon between the Chiricahua and the Pedregosa Mountains (Lindberg, 1987); (d) Ringbone Formation (Lawton et al., 1993; Basabilvazo, 2000) for strata in the bootheel of southwestern New Mexico that rest unconformably on Bisbee Group and are overlain conformably by Maastrichtian Hidalgo Volcanics (base of the latter near the Campanian-Maastrichtian time boundary based on a recent $^{40}Ar/^{39}Ar$ age); (e) Campanian-Maastrichtian Cabullona Group for strata deposited in the Cabullona basin of northernmost Sonora south of the Mule Mountains (González-Léon and Lawton, 1995; Lucas et al., 1995).

In southwestern Arizona, some individually named formations include both Bisbee and Fort Crittenden equivalents. Near the Colorado River, for example, the lower McCoy Mountains formation is correlative with the Bisbee Group (Busby-Spera et al., 1990; Fackler-Adams et al., 1997; Dickinson and Lawton, 2001), but the upper McCoy Mountains Formation, above a locally angular intraformational unconformity (Tosdal et al., 1989; Tosdal and Stone, 1994), contains a tuff within the lower of its three members that has yielded a U-Pb age of 79 ± 2 Ma, and was deposited during deformation of the east-west Maria fold-and-thrust belt during Laramide time (Dickinson and Lawton, 2001). On the Tohono O'odham Indian Nation, the Sand Wells Formation includes basal conglomerate and overlying sedimentary strata that are probably Bisbee-equivalent (Tosdal et al., 1989), but also contains intercalated volcanic rocks (Haxel et al., 1980) suggesting that part of the unit may be Fort Crittenden-equivalent.

In the Tucson Mountains, the Amole Arkose (Risley, 1987) contains lacustrine beds that are lithologically similar to the Apache Canyon Formation (Soreghan, 1999) of the nonmarine western facies of the Bisbee Group exposed in the Empire and Whetstone Mountains southeast of Tucson. The lithologic correlation is strengthened by recognition of the Apache Canyon Formation in the subsurface of the intervening Tucson basin (Houser and Gettings, 2000), but the Laramide (~73 Ma) tuff of Confidence Peak erupted from the Silver Bell caldera is interbedded with upper horizons of Amole Arkose where exposed in a roof pendant of the Amole pluton (Lipman, 1993), a resurgent pluton of the caldera system. The interbedded tuff poses unresolved stratigraphic questions that are complicated by exposure of much of the Amole Arkose as megabreccia encased within the Cat Mountain Tuff, an ash-flow tuff body largely ponded within the Laramide Tucson Mountains caldera. Amole lacustrine, lakeshore, floodplain, and fluviodeltaic facies of Risley (1987), exposed in his Golden Gate, Arrastre Wash, and King's Canyon sections, lie outside the caldera rim (or below the caldera floor), and are apparently Bisbee-equivalent, but his conglomeratic fan facies is exposed largely or entirely within the caldera margin, and is probably Laramide in age (the unresolved stratigraphic and structural relationships are ripe for attention by an enterprising student!).

Stop #3 to Stop #4. Continue up Cave Creek nearly a mile and a half, passing white outcrops of Tertiary rhyolite porphyry intrusions on the points of two curves, and park on the left just before a creek crossing beyond a steep rocky grade that avoids a slot gorge on the left (non-4WD vehicles should park on the right just before the steep rocky grade).

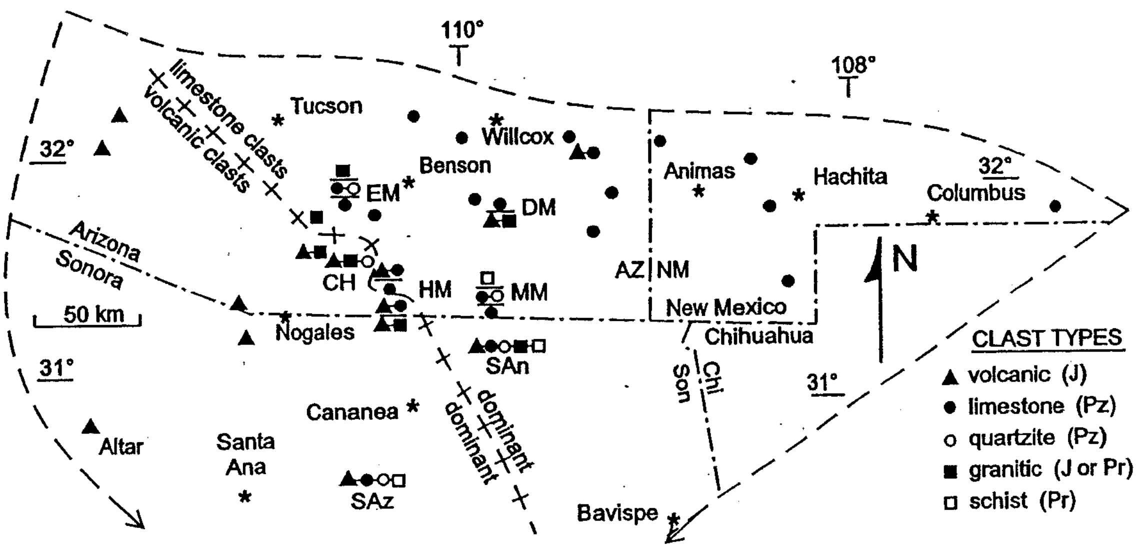
STOP #4. ***(walking stop)*** Glance Conglomerate (#4A) and Jurassic eolianite (#4B).

Stop #4A. A mixed-clast facies of Glance Conglomerate is well exposed in the slot gorge between the main and the alternate parking areas (but is best viewed at the cliff edge beside the road). Glance rests unconformably on volcanic and volcaniclastic rocks (rifted arc facies) of the Mt. Wrightson Formation.

***Expanded Focus:* Glance Conglomerate Rift Faults and Lithofacies**

The Glance Conglomerate is a diachronous (Upper Jurassic to Lower Cretaceous) formation, varying markedly in thickness (20 m to 2000 m), at the base of the Bisbee Group in southeastern Arizona and northeastern Sonora (see *expanded focus* on Bisbee basin at Stop #2). The unit is a syntectonic deposit of dominantly fanglomerate and sedimentary breccia (hyperconcentrated clast-supported streamflood deposits, matrix-supported debris-flow deposits, massive bodies of debris-avalanche megabreccia) filling the keels of deep half-grabens, and onlapping their faulted and tilted flanks, across a corrugated synrift paleotopography (Bilodeau, 1978, 1979, 1982; Bilodeau and others, 1987). Clast types vary with the nature of the faulted substratum beneath the Bisbee basin (see figure on next page from Dickinson and Lawton, 2001), and range from dominantly Paleozoic limestone on the northeast; to dominantly plutonic and metamorphic rocks derived from Precambrian basement along a central belt of the basin, and finally to Jurassic volcanic and plutonic rocks (see *expanded focus* on Jurassic arc assemblage at Stop #1) on the southwest; quartzite clasts are also prominent locally.

In several ranges, most notably in the Empire Mountains north of here and in the Mule Mountains east of here, inverted clast stratigraphy (Bilodeau, 1978, 1979, 1982; Bilodeau et al., 1987) within the Glance Conglomerate records progressive unroofing of fault blocks adjacent to thick accumulations of syntectonic conglomerate (see figure below from Dickinson and Lawton, 2001). In both southeastern Arizona and southwestern New Mexico, syndepositional faults that break the substratum of the Bisbee basin generally trend west-northwest to east-southeast (Bilodeau, 1978, 1979, 1982; Bilodeau et al., 1987; Lawton, 2000; Dickinson and Lawton, 2001), reflecting crustal extension oriented north-northeast to south-southwest. Extension has been attributed to the influence of slab rollback (Lawton and McMillan, 1999) of the Mezcalera oceanic plate (Dickinson and Lawton, 2001) beneath the Jurassic Cordilleran arc as an intraoceanic island-arc complex, the Guerrero superterrane of western Mexico and Baja California, neared the continental block prior to its tectonic accretion in Early Cretaceous time.



Areal distribution of dominant clast types in Glance Conglomerate of Arizona-Sonora, and equivalent strata in basal conglomerate of Hell-to-Finish Formation in New Mexico and Sand Wells Formation of Tohono O'Odham Indian Nation west of Tucson. Outline of Bisbee basin (dashed line) from Fig. 3. Tie lines between symbols denote mixed-clast conglomerate, most polymictic in the Canelo Hills (CH), Sierra Azul (SAz) and Sierra Anibacachi (SAn). Bars between stacked symbols separate clast assemblages of stratigraphic units defining inverted clast stratigraphy of Empire (EM) and Mule Mountains (MM), or more complex but also successive clast facies of Huachuca (HM) and Dragoon (DM) Mountains. Legend symbols denote ages of source rocks in basin substratum: J — Jurassic; Pz — Paleozoic; Pr — Proterozoic. Data from Bilodeau (1978, 1979), Haxel et al. (1980), Mack et al. (1986), Archibald (1987), Bilodeau et al. (1987), Lindberg (1987), Riggs (1987), Segerstrom (1987), González-León and Jacques-Ayala (1990), Jacques-Ayala (1995), Lawton and Olmstead (1995), Lawton and Harrigan (1998) and Lucas and Lawton (2000).

In southeastern Arizona, Upper Jurassic volcanic rocks, both mafic and felsic in character (Lawton and McMillan, 1999), are interstratified within the Glance Conglomerate of the Santa Rita Mountains, Canelo Hills, and Huachuca Mountains (Vedder, 1984; Bilodeau et al., 1987), and within overlying marine and nonmarine strata of the Bisbee Group in the Chiricahua Mountains (Lawton and Olmstead, 1995). Their occurrence induced Drewes (1968, 1971b, 1971c) to propose the local names Temporal Formation and Bathtub Formation for Glance Conglomerate containing intercalations of volcanic rocks in the Santa Rita Mountains, but subsequent work has shown that Temporal and Bathtub are local lithologic expressions of Glance Conglomerate (Bilodeau, 1979, 1982; Bilodeau et al., 1987).

The "Temporal-Bathtub" Glance succession accumulated in two subbasins (northern and southern), separated by an intervening sill and both now tilted eastward, to stratal thicknesses of ~1250 m and ~750 m, respectively, as internally complex successions of interfingering sedimentary and volcanic rocks broken by multiple intrabasinal unconformities (C.J. Busby, personal communication, 2002). The Temporal-Bathtub subbasins probably developed against the Sawmill Canyon fault zone (Bilodeau et al., 1987), which had earlier formed the cratonward edge of an arc graben and was later reactivated in Laramide time. The northern subbasin (from Gardner Canyon to Mansfield Canyon) accumulated dominantly sedimentary and volcaniclastic strata, but the southern subbasin (exposed in lower Temporal Gulch) accumulated dominantly volcanic and volcaniclastic strata. Clasts in conglomerates and sedimentary breccias are dominantly igneous rocks (both volcanic and granitic).

Syn-Glance volcanism accompanied incipient burial of the thick Jurassic arc assemblage beneath the evolving Bisbee basin, but whether the igneous assemblage should be termed post-arc or rifted-arc has long posed a semantic problem (Krebs and Ruiz, 1987). On the one hand, the Glance volcanic assemblage of the Canelo Hills and Huachuca Mountains has a bimodal character atypical for magmatic arc suites (Lawton and McMillan, 1999), and the pillow basalts, hyaloclastites, and terrestrial lavas associated with strata overlying the Glance Conglomerate in the Chiricahua Mountains were erupted in a backarc position with respect to the Jurassic arc trend. On the other hand, the Glance volcanic assemblage of the Santa Rita Mountains ("Temporal-Bathtub") includes polymodal andesitic lavas and breccias, dacitic ash-flow tuffs (including ignimbrites), and rhyolitic domes and tuffs that closely resemble arc suites (C.J. Busby, personal communication, 2002). In any case, the volcanism that accompanied Bisbee rifting and Glance deposition represented either a waning phase of arc magmatism or a transient phase of rift magmatism that terminated igneous activity in southern Arizona until reactivation of arc magmatism in Laramide time. The rift system that propagated into the continental block from the Gulf of Mexico evidently traversed the backarc region to penetrate into the Cordilleran magmatic arc as far as the McCoy basin of Arizona-California.

Glance ignimbrites from the Canelo Hills (Kluth et al. 1982: Bilodeau et al., 1987; Dickinson et al., 1987) and "Temporal" volcanics of the Glance Conglomerate in the Santa Rita Mountains (Asmerom et al., 1990) have yielded identical Rb-Sr isochrons of 151 ± 2 Ma and 151 ± 5 Ma, respectively. A single K-Ar age of 147 ± 6 Ma for correlative welded tuff in the Huachuca Mountains (Marvin et al., 1973; Vedder, 1984; Bilodeau et al., 1987) is statistically indistinguishable. Although alkali metasomatism (Krebs and Ruiz, 1987) after eruption may have disturbed the Rb-Sr isotopic systems of the samples, the indicated age near the Kimmeridgian-Tithonian boundary (Gradstein et al., 1994; Pálfry et al., 2000) is compatible with fossil collections from the lower Bisbee Group farther east. The Crystal Cave Formation overlying Glance Conglomerate in the northern Chiricahua Mountains has yielded mid-Oxfordian to mid-Kimmeridgian (~155 Ma) ammonites (Lawton and Olmstead, 1995; Olmstead and Young, 2000), and marine invertebrates from the generally correlative Broken Jug Formation (Lawton and Harrigan, 1998; Lucas and Lawton, 2000) of the Little Hatchet Mountains in the bootheel of New Mexico indicate a Kimmeridgian-Tithonian age (Lucas et al., 2001).

Silicic quartz porphyry overlain either disconformably (Harding and Coney, 1985) or gradationally (Fackler-Adams et al., 1997) by the McCoy Mountains Formation near the Colorado River has yielded U-Pb ages (discordant) of 162 ± 3 Ma and 155 ± 8 Ma in California, and discordant U-Pb data from Arizona project to concordia at comparable ages of 165-155 Ma (Dickinson and Lawton, 2001), slightly older (~Callovian) than Glance Conglomerate (as expected).

The Glance Conglomerate exposures including interbedded ignimbrites in the Canelo Hills were once mapped as a supposedly lower member of the Canelo Hills Volcanics (Hayes at al., 1965), but Kluth (1982, 1983) showed that they actually overlie the Canelo Hills Volcanics, with his "Canelo Pass Member of the Mount Hughes Formation" being Glance Conglomerate (Vedder, 1984; Bilodeau et al., 1987). Mesozoic megabreccias in the Canelo Hills have puzzled generations of field geologists for decades (Simons et al., 1966; Denney, 1971; Davis et al., 1979), but include both intracaldera landslide deposits (Lipman and Hagstrum, 1992) within the Canelo Hills Volcanics (see *expanded focus* on Jurassic arc assemblage at Stop #1) and piedmont debris-avalanche deposits (Vedder, 1984; Bilodeau et al., 1987) within the Glance Conglomerate. Interpretations can be clarified locally by close attention to the nature of megabreccia matrix (tuff matrix in the case of intracaldera megabreccias), the nature of associated strata (alluvial conglomerate in the case of piedmont megabreccias), and the internal character of the megabreccias (more intricately disrupted in the case of the piedmont megabreccia bodies than in the case of the intracaldera megabreccia bodies which were cushioned to some extent by the ash-flow tuff that encloses them). Stratigraphically, the down-faulted successions of Glance Conglomerate are also superimposed across caldera-bounding structures that confine the intracaldera megabreccias (Vedder, 1984). Along strike in the Glance Conglomerate of the Huachuca Mountains, for example, clast types vary from mostly Paleozoic limestones to the north (outside all Jurassic caldera margins), to dominantly volcanic and plutonic to the south, where fully half the clasts in Glance Conglomerate deposited locally above the Montezuma caldera are Huachuca Quartz Monzonite, a resurgent intrusion of the caldera complex already exposed to erosion by the time of Glance deposition (Bilodeau et al., 1987). However, where megabreccia bodies have been deformed by intricate Laramide faulting associated with the broad Sawmill Canyon fault zone, individual exposures may nevertheless be almost enigmatic in areas of limited outcrop, even with improved interpretive concepts tucked firmly into the field kit bag!

Stop #4B. Walking ahead on the road for about a quarter mile, past two creek crossings where Glance Conglomerate is less well exposed, go uphill (north) on Road 92, but just as soon as Road 92 swings to the left at the top of a steep rocky grade, angle off the road to the right through an oak grove and work up the spur crest to buff outcrops of quartzose eolianite (with sweeping crossbeds) interbedded within the Mt. Wrightson Fm (if you delay swinging off the road, you will find yourself stuck in manzanita thickets on the sidehill!).

***Expanded Focus:* Southern Limit of Colorado Plateau Jurassic Ergs**

Quartzose eolian sandstones of extra-arc sedimentary provenance are closely associated stratigraphically with Jurassic volcanic rocks for 600 km along the trend of the Mesozoic Cordilleran magmatic arc from south-central Arizona to the central Mojave Desert of California (Bilodeau and Keith, 1986; Busby-Spera, 1988; Tosdal et al., 1989). Eolian sand was blown into the active arc from the extensive sand seas of Jurassic ergs lying to the north on the Colorado Plateau.

Correlation of the arc eolianites with specific eolian units on the Colorado Plateau is difficult because of combined uncertainties in the biostratigraphic ages of erg deposits and in the chronometric calibration of biostratigraphic stages. The problem is further complicated by the possibility that Jurassic formations composed of eolianites on the Colorado Plateau may be regionally diachronous in age (Freeman, 1976). That view is disfavored by standard correlations (Blakey et al., 1988) based on the presumed synchroneity (Blakey, 1996) of widespread unconformities (Pipiringos and O'Sullivan, 1978) that seemingly partition the Jurassic eolianite succession into discrete stratal packages (Riggs and Blakey, 1993), but cannot be wholly dismissed with presently available geochronological tie points.

The oldest Jurassic paleoerg is the Wingate Sandstone (Sinemurian), 202-195 Ma from Gradstein et al. (1994) or 196-192 Ma from Pálfry et al. (2000), which may correlate with the minor quartzose sandstone bodies in the Gardner Canyon Formation (~200 Ma) and its correlatives. The largest Jurassic paleoerg includes the well-known Navajo Sandstone and the correlative Aztec sandstone of the northeastern Mojave near Las Vegas, as well as the contiguous Nugget Sandstone of northern Utah and southwest Wyoming (together forming an ancient sand sea comparable in overall size to the largest known modern sand sea of the vast Rub' al Khali in the Empty Quarter on the Arabian Peninsula). The Navajo Sandstone and its correlatives are thought to range in age from mid-Pliensbachian to mid-Toarcian, a time span of 192-185 Ma (Gradstein et al., 1994) or 188-181 Ma (Pálfry et al., 2000). Younger and more restricted eolian units at the base of the overlying San Rafael Group, but closely associated with the top of the Navajo Sandstone on the Colorado Plateau, include both the Temple Cap Sandstone (Aalenian, 180-176 Ma or 178-174 Ma from the alternate time scales) and the Page Sandstone (mid-Bathonian to mid-Bajocian, 173-167 Ma or 170-163 Ma from the alternate time scales). The youngest extensive paleoerg of the Entrada Sandstone (Callovian, 164-159 Ma or 160-156 Ma from the alternate time scales), higher in the San Rafael Group, is probably too young (<165 Ma) to correlate with any intercalations of eolian sand in the Jurassic arc.

In the Mojave Desert, quartzose eolianite of the Palen Formation underlies arc volcanic rocks dated by a U-Pb concordia intercept as 175 ± 8 Ma (Fackler-Adams et al., 1997), an age comparable to that of the Canelo Hills Volcanics (~175 Ma) overlying strata that include quartzose sandstones in the Canelo Hills and Mustang Mountains (see *expanded focus* on Jurassic arc assemblage at Stop #1). An upper age limit of ~175 Ma for the arc eolianites would suggest correlation with either the Navajo Sandstone or the closely associated Temple Cap Sandstone.

With analytical uncertainties taken into account (see *expanded focus* on Jurassic arc assemblage at Stop #1), U-Pb-dated ignimbrites of the middle and upper members of the Mount Wrightson Formation (containing prominent intercalations of eolianite) were erupted during the time interval of 185-169 Ma, with the thickest eolianite lenses in the upper member (~170 Ma). These chronological ages are only marginally correlable with the Navajo Sandstone, and match better with the overlying Temple Cap Sandstone and Page Sandstone (the latter especially for the upper member and the correlative tuff of Pajarito) of the basal San Rafael Group.

Despite the problems of correlation that emerge in detail, the huge Navajo-Aztec erg still seems the most likely source for quartzose eolian sand lenses in the arc assemblage, as inferred by Bilodeau and Keith (1986). Reaching toward a possible sedimentological rationale for the discrepancies in apparent age, perhaps eolian sand was blown toward the arc, off the Navajo-Aztec erg, during a regime of widespread deflation on the Colorado Plateau that developed the unconformities between the Navajo Sandstone and overlying eolian units (Temple Cap, Page) of the San Rafael Group. Through this line of reasoning, it is possible to envision times of maximum eolianite accumulation that were out of phase within the erg and along its arc margin.

The thickest lens (~250 m) of eolianite within the upper member of the Mount Wrightson Formation is comparable in thickness to the full Navajo Sandstone in the central part of the Colorado Plateau (southern Utah), and suggests that southward advance of the Early (to Middle) Jurassic erg margin was halted by highstanding paleotopography (Bilodeau and Keith, 1986), or arrested by the lowstanding sump of an arc graben (Busby-Spera, 1986), aligned along the arc trend. Eolian transport of sand southward through central Arizona presumably occurred across the later locus of the rift shoulder of the Bisbee basin (see *expanded focus* on the Bisbee basin at Stop #2) before the Mogollon highlands had formed along the flank of the Bisbee basin (Bilodeau, 1986; Bilodeau and Keith, 1986: Dickinson et al., 1989). The present absence of Jurassic eolianite units from central Arizona can therefore be attributed to removal by erosion along the Mogollon highlands (and synrift Bisbee paleotopography farther south), rather than to nondeposition.

RETURN to Hiway 83 and turn left toward Tucson, but after about four miles (just beyond the INS checkpoint), turn left (west) toward Greaterville. For about five miles, the route lies through dissected benchlands underlain by Sonoita gravels ***(about four miles from Hiway 83, bear right toward Madera Canyon, leaving the paved road to Greaterville at the turn)***. Just past a dirt crossroads about five miles from Hiway 83, the route crosses a fault contact (steep Neogene Basin-and-Range fault) between Sonoita gravels in the downthrown hanging wall (near side) and indurated Bisbee Group exposed ahead in the upthrown footwall (far side). Sonoita gravels near the faulted basin margin are well exposed along a small winding canyon as the road descends into Box Canyon from the benchlands of Sonoita valley, and Bisbee Group is first exposed at a spur end on the right just beyond the fault contact near the crossroad. Our last stop (in three parts) examines controversial structural relations between the Bisbee Group and Precambrian basement.

STOP #5A. A quarter mile beyond the fault contact, pull out ***(carefully)*** on the left to view fluvial sandstone and intercalated red mudstone of the Willow Canyon Formation (overlying Glance Conglomerate within the Bisbee Group).

STOP #5B. A half mile beyond the fault contact, pull out on the right shoulder to view a depositional contact between Precambrian granitic rock and the overlying Glance Conglomerate at the base of the Bisbee Group. Outcrops at the downhill end of the roadcut are Precambrian granitic rock in place. Outcrops at the uphill end of the roadcut are indurated but fragmental sedimentary breccia (Glance Conglomerate) composed of granitic detritus. Near the downhill end of the parking apron is a gradational zone of paleogrus where Glance rests unconformably on granitic basement across intervening outcrop of weathered and slightly displaced granitic detritus.

STOP #5C. About a mile and a quarter beyond the base of the Glance Conglomerate, pull out to the right at a sharp bend (lefthand curve) with bold outcrops (white-streaked) of Precambrian basement (examine the latter briefly and regroup to travel home).

Expanded Focus: Regional Thrust Faults in Southeastern Arizona

Drewes (1971a) mapped the contact we have examined between Glance Conglomerate and Precambrian basement as a fault, but Drewes and Finnell (1968, p. 319) had earlier concluded that fault displacement at the contact is minor. They noted also that a lenticular exposure of Cambrian Bolsa Quartzite, present along the contact in the ravine below the road, is "nearly in place" as an erosional remnant of Paleozoic strata preserved beneath the sub-Bisbee unconformity. The contacts both above and below the exposure of Bolsa Quartzite are viewed here as unconformities (Dickinson et al., 1987, p. 270).

Drewes (1976, fig. 3; 1978, fig. 3; 1980, sheet 1 inset; 1981, fig. 3) later interpreted the supposed fault in Box Canyon as a deformed segment of his postulated subregional Cochise thrust, a structure associated with the analogous Hidalgo thrust thought to be present at a deeper structural level. The Hidalgo-Cochise thrust complex was inferred to have transported both basement and sedimentary cover 20-200 km toward the northeast in Laramide time (Drewes, 1978, 1981).

The other most prominently exposed segment of the alleged Cochise thrust has been described as an unconformity in the Dragoon Mountains east of Benson (Keith and Barrett, 1976; Bilodeau et al., 1987), and the principal exposed segments of the Hidalgo thrust in the Little Dragoon Mountains and Johnny Lyon Hills north of Benson are low-angle normal faults of mid-Tertiary age (Dickinson, 1984). The now well documented stratigraphic and sedimentological framework of the Bisbee basin is not supportive of hypothetical Hidalgo-Cochise thrust disruption of depositional systems (Dickinson and

Lawton, 2001), and the "working hypothesis" (Drewes, 1981, p. 22) of subhorizontal basement-involved thrusts of regional scale in southeastern Arizona can be rejected as unsupported by any subsequent work (Dickinson, 1984).

EXIT ROUTE: From the last stop, continue ahead on the main route of vehicle travel to I-19, then proceed north toward Tucson. Ahead down Box Canyon, Baboquivari Peak is visible on the west skyline, and the Box Canyon bridge is reached about a mile and a quarter from the last stop. Thereafter, the route lies across dissected piedmont fans at the foot of the Santa Rita Mountains, then down Madera Canyon Road to Continental (to reach I-19 back to Tucson, turn left as directed at the stop sign about 15 miles from the Box Canyon bridge, then right at the I-19 entry ramp). Bon Voyage! (you are on your own to find Tucson).

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