MID-TERTIARY SYNEXTENSIONAL SEDIMENTATION AND STRUCTURE
in the Northern
TORTILLA MOUNTAINS
Pinal County, Arizona

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Arizona Geological Society Spring Field Trip
April 17, 2004

Road Log

Distance Between Stops	Distance	Cummulative Distance	Description
	0	0	Depart Texaco in Winkelman. Go south on HWY 77
	1.1	1.1	Turn off paved road to west, Cattle guard and fence with green sign "10940" (between mileposts 133 & 134)
	0.2	1.3	Cross San Pedro River
	0.5	1.8	Turn right at stop sign and follow railroad grade
	0.3	2.1	Teapot Mountain seen to North at skyline (18.6 Ma Apache Leap dacite tuff), Saddle Mountain seen to East-southeast (Williamson Canyon Volcanics)
	0.8	2.9	Cross railroad tracks and continue north
	0.5	3.4	Intersection in road, continue straight ahead
	1.9	5.3	Fork in road, main road veers left up Romero Wash (marked with sign), take right (smaller) fork along Gila River
	0.2	5.5	Gate 1
	1.8	7.3	Gate 2
	1.9	9.2	Gate 3
	1.1	10.3	Gate 4 (Radio Tower)
	0.2	10.5	Gate 5
	0.3	10.8	Forks in road: Take middle fork
	0.2	11.0	Straight ahead in distance, gray cliffs are limestone megabreccia deposits in lower Hackberry Wash section
	0.5	11.5	Top of measured section
	0.1	11.6	Road veers west and climbs hill, driving down section
	0.3	11.9	Gate 6
	0.4	12.3	Near top of measured section
	0.3	12.6	Gate 7 (junkyard) Note!! Do not go through this gate! Turn left just before gate. Enter Hackberry Wash
12.8	0.2	12.8	Stop 1 Park here and walk due north 100 meters.
	0.6	13.4	Light-colored ash-fall tuff bed in sandstones to south (left)
	1.9	15.3	Gate near Hackberry Spring, turn right and follow fence immediately past (south of) the gate
	0.3	15.6	Take right fork and follow road up steep hill to west
	0.2	15.8	Gate
3.1	0.1	15.9	Stop 2: Turn around at small side road about 100 meters beyond the gate and park.
	0.5	16.4	Drive back down hill and back through second gate
	0.4	16.8	Take left fork into Falls Canyon
1.0	0.1	16.9	Stop 3: Turn around at fence and park.
	0.1	17.0	Drive back to main road in Hackberry Wash and turn left. Drive 0.7 Miles to Stop 4. Note decrease in dip of bedding as you drive east down Hackberry Wash.
0.8	0.7	17.7	Stop 4: Park and walk about 100 meters up Gila Monster Canyon
	1.3	19.0	Drive East in Hackberry Wash to small side road up Rattlesnake Canyon. Again, note decrease in dips and several outcrops with well-developed growth folds.
	0.4	19.4	Gate
2.6	0.9	20.3	Stop 5: Turn around and park.

	0.9	21.2	Gate (returning down Rattlesnake Canyon)
1.0	0.1	21.3	Stop 6: Park and walk up small hill to east.
13.3	13.3	34.6	Return to Winkelman

Timetable

Duration	Time		Description
		9:00 AM	Depart Texaco in Winkelman. From here, go south on HWY 77
0:40	9:00 AM	9:40 AM	Drive to Stop 1 (East end of Hackberry Wash)
0:45	9:40 AM	10:25 AM	Stop 1: Brief Introduction. Hike 100 meters north. Look at the rocks for a few minutes. Then we'll have a discussion.
0:20	10:25 AM	10:45 AM	Drive to Stop 2 (Top of ridge west of Hackberry Spring)
0:45	10:45 AM	11:30 AM	Stop 2: Park where the side road branches off to the south up a small steep hill. Walk north-northeast about 50 meters to the south flank of the limestone ridge. Regional geology discussion.
0:10	11:30 AM	11:40 AM	Drive to Stop 3 (Falls Canyon)
0:45	11:40 AM	12:25 PM	Stop 3: Hike up Falls Canyon. Short discussion here, then look at the rocks on the way back to the vehicles.
0:10	12:25 PM	12:35 PM	Drive to Stop 4 (Gila Monster Canyon)
0:45	12:35 PM	1:20 PM	Lunch: Grab your lunches & drinks. Hike ~ 100 meters north into Gila Monster Canyon. Eat lunch here. **Note!** From this point, we will hike after lunch (we will NOT return to the vehicles after lunch).
1:00	1:20 PM	2:20 PM	Stop 4: Hike up Gila Monster Canyon to megabreccia deposits. Short discussion and look at section on return trip.
0:15	2:20 PM	2:35 PM	Drive to Stop 5 (Rattlesnake Canyon)
1:00	2:35 PM	3:35 PM	Stop 5a: Hike west-southwest up Rattlesnake Canyon. Again, we will hike up the canyon first and look at the rocks as we hike back.
0:20	3:35 PM	3:55 PM	Stop 5b: Look at the rocks immediately north of the area we parked.
0:15	3:55 PM	4:10 PM	Drive to Stop 6 (Mouth of Rattlesnake Canyon)
1:00	4:10 PM	5:10 PM	Stop 6: Hike up small hill to east-northeast. Summary of trip and extended discussion of observations and implications. Discuss maps and cross sections and brief introduction of future trip.
0:40	5:10 PM	5:50 PM	Return to Winkelman

Middle-Tertiary Synextensional Sedimentation and Structure

in the northern

Tortilla Mountains

Pinal County, Arizona

David Maher[1], Aaron Martin[2], David Mauel[3], Deborah Bryan[4], Steven Hubbs[1], and Eric Seedorff[1]

Overview:

This field guide is one of the products of a study conducted during the spring of 2002 by students of a University of Arizona advanced mapping course in the northern Tortilla Mountains, southwest of the Ray Mine, in Pinal County, Arizona. The study was sponsored by the Educational Component of the USGS National Cooperative Geologic Mapping Program (EDMAP). The goal of the class was to improve observation and geologic mapping skills while developing an understanding of magmatic-hydrothermal and structural processes in the region of study.

In the Tortilla Mountains, normal faulting and tilting caused by mid-Tertiary extension--superimposed upon local, pre-Laramide, compressional deformation--resulted in ~90° of rotation of large crustal blocks and the development and variable tilting of sedimentary basins. Geologic maps of the area, therefore, are actually sets of paleo cross sections! The cross-sectional exposure provides several kilometers of excellent exposure of the pre-Tertiary crust as well as the Tertiary syn-extensional sedimentary succession (Figs. 1, 2). The pre-Tertiary geology of the region can be reconstructed by working backward in time using the syn-extension sedimentary record, much of which is exposed in Hackberry Wash. In Hackberry Wash we will observe bedding ranging from ~90° at the mid-Tertiary unconformity to ~30°, where the section meets the modern Gila River drainage basin, with near continuous exposure.

The study was divided into two components, each addressed by a team of geologists. One group distinguished previously unmapped pre-Tertiary igneous rock phases and mapped related hydrothermal mineral assemblages. A second group conducted a detailed study of syn-extensional sedimentary rocks including recognizing and recording pre-Tertiary clasts. The geology of the region is significantly influenced by the middle Tertiary extensional structure, and an understanding of both aspects of the study required a close working relationship between the two groups. This trip, however, is divided into two sections for logistical purposes. The first portion of the trip is presented here in this guide. The second portion will be the subject of a future trip (perhaps fall of 2004).

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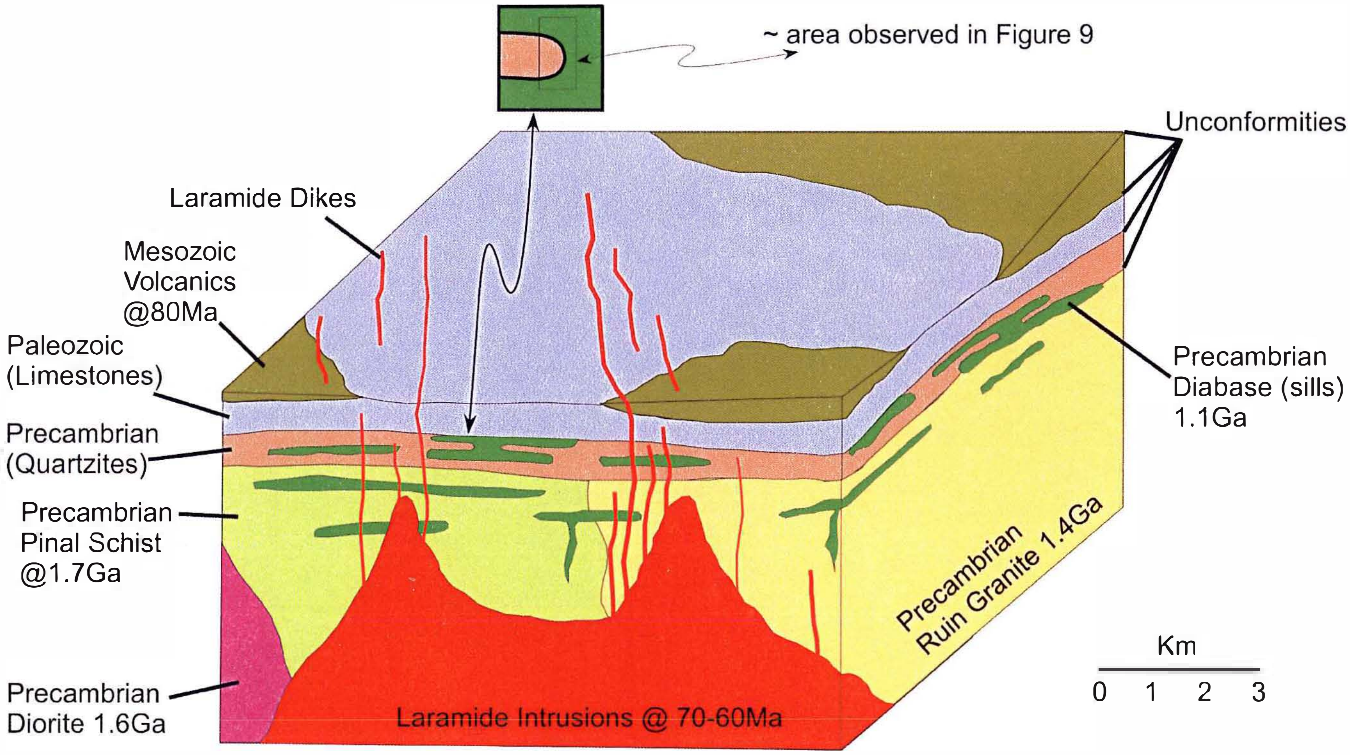


Figure 1. Schematic reconstruction of the crust (units grossly simplified) before extensional faulting and tilting in the middle Tertiary. This figure does not show (smaller-scale?) thrust faults and folds that occur locally throughout the region. The front face (cross section) of the block diagram represents the present-day map view, with the top of the figure facing present-day east.

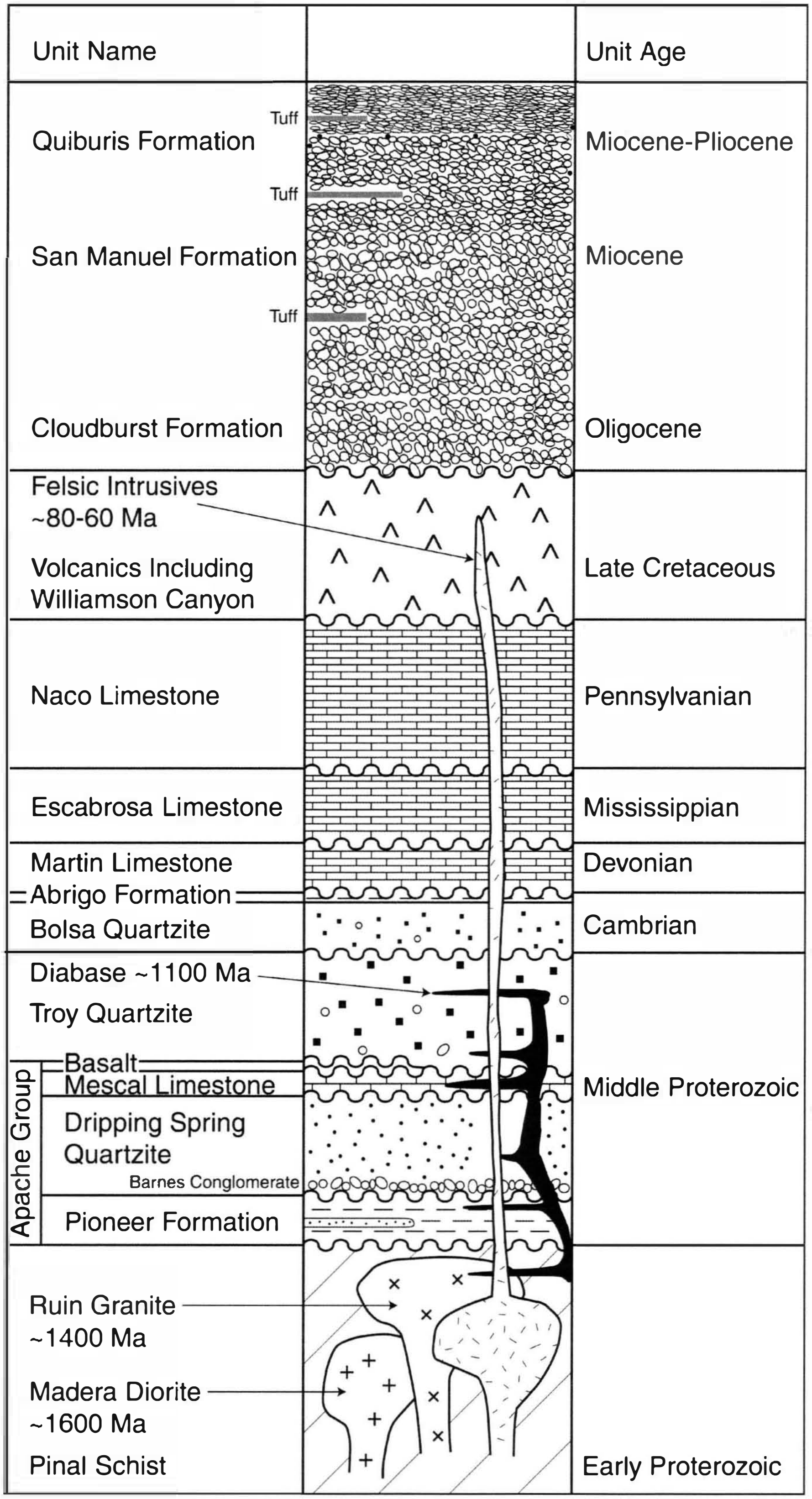


Figure 2. Rock units in the upper crust in the vicinity of the Tortilla and Dripping Spring Mountains. All pre-Tertiary rock units shed clasts into the middle Tertiary basins.

Part I

Mid-Tertiary syn-extensional sedimentation in the Hackberry Wash area

Key points:

Middle Tertiary basin development during extension
- At least three episodic tilting events
- Total of approximately 90° tilting

Stratigraphic characteristics
- Depositional environment was mostly braided stream-dominated alluvial fans
- Local large-scale catastrophic rock avalanches
- Below the rock avalanche deposits, clasts are dominated by Paleozoic and Proterozoic fragments.
- Above the rock avalanche deposits, clasts are dominated by Cretaceous and/or Tertiary volcanic fragments.

Purpose:

The study of middle Tertiary stratigraphy in the Tortilla Mountains and the Dripping Spring Range is essential for developing an understanding of the regional faulting and tilting history as well as erosional and depositional processes and the crustal scale recycling of materials. For example, where Tertiary sedimentary rocks have been tilted, bedrock has been tilted by a minimum of that amount (depending on how much tilting took place before deposition occurred to preserve the record). A well-exposed section of middle Tertiary sedimentary rocks, the Hackberry Wash facies of the Oligocene Cloudburst Formation, outcrops in the Hackberry Wash area. The excellent exposure makes Hackberry Wash an ideal location for conducting this study.

The study of Tertiary sedimentary rocks may aid our understanding of the dispersion of metals from mineralized systems in the surface environment at different stages of recent geologic history. If highly-altered and mineralized material is exposed to surface conditions and weathered, we can look for evidence for how it was dispersed into the surface environment in the sedimentary record. Was it more concentrated by mass movement or short transport distances? Or was it diluted by significant mixing with other material, sluggish erosion rates, or rapid dispersion over a larger area? Through provenance studies of sedimentary rocks and by conducting geochemical analyses in the context of that understanding, we can assess the geochemical flux in the environment at the time of erosion and deposition of those sediments.

Location:

The study area is located in the vicinity of Hackberry Wash, on the east side of the Tortilla Mountains, Pinal County, Arizona (Figs. 3, 4). Hackberry Wash is located about 3 km southwest of the town of Kearny (Figs. 5,6). It sits approximately 100 km (60 mi) north of Tucson and it is southeast of Phoenix.

Access:

The area is accessible by a dirt road leading from the west side of HWY 77 between mileposts 133 and 134 (turn off: UTM 522045 E, 3648200 N; note all UTM coordinates given in NADS '27 CONUS

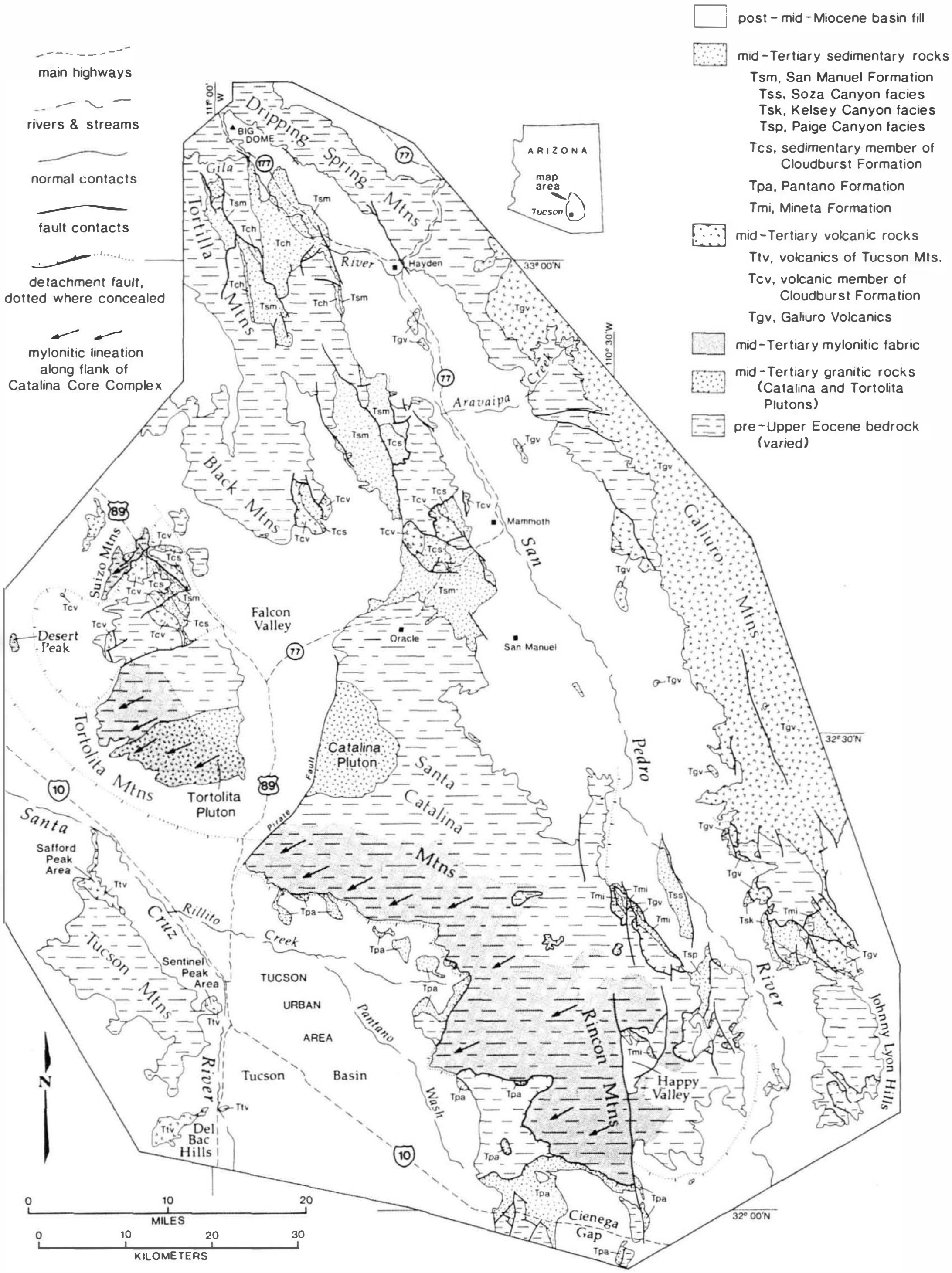


Figure 3. Geologic sketch map of Catalina core complex (mylonitic foliation and lineation along southwest flank) and San Pedro trough (traversed by San Pedro River and by Gila River below their confluence) showing areal distribution of tilted homoclines of mid-Tertiary volcanic and sedimentary successions in relation to exposures of older bedrock and younger basin fill; modified after Dickinson and Shafiqullah (1989).

(Dickinson, 1991, p.4)

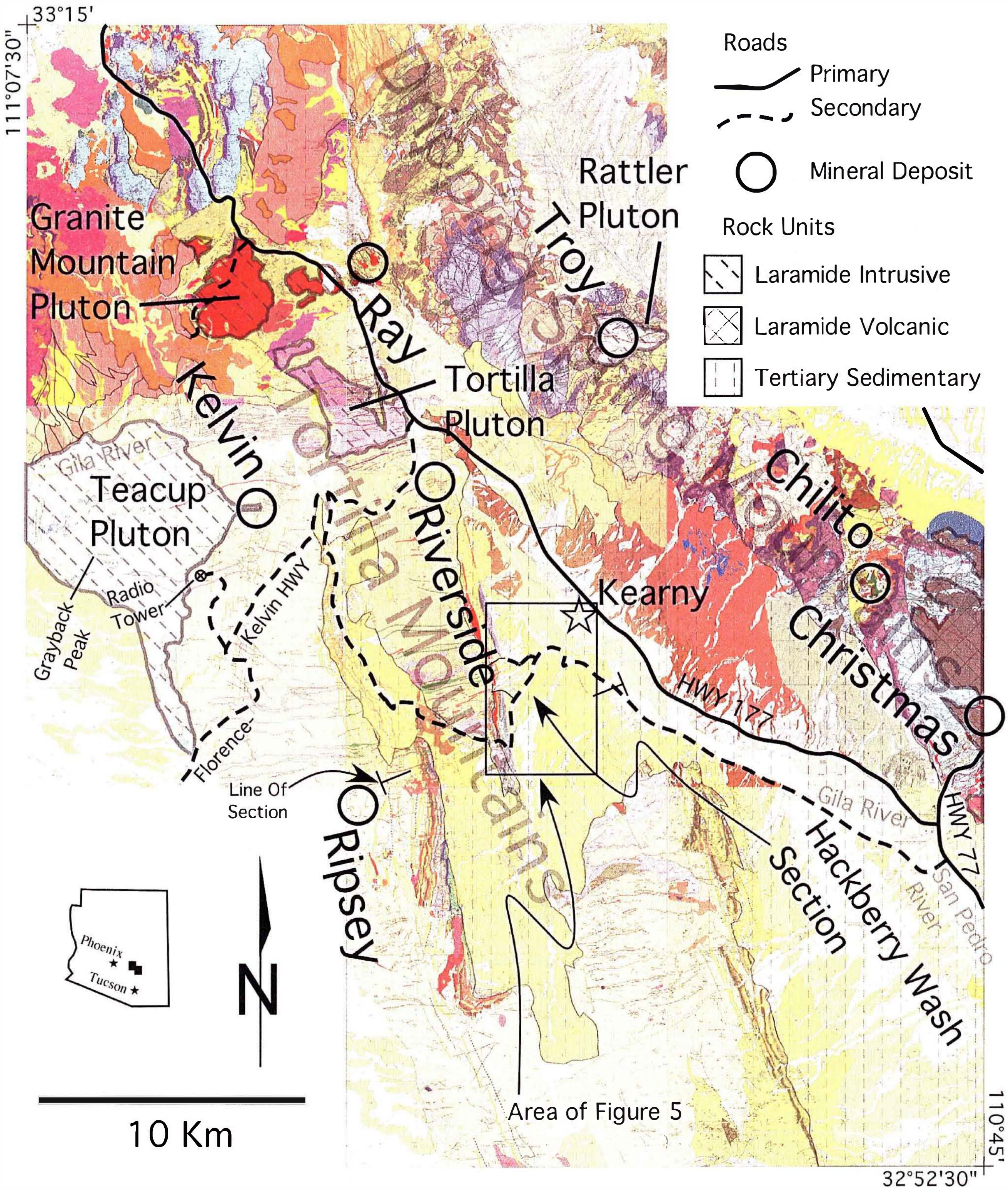


Figure 4. Reduced geologic map compilation of the northern Tortilla and Dripping Spring Mountains. Important geological and geographical features are highlighted. Compiled from USGS Geologic Quadrangle maps.

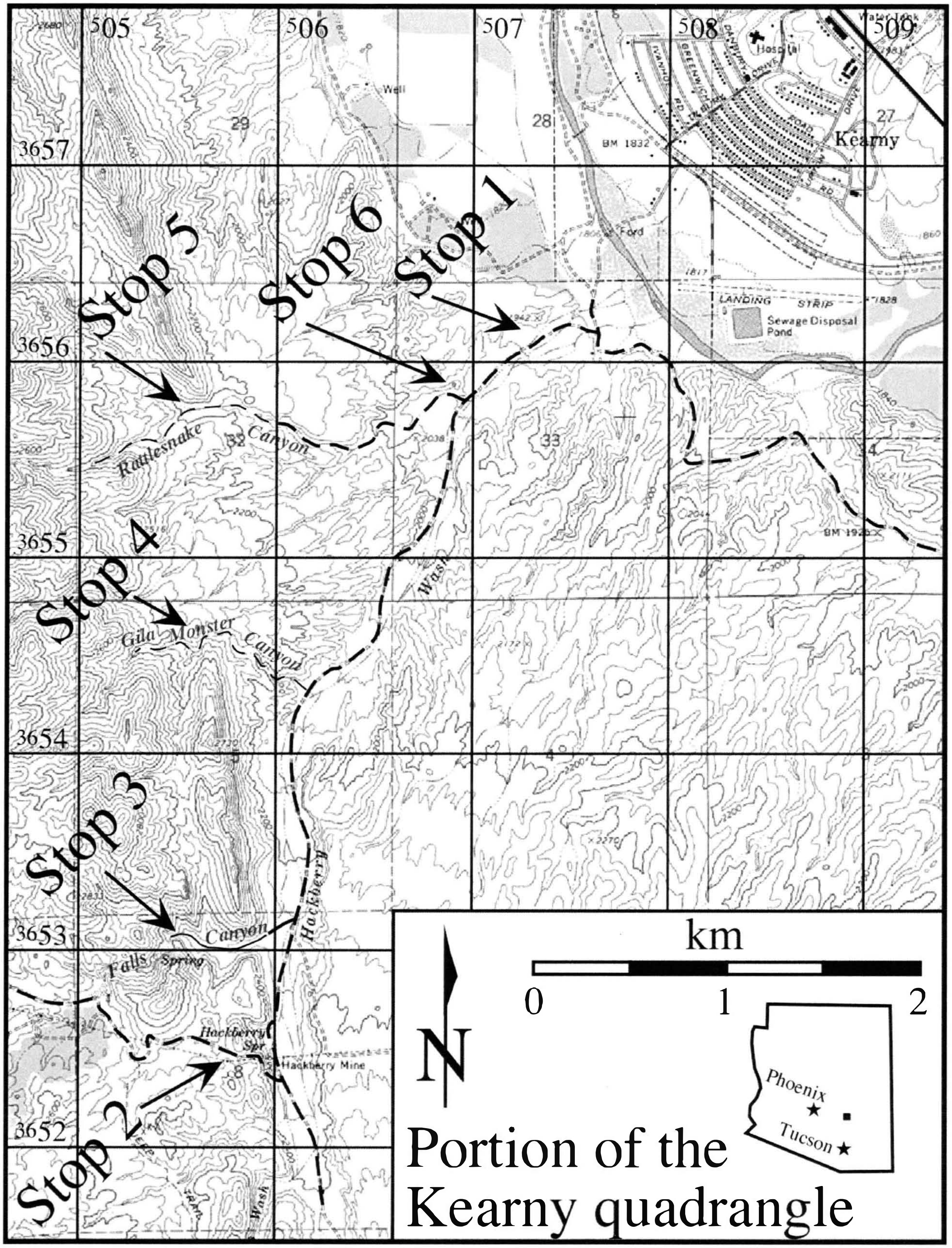


Figure 5. Field trip stops in the Hackberry Wash area: Stop 1) Mouth of Hackberry Wash; Stop 2) Overview; Stop 3) Falls Canyon (informal name); Stop 4) Gila Monster Canyon (informal name): Stop 5) Rattlesnake Canyon (informal name); Stop 6) Mouth of Rattlesnake Canyon. Note: UTM coordinates in thousands, projection is NAD '27 CONUS.

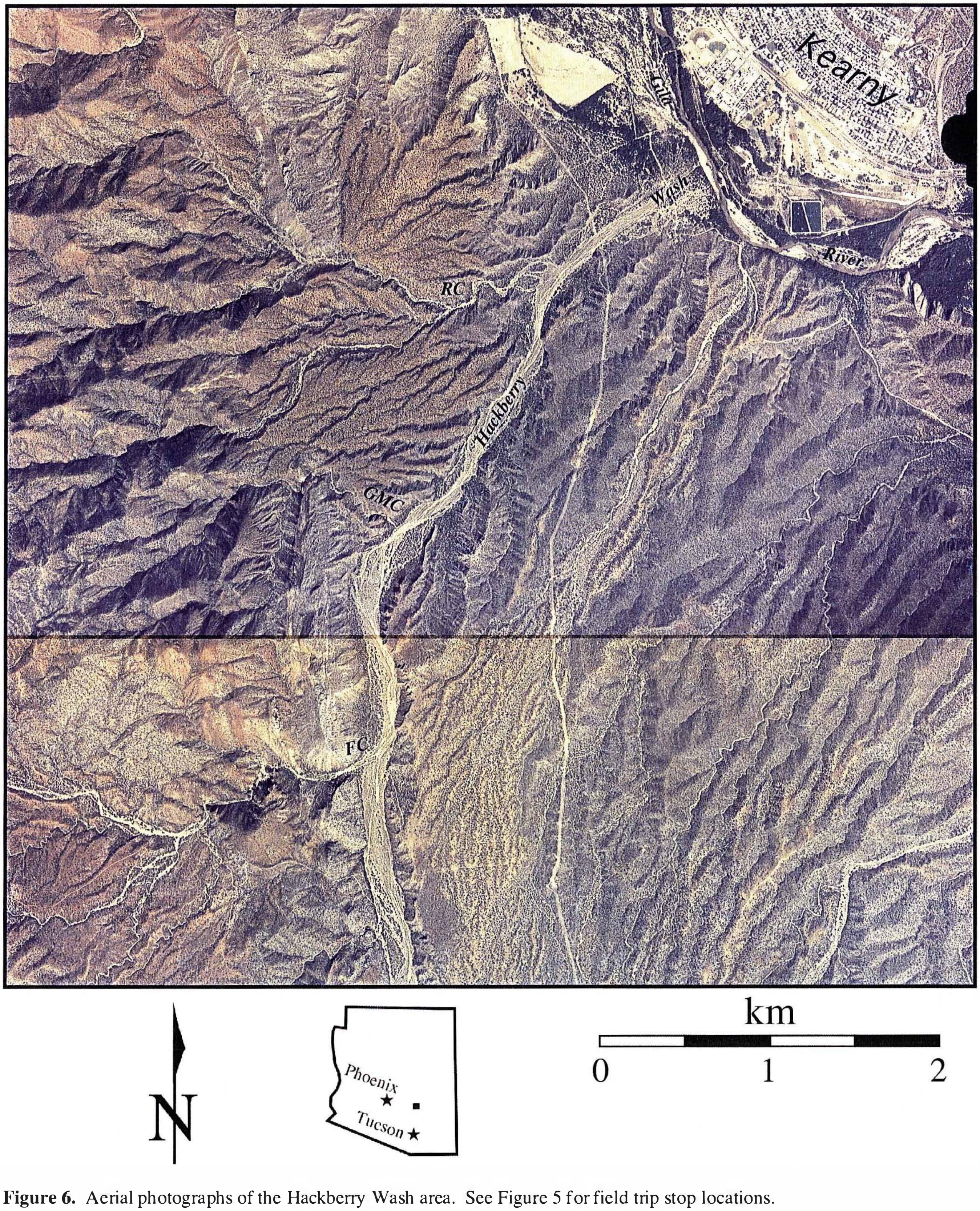


Figure 6. Aerial photographs of the Hackberry Wash area. See Figure 5 for field trip stop locations.

projection). (Figure 1.1) Follow the road west across the San Pedro River (ford). Follow the main road where it turns north along the railroad tracks for about one kilometer (half a mile) where it crosses the tracks to the west and continues north. Follow the main road north. After about 3 kilometers (@ 2 miles), the main road veers sharply west and begins climbing into Smith Wash (UTM 516680 E, 3650725 N). Do not follow this road. Instead take the small road that continues

straight ahead to the north. You will pass through several gates on the way (please close all gates). After about 5 kilometers (@ 3 miles), the road will again veer west (take the left fork at UTM 509753 E, 3654945 N) and climb a hill with a gate near the top. The road will then turn sharply and descend the same hill to the east and continue north into Hackberry Wash. (Figure 1.2). After a few hundred more meters, turn left, just before the next gate (UTM 507651 E, 3656117 N) and continue west up Hackberry Wash.

Background:

We measured and described approximately 1900 meters of dominantly fluvial rocks with locally interbedded debris flow deposits (Fig. 7) in Hackberry Wash. This part of the stratigraphic succession of Tertiary-age clastic sedimentary rocks was correlated with the Cloudburst Formation in the vicinity of San Manuel to the south (Dickinson, 1991, 2002). Dickinson named these rocks in and around Hackberry Wash the Hackberry Wash facies of the Cloudburst Formation. This area was mapped in detail by Cornwall and Krieger (1975a) and Krieger (1977). Subsequent to our study, Dickinson (2002) subdivided the Hackberry Wash facies of the Cloudburst Formation into a lower and upper member.

The age of the Hackberry Wash facies of the Cloudburst Formation is constrained by one whole-rock K-Ar age of 25 Ma on a basaltic andesite mapped near the bottom of the facies, correlated from Jim Thomas Wash (Dickinson, 1991). Silicic ash fall tuff interbedded with the San Manuel Formation (overlying the Hackberry Wash facies), also in Jim Thomas Wash, yields a biotite K-Ar age of 20 Ma (Dickinson, 2002).

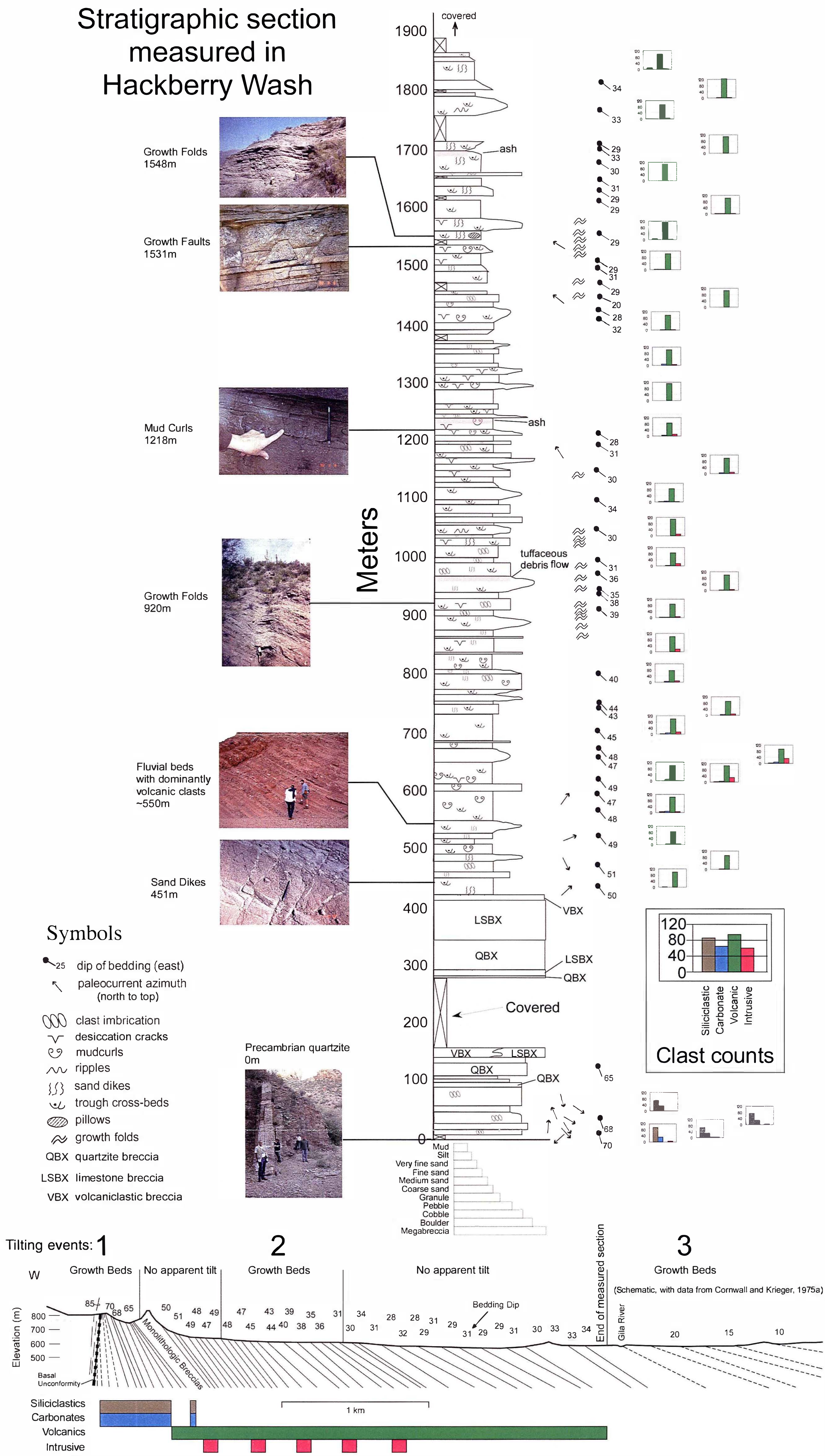
At the bottom of the measured section, Tertiary sedimentary rocks rest on Middle Precambrian Troy quartzite with a slight angular unconformity. The dips of the Tertiary sedimentary rocks at the unconformity are near vertical and progressively (though not uniformly) decrease in dip up-section, ultimately recording approximately 90° of Oligocene-Miocene (Figure 1.3) tilting. In a broad sense, the dips fan upward (growth beds). However, in detail, there appears to be episodic tilting separated by periods of deposition during tectonic quiescence. Bedding tilts progressively decrease from near vertical at the unconformity to dips of about 50° (suggesting 35 to 40° of rotation during deposition of these sediments). Above this growth panel, dips are consistent with little variation for several hundred meters of section. Stratigraphically above the panel of constant dips, another growth panel with 20° decrease of dip produces dips that range from about 50° to about 30°. The last 30° (or more?) of tilt is recorded in sedimentary rocks above the measured portion of the section in Hackberry Wash. These shallowly-dipping sedimentary rocks are partially covered by Gila River alluvium, although they outcrop again east of the Gila River in the Dripping Spring Mountains. This episodic fanning of dips suggests three periods of tilting (on perhaps three sets of faults).

Regionally, the variety of source rocks for the Tertiary sedimentary rocks varies significantly and includes clasts from all of the older rocks units. Locally (at the scale of tens to even hundreds of meters), however, the clast content of the sedimentary rocks often exhibits little variability. In the Hackberry Wash section, we conducted clast counts approximately every 50 meters and found variability from the base to the top of the measured section. However, clast content was commonly consistent over significant intervals, punctuated by relatively abrupt changes (Figure 1.3).

Near the base of the section, the sedimentary rocks are generally coarse, poorly sorted, and angular, which suggests short transport distances in a relatively high-energy environment. The clasts are dominated by Apache Group siliciclastic sedimentary rocks and Paleozoic carbonates, with minor quantities of porphyritic igneous intrusive rocks also present. The depositional environment was probably a gravelly braided stream.

From about 100 to 400 meters above the base of the section, a number of landslide megabreccias (Krieger, 1977) are interbedded with the sedimentary rocks described above. These moderately to locally very thick (over 100 meters) oligomictic (monolithologic) sedimentary rocks are typically brecciated, but still internally exhibit original stratigraphic and sedimentary structural features at a larger scale, suggesting large-scale mass movement. The landslide blocks occur in rocks dipping from about 70° to 50° (i.e., about 20 to 40° of original tilt) and may have occurred when bedrock sedimentary rocks were tilted to an angle at which stratigraphic horizons became unstable slip planes.

Figure 7 (following page). Sratigraphic column of the 1900 meters of section measured in Hackberry Wash. Note that the sedimentary rocks become finer-grained and exhibit more features of saturated sediment deposition up section. Along the bottom a schematic cross section approximately along Hackberry Wash (along the line of the measured section) shows dips of beds (each measurement shown is usually an average of 4 to 6 individual measurements in a given area) from the base of the measured section at the head of Falls Canyon (Stop 3) to the top of the measured section near the Gila River (no vertical exaggeration). Apparent periods of sedimentation during active tilting events are identified. Results of individual clast counts are shown adjacent to the stratigraphic column; the bar graph at the bottom of the schematic section summarizes the types of clasts observed within the conglomerates.


Stratigraphic section measured in Hackberry Wash
Meters
covered
ash
tuffaceous debris flow
LSBX
QBX
VBX
Covered
Growth Folds 1548m
Growth Faults 1531m
Mud Curls 1218m
Growth Folds 920m
Fluvial beds with dominantly volcanic clasts ~550m
Sand Dikes 451m
Precambrian quartzite 0m
Mud
Silt
Very fine sand
Fine sand
Medium sand
Coarse sand
Granule
Pebble
Cobble
Boulder
Megabreccia
Clast counts
120
80
40
0
Siliciclastic
Carbonate
Volcanic
Intrusive
Symbols
25 dip of bedding (east)
paleocurrent azimuth (north to top)
clast imbrication
desiccation cracks
mudcurls
ripples
sand dikes
trough cross-beds
pillows
growth folds
QBX quartzite breccia
LSBX limestone breccia
VBX volcaniclastic breccia
Tilting events: 1
2
3
W
E
Growth Beds
No apparent tilt
Growth Beds
No apparent tilt
Growth Beds
(Schematic, with data from Cornwall and Krieger, 1975a)
End of measured section
Gila River
Bedding Dip
Monolithologic Breccias
Basal Unconformity
Elevation (m)
800
700
600
500
1 km
Siliciclastics
Carbonates
Volcanics
Intrusive

A megabreccia deposit composed of Mesozoic Williamson Canyon intermediate to mafic volcanic rocks occurs at the top of the megabreccia-dominated stratigraphic interval. Intermediate to mafic volcanic rocks are the dominant clast type in the sedimentary rocks above the megabreccias in the Hackberry Wash section, with dramatically fewer clasts of siliciclastics and carbonates. These volcanic clasts may also Williamson Canyon volcanic rocks, although some or all of these volcanic clasts might be Oligocene intermediate volcanic rocks equivalent to those found in the Galiuro Mountains to the southeast.

The Tertiary sedimentary rocks become progressively finer-grained and relatively better-sorted up section. Upsection, the sedimentary rocks also exhibit sedimentary structures consistent with a more saturated environment such as sand dikes, lode casts, and growth folds, as well as common mud cracks and mud curls that suggest repeated subaqueous and subaerial exposure (Figure 1.3). The depositional environment was probably a gravelly, stream-dominated alluvial fan near the bottom of the volcanic-dominated interval (just above the megabreccia deposits). The braided streams became more sand-dominatd over time.

There is variability, however, in the clast content of sedimentary rocks throughout the Hackberry area and in the region (Fig. 8). To the north of the Hackberry wash section, clasts are dominantly coarse-grained porphyritic granite (Precambrian Oracle granite) and porphyritic and fine to medium grained equigranular, felsic to intermediate igneous rocks (probably various Laramide intrusive rocks).

There are relatively few clasts exhibiting alteration in the Hackberry Wash section. Near the base of the section (within and below the landslide megabreccias) there are carbonate clasts that show partial to complete replacement by silica + pyrite (oxidized to goethite) or pyrolusite (such as distal carbonate replacement seen near the Magma Porphyry deposit at Superior). In the Hackberry section, generally 1 to 10% (locally more) of igneous clasts contain (minor) chlorite ± epidote ± rare pyrite (oxidized to goethite). To the north, altered clasts are more common and locally exhibit strong quartz + sericite + pyrite (oxidized to goethite) alteration.

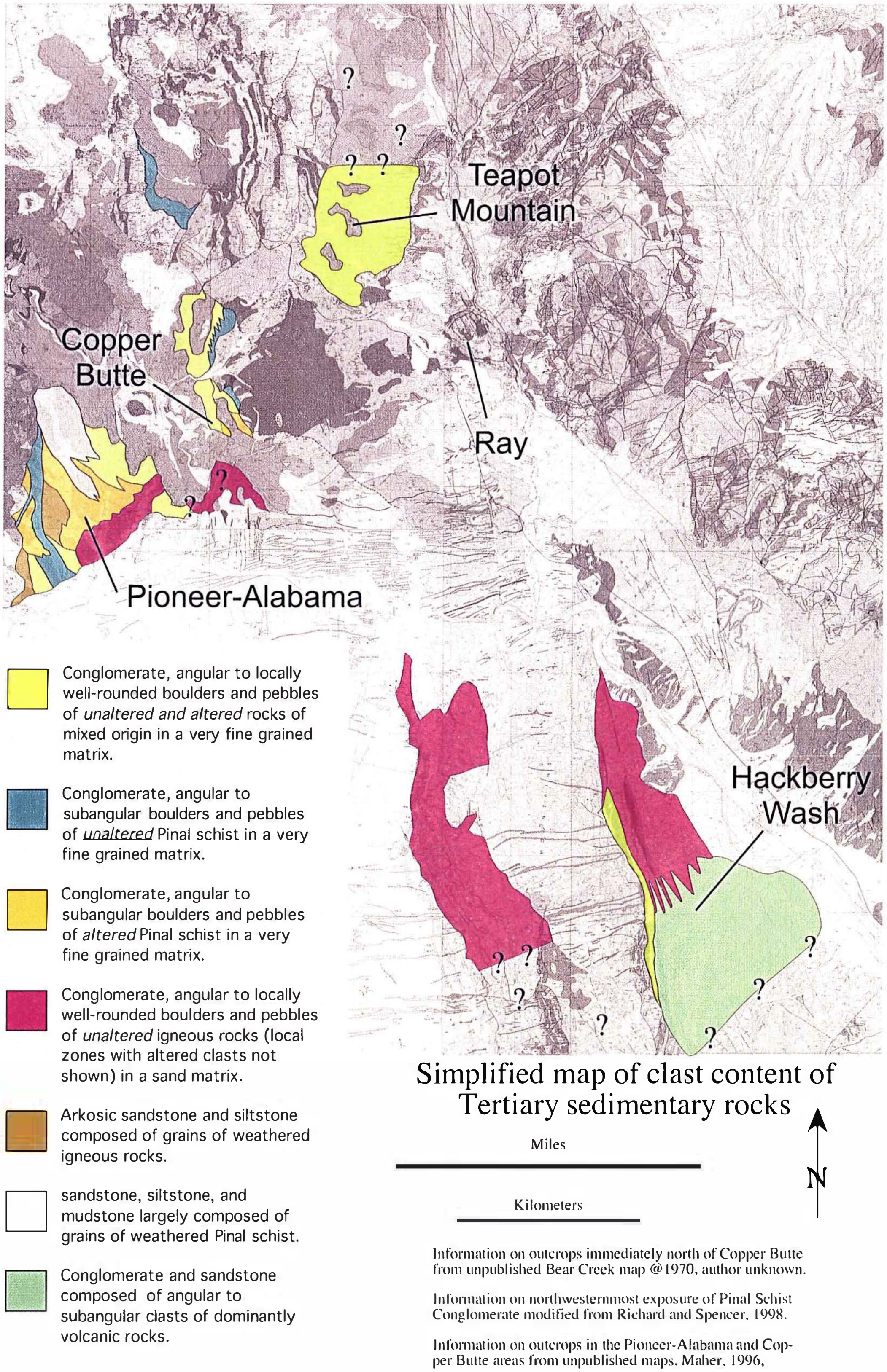


Figure 8. Simplified map of clast content of Tertiary sedimentary rocks in the vicinity of the study area. Intertonguing of conglomerates in the area just northwest of Hackberry Wash and north of Copper Butte is shown schematically.

Field Trip Stop Descriptions

STOP 1: Near mouth of Hackberry Wash

Observations

1) *Lithofacies 1a:* Clast-supported conglomerate and sandstone with prominent graded bedding and clast imbrication. Erosional scours are found at the lateral margins of lithofacies 1a beds and scours are typically about ten centimeters deep. The basal surface of lithofacies 1a lithosomes is erosional. Pebble-sized clasts are the largest clasts observed at Stop 1, but clasts up to 0.5 meters in diameter are common lower in the section (Stops 3 and 4). Clasts are sub-angular to rounded. Lithofacies 1a beds are 10-30 cm thick at Stop 1, but are as thick as 100 cm lower in the section.

Lithofacies 1b: Clast-supported, moderately-sorted sandstone and pebble conglomerate with abundant trough cross-beds. Erosional scours are found at the lateral margins of lithofacies 1b lithosomes, and the basal surface of lithofacies 1b beds is erosional. Clasts are sub-angular to well-rounded. Lithofacies 1b beds are 10-40 cm thick at Stop 1, but are as thick as 100 cm lower in the section.

Lithofacies 1c: Planar-bedded, well-sorted sandstone. Average grain size is medium sand, which is smaller than the average grain size in other lithofacies. The basal surface of lithofacies 1c usually is not erosional. Lithofacies 1c lithosomes are usually cut laterally by lithofacies 1a and 1b beds.

2) *Lithofacies 2:* Matrix-supported, massive conglomerate. Dewatering structures are common (better exposed at stop 4), but other sedimentary structures are not observed. The basal surface of lithofacies 1 is not erosional. Clasts are angular to sub-angular. Grain size ranges from mud in the matrix to pebble-sized clasts at Stop 1 (coarser-grained lower in the section). Lithofacies 2 lithosomes are 20-150 cm thick and are typically thicker than intercalated lithofacies 1 beds.

3) *Clast Composition:* Intermediate volcanic clasts dominate here.

4) *Dip of bedding:* Bedding dips about 30° east.

5) *Folding of bedding:* Bedding folds have maximum amplitudes of several meters and lose amplitude upsection and downsection. The thickness of the folded layers does not change from the limb to the hinge of the fold. The axial surface of each fold is oriented at a steep angle to unfolded bedding surfaces, and the corresponding hinge line of the fold is nearly parallel to bedding surfaces. Thus restoration of bedding to horizontal rotates the folds into an upright, sub-horizontal attitude. Some depositional units are thinner over the anticlines and thicker in the synclines. It is sometimes possible to observe overlying beds onlap an anticline.

Interpretations

1) We interpret lithofacies 1 to be braided stream deposits. Streams were of modest size. At Stop 1, the braided streams were dominated by sand-sized clasts, but lower in the section, gravel-sized material dominated the braided streams.

2) We interpret lithofacies 2 to be debris flow deposits.

1+2) We interpret the depositional environment for lithofacies 1 and 2 to be the medial portion of a stream-dominated alluvial fan. Streams were fairly small and were dominated by gravel-sized clasts early in the history of the basin, with sand-dominated braided streams more common later. Paleocurrent indicators (mostly trough cross-beds) show that clasts in the upper 800 meters of our measured section were derived mostly from the southeast.

3) In the portion of the basin covered by our measured section, the average grain size of the volcanic clasts is pebble-size and clasts up to 0.5 meters in diameter are fairly common. This large grain size indicates a proximal source for these clasts. The thickness of the volcaniclastic-dominated Tertiary sedimentary rocks is several kilometers, which indicates that the source of the volcanic clasts was voluminous. These observations require that a large source of volcanics existed to the south of Hackberry Wash during the Oligocene-Miocene. Two volcanic units currently outcrop in this position: 1) Upper Cretaceous Williamson Canyon Volcanics, and 2) Oligocene Galiuro Volcanics. Either or both of these volcanic units could have produced the volcanic clasts in the Cloudburst Formation in Hackberry Wash. Dickinson (2002) suggests that the volcanic clasts were derived from the Williamson Canyon Volcanics.

4) This outcrop is near the top of our measured section, but it is near the middle of the full Tertiary sedimentary section. More steeply-dipping Tertiary sedimentary rocks outcrop to the west (Stops 3 and 4), and more shallowly-dipping Tertiary sedimentary rocks are exposed to the east in the Dripping Spring Mountains.

5) The key observation that constrains the timing of formation of the bedding folds is their progressive loss of amplitude upsection and downsection. Another important observation is the occasional onlap of overlying sediments onto anticlines. These observations demonstrate that folding occurred during deposition, thus these structures are growth folds. The sediments likely were not lithified during folding, and in some cases the sediments probably were not even well consolidated during folding. Below we discuss two possible processes to explain the generation of the growth folds.

I. *Slumping of beds on a tilted depositional surface.* Still-wet sediments would slump down a tilted surface, but the surface would need to be tilted to a fairly steep angle, perhaps steeper than 10°. It seems unlikely that such a steep depositional slope could be maintained for long periods of time, even with active normal faults beneath the basin. It is possible that earthquakes generated on the underlying normal faults created instabilities in the sediments due to sudden fluidization, causing slumping down a shallowly-dipping surface on which the sediments would otherwise have been stable.

II. *Folding due to the regional stress field.* The poorly-consolidated sediments may have folded in response to the regional extensional stress field, or perhaps to a more local stress field. One problem with this explanation is the difficulty in transmitting enough stress to the recently deposited sediments to fold them. If this were a common process, most sedimentary rocks on earth would contain this type of growth folds. A second difficulty with this explanation is the orientation of the growth folds with respect to bedding. In Anderson's simple theory of faulting, the maximum compressive stress is oriented perpendicular to the surface of the earth in normal fault-dominated regions. This orientation should produce folds whose axial surface is perpendicular to the maximum compressive stress. In this case, the axial surface of the folds should be nearly parallel to bedding. This orientation is not observed in Hackberry Wash.

STOP 2: Near the base of the Hackberry Wash section south of Falls Canyon

Park where the side road branches off to the south up a small steep hill. Matrix supported quartzite megabreccia is exposed at the top of the hill. Walk north-northeast about 50 meters to the south flank of the limestone ridge. This is a large landslide/ megabreccia deposit of mostly Martin Limestone. Here we will introduce the regional geology and overview a portion of the Middle Tertiary section exposed in Hackberry Wash.

Looking to the north-northwest, we can see distinct limestone ridges that are landslide deposits tilted so that dips are in the range of about 50° to 60° (at our next stop, we will walk through an east-west canyon that cuts the landslide deposits and conglomerates in cross section). To the northeast, we see ~50° dipping, reddish-brown sandstone and conglomerate beds. This unit has been correlated with the Cloudburst Formation to the south (in the San Manuel area) and subdivided into the Lower Member of the Hackberry Wash Facies (Dickinson, 2002). Looking to the east we see dips in the range of 20°. This is siltstone to sandstone with interbedded conglomerates of the Upper Member of the Hackberry Facies of the Cloudburst Formation (Dickinson, 2002). The sedimentary rocks of the Upper Member onlap and overlap the more steeply dipping beds of the Lower Member.

Looking to the immediate northwest, you can see prominent outcrops of Precambrian quartzite that are dipping approximately 90°. About 4 km to the west southwest, you can see gray (limestone) and tan (quartzite) beds that are also dipping very steeply. These limestones and quartzites are in the next tilted fault panel to the west. About 15 km to the east, you can see more shallowly-dipping, gray, Paleozoic limestone beds (Paleozoic) in the Dripping Spring Mountains.

We will spend a few minutes here discussing the regional geology in order to place the middle Tertiary section exposed in Hackberry Wash in the tectonic context.

STOP 3: Falls Canyon (Informal Name)

Observations (Not seen at previous stops)

1) *Dip of bedding:* Bedding in the pre-Tertiary basement dips about 90°. Tertiary sediments immediately above the basal unconformity are covered, but they probably also dip nearly 90°, as observed to the north (Stop 4). The first exposed Tertiary bed, about 10 meters above the unconformity, dips 70° east. Dips decrease about 20° between the basal unconformity and the megabreccia deposits.

2) *Pre-Tertiary basement:* The pre-Tertiary basement in Falls Canyon is Middle Proterozoic Troy Quartzite, which was intruded by diabase at about 1100 Ma. Thus the unconformity between Tertiary and pre-Tertiary rocks here spans at least 1 billion years.

3) *Clast composition:* Quartzite and limestone clasts dominate here. There are very few granitic clasts, and no volcanic clasts. A few of the limestone clasts have oxidized silica-pyrite veins and massive Mn oxide veins. Some clasts (up to 4 cm across) of massive, botryoidal Mn oxide also occur. These may be weathered from an area of distal alteration of limestone by hydrothermal fluids related to a porphyry system. Similar alteration of limestones occurs west of the Magma porphyry system near Superior, AZ.

4) *Sedimentary structures:* Clast imbrication is particularly well-developed here. Graded bedding is common, and trough cross-beds are present in the sandstones. Note no folding of bedding here. There are also no desiccation cracks, mud curls, or sand dikes, all of which we will see at Stop 4. There are no matrix-supported lithosomes below the interval of lithofacies 3 (the megabreccias).

5) *Grain size:* The average grain size of the conglomerates at the base of our measured section is cobble, and boulders up to 0.5 meters are common. Note that clasts are much larger here than at Stop 1.

6) *Lithofacies 3:* Massive monolithologic megabreccias. Each megabreccia body is composed entirely of a pre-Tertiary unit which is often identifiable on the basis of fossils, grain size, phenocryst composition, or other distinguishing characteristics. The boundaries of the megabreccia deposits are parallel to the bedding in underlying and overlying conglomerates and sandstones. The megabreccia deposits are often matrix supported, and the matrix composition is identical to the composition of the larger clasts.
Individual clasts within the megabreccias are commonly fractured, and clasts are rotated with respect to one another. At a larger scale, the depositional unit scale, each megabreccia deposit remains very coherent. That is, different pre-Tertiary units are not mixed together within the megabreccias – the megabreccia deposits are very different from the conglomerates above and below them.
In Falls Canyon, the megabreccia deposits are mostly composed of quartzite and limestone. A few volcanic megabreccia bodies are also present, including one whose clasts were probably derived from the Williamson Canyon Volcanics.

Interpretations
1) Tertiary sediments deposited on the basal unconformity have been rotated approximately 90°.

3) The limestone and quartzite clasts were derived from Proterozoic and Paleozoic strata. Clast imbrication yields paleocurrent directions dominantly from the northwest, the hanging wall of the basin-bounding normal fault. Thus at the base of the section in Falls Canyon, clasts were derived mostly from Proterozoic and Paleozoic sedimentary rocks that were exposed in the hanging wall of the basin-bounding fault, with a few clasts derived from underlying granite.

4) The depositional environment for the conglomerates and sandstones was a gravelly braided stream. Deposition may have occurred on a stream-dominated alluvial fan, although deposition on a braid plain not associated with an alluvial fan cannot be excluded.

6) We interpret lithofacies 3, the monolithologic megabreccia deposits, to be rock avalanche deposits. In this interpretation, the clasts were supported during transport by a layer of compressed air generated at the boundary between the rock avalanche and the ground. The rock avalanches may have originated in the hanging wall when it was tilted 20° to 40°. Derivation from the footwall cannot be excluded, however.

DRIVE FROM STOP 3 TO STOP 4: Note the decrease in dip of bedding in the north wall of Hackberry Wash as you drive to the east down the wash.

STOP 4: Gila Monster Canyon (Informal Name)
Observations (not seen at previous stops)
1) *Sedimentary structure 1:* Discontinuous, concave up, 1-10 mm-thick mudstone bodies contained within sandstone. The long dimension of each mudstone body is parallel to bedding, and the bodies often lie along a horizon that is in the middle or upper part of the sandstone bed. Each mudstone body characteristically curls at the edges, usually through about 90°, sometimes through as much as 360°. Mudstone bodies are 3-10 cm long.

2) *Sedimentary structure 2:* Carrot-shaped sandstone bodies hosted in a bed that contains some mud. The long dimension of each sandstone body is oriented perpendicular to bedding. The widest part of each body is located at the top of its host bed. The sandstone bodies taper downward and do not cut through their host bed. The sand grains in each body appear to be derived from an overlying sandy bed. In plan view, bodies join in a quasi-polygonal (or circular) pattern.

3) *Sedimentary structure 3:* Sandstone bodies hosted in a bed that does not necessarily contain a large amount of mud. The long dimension of the bodies is oriented 60° to 90° to bedding, but many sandstone bodies change orientation within their host bed. Bodies cut through their host bed with no significant change in thickness. The sand grains in each body appear to be derived from an underlying sandy bed. The bodies often join sandy lithosomes above and below their host bed. No polygonal pattern is apparent in plan view.

4) Lithosomes are typically 20-50 cm thick and hundreds of meters long. Gila Monster Canyon is a good place to follow an individual bed laterally to observe the lateral dimension of that bed. As you walk, think about the stratigraphic architecture of these deposits.

5) *Clast composition:* Intermediate volcanic clasts dominate here. There are also some granitic clasts present.

6) *Dip of bedding:* Bedding dips about 55° east here.

7) *Lithofacies 3 (Megabreccia Deposits):* Clasts in the megabreccia deposits rotated relative to one another. This rotation is particularly noticeable in the fine-bedded limestone above the diabase megabreccia deposit. At the intrusive contacts between the diabase and the Mescal Limestone, clasts are also rotated and the two units are slightly mixed over a few centimeters. At the outcrop scale, however, the contacts between the diabase and the Mescal Limestone are intact, with both the chilled margins in the diabase and the baked zones in the limestone preserved (Fig. 9).

Interpretations

1) We interpret sedimentary structure 1 to be mud curls. Mud curls form upon drying a thin muddy deposit. The lack of pillar structures associated with the mudstone bodies and their extreme curl (in some cases) argues against an interpretation of sedimentary structure 1 as dish structures.

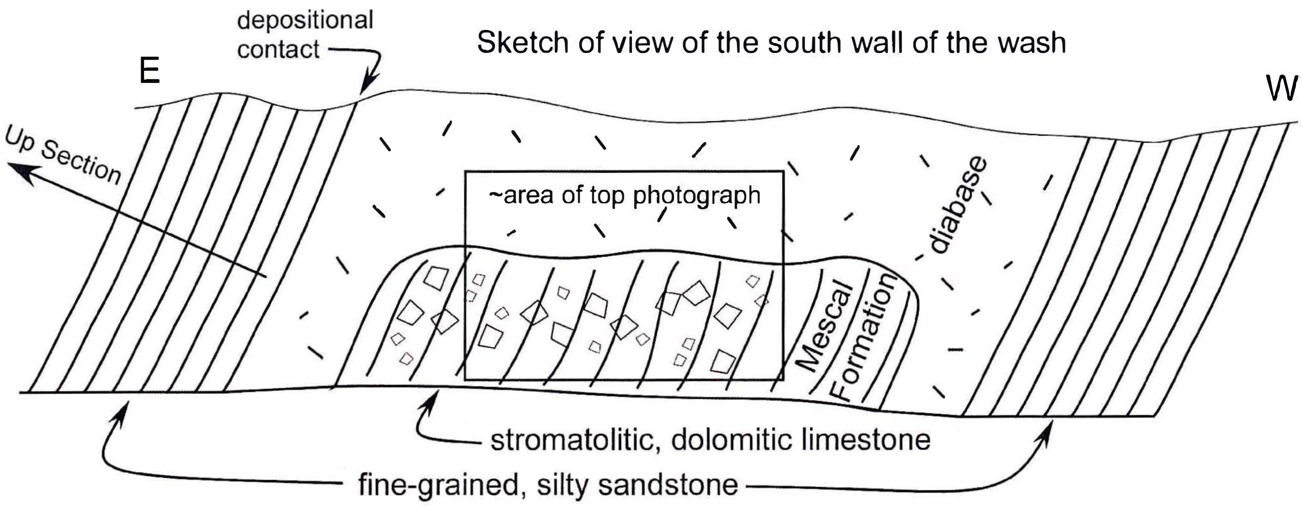
2) We interpret sedimentary structure 2 to be sand-filled desiccation cracks. Desiccation cracks form when host lithosome was exposed subaerially after deposition, allowing it to dry and crack. The next lithosome deposited atop the cracked surface filled the underlying dessication cracks.

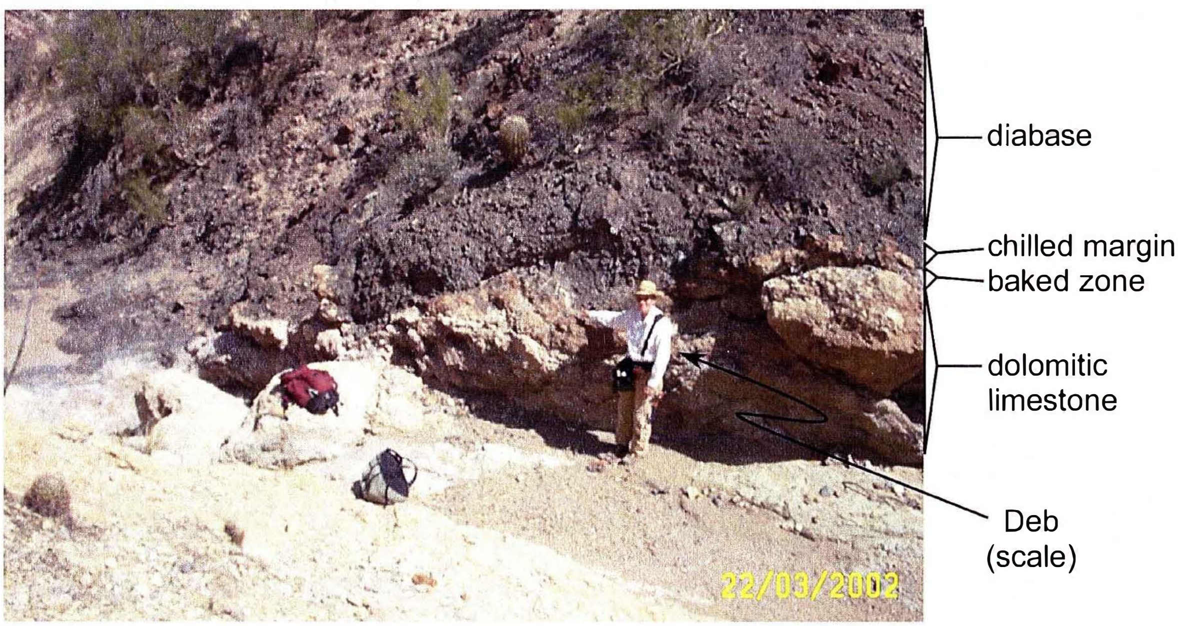
3) We interpret sedimentary structure 3 to be sand dikes (also called pillar structures). Sand dikes are a dewatering structure and form as water escapes from a saturated bed after rapid loading. The escaping water forces its way through the overlying bed, carrying sand grains with it.

4) The aspect ratio of these lithosomes is approximately 1000:1. The lithosomes are broadly lenticular. These deposits are composed of numerous thin, very wide sheets stacked laterally and vertically with erosional contacts separating lithosomes except at the base of debris flow deposits.

6) Above the stratigraphic level of the megabreccia deposits, volcanics dominate the clast composition.

7) Clasts within each megabreccia deposit clearly rotate relative to one another, however there is little mixing of clasts within each rock avalanche.





Example of texture within landslide block. Note fragmentation and some rotation and translation of the fragments within fine (milled) matrix. With only minor translation of the fragments (a few centimeters), the gross contact relationships are preserved.

Figure 9. Intrusive contact between diabase and Middle Proterozoic Mescal Limestone preserved within a large landslide block in sedimentary rocks dipping steeply eastward. Schematic diagram at top shows general field relationships.

STOP 5: Rattlesnake Canyon (Informal Name)

A) Walk up southwest canyon to the nonconformity between the Pioneer Formation and the Ruin Granite.

Observations

1) *Pre-Tertiary basement:* Tertiary sediments were deposited on diabase that intruded Dripping Spring Quartzite. Note the prominent outcrops of sub-vertical Barnes Conglomerate, which is the basal member of the Dripping Spring Quartzite. West of the Barnes Conglomerate (stratigraphically below it), the Pioneer Formation sits nonconformably on Ruin Granite (here cut by late-stage aplitic dikes). Note that this Proterozoic unconformity is approximately parallel to the Tertiary unconformity.

2) *Dip of bedding:* Bedding dips ~90° at the basal unconformity. Dips decrease upsection.

3) *Clast composition*: Near the basal unconformity, clast composition is dominated by Ruin granite, with subordinate quantities of other Proterozic clasts. Above the megabreccia deposits, intermediate volcanics dominate the clast composition, with subordinate quantities of Ruin granite clasts.

4) *Grain size:* Average grain size near the base of the Tertiary section in Rattlesnake Canyon is medium sand-size, significantly finer than the base of the Tertiary section in Falls Canyon.

Interpretations

1) The basal Tertiary unconformity cuts down section between Falls Canyon and Rattlesnake Canyon to the north.

3) The absence of granitic clasts in conglomerates in Falls Canyon is puzzling. Large bodies of granitic rocks are exposed to the west and to the north of Falls Canyon, and paleocurrent directions indicate that clasts in these conglomerates were dominantly derived from the northwest. It seems reasonable to expect granitic clasts in conglomerates in Falls Canyon as in conglomerates in Rattlesnake Canyon. A local source restricted to Paleozoic and Proterozoic strata might be the best explanation for the absence of granitic clasts in the Falls Canyon conglomerates.

B) Walk up northwest canyon a few hundred meters to recessive weathering claystone deposits on the east side of the canyon.

Observations

1) ~25° east-dipping claystones are plastered on the side of the hill, topographically beneath cliffs of limestone megabreccia deposits. The claystones sit atop units that dip ~70° east. The claystones are thin-bedded. Both sandstones and gypsum beds are occasionally found intercalated with the claystones. Gypsum veins are also sometimes observed in the claystones.

Interpretations

1) The claystones suggest deposition in a lacustrine environment. The dips of the claystones suggest that the claystones are younger than the conglomerates beneath them. One explanation for these observations: The conglomerates were deposited and tilted, partially eroded, then covered by a small lake. Tertiary lacustrine sediments to the south of Rattlesnake Canyon also dip ~25° east, suggesting the presence of a basin-sized lake. Sediments deposited in this lake would rest in angular unconformity on older, tilted Tertiary sedimentary rocks.

STOP 6: Mouth of Rattlesnake Canyon (Informal Name)

Climb the small hill to the east of the mouth of Rattlesnake Canyon for summary and discussion. We will discuss field relationships shown in Figure 10, and the cross-section shown in Figure 11.

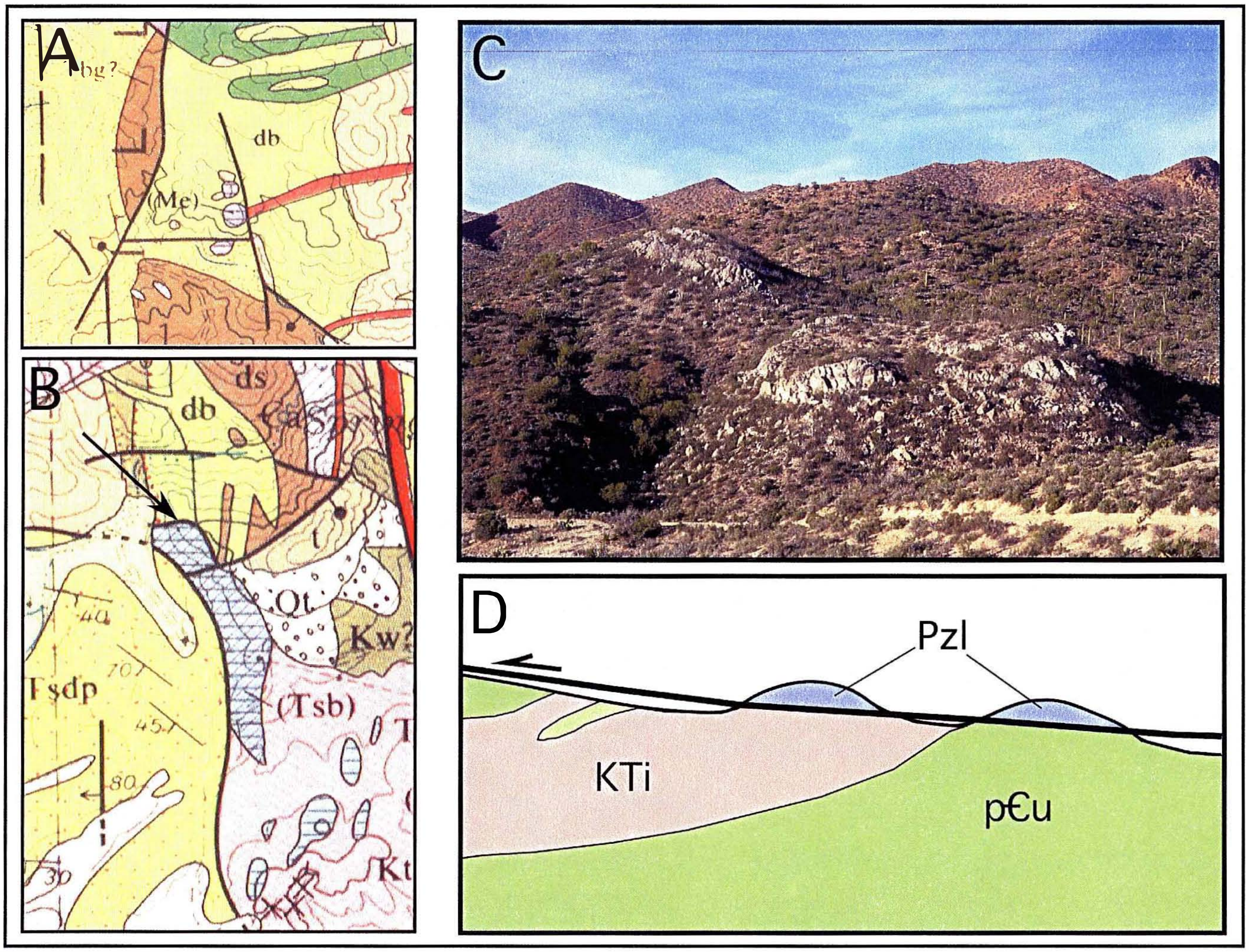


Figure 10. Paleozoic limestone outcrops (typically brecciated) overlying Precambrian metasedimentary rocks and diabase. These outcrops differ from the megabreccia deposits seen in Hackberry Wash in that they are not depositionally bound by clastic sedimentary rocks, but instead overlie bedrock units deeper in the stratigraphic succession. We suggest these are structural blocks that may have been transported down section by normal faults (some of these faults may have been tilted to low angles or even past present-day horizontal).

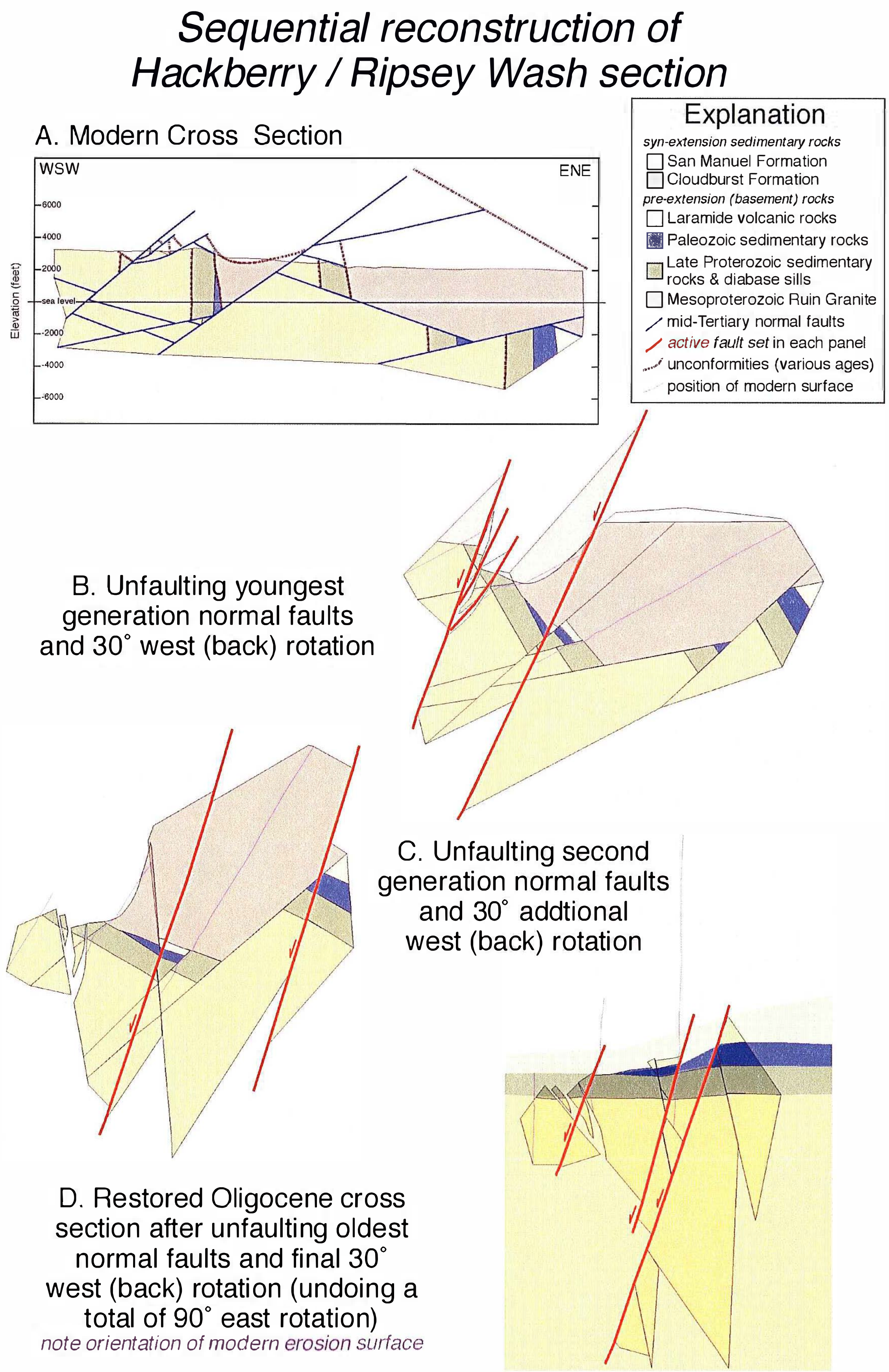


Figure 11. Reconstructed geologic cross section for the Hackberry Wash area (line of section on Figure 3) by E. Seedorff.

Part II

Evolution of the upper crust in the vicinity of the Ray copper deposit, Arizona: A 1.4 billion year saga of magmatism, metasomatism and extreme crustal extension

To be continued…

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